

Djanibekov, Nodir; Kurbanov, Zafar; Tadjiev, Abdusame; Dhehibi, Boubaker; Akramkhanov, Akmal

## Working Paper

# Determinants and impacts of individual and combined adoption of sustainable agricultural practices in Uzbekistan

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## Determinants and impacts of individual and combined adoption of sustainable agricultural practices in Uzbekistan

Nodir Djanibekov, Zafar Kurbanov, Abdusame Tadjiev,  
Boubaker Dhehibi, Akmal Akramkhanov

## AUTHORS

**Nodir Djanibekov<sup>a</sup>** is a researcher and a deputy head at the Department of Agricultural Policy, IAMO. He obtained his PhD from the Center for Development Research (ZEF), University of Bonn, Germany. Prior to joining IAMO, he was a researcher in the German-Uzbek development research project on the restructuring of land and water use in Uzbekistan. His research explores how agricultural policies, (in)formal institutions, and behavioral factors shape farmers' decisions on land-water use, and the adoption, adaptation, and resilience outcomes, with a particular focus on irrigated areas of Central Asia. He leads the research group on rural community resilience (CARE) and serves as a contact person for IAMO's Central Asia International Research Group.

**Email: [Djanibekov@iamo.de](mailto:Djanibekov@iamo.de)**

**Zafar Kurbanov<sup>a</sup>** is a researcher at the Department of Agricultural Policy, IAMO. He joined IAMO in January 2019 as a doctoral researcher within the SUSADICA project. Before his work at IAMO, he had been teaching an undergraduate economics and research methods module at Westminster International University in Tashkent (WIUT). He completed his MSc. in Environmental and Natural Resource Economics with a Fulbright scholarship at the University of Rhode Island, USA. He obtained his doctorate at the Martin Luther University Halle-Wittenberg in 2025. He is currently engaged in research on property rights, agricultural technology adoption, and behavioral economics, with broader interests in how institutions and incentives shape decision-making.

**Email: [Kurbanov@iamo.de](mailto:Kurbanov@iamo.de)**

**Abdusame Tadjiev<sup>a,b</sup>** joined IAMO in January 2019 as a doctoral researcher in the Department of Agricultural Policy, working within the framework of the SUSADICA project, funded by the Volkswagen Foundation. He earned his doctorate at the Martin Luther University Halle-Wittenberg, Germany, in 2024. He studied Agricultural Economics at Samarkand Agricultural University, Uzbekistan, where he also worked as an assistant professor. His research interests focus on the adoption of sustainable

agricultural practices in irrigated areas of Central Asia. He investigates the role of behavioral economics in understanding farmers' decision-making, with particular attention to behavioral factors such as risk and time preferences. His work involves designing and conducting lab-in-the-field experiments to measure these preferences and assess how they influence farmers' decisions to adopt sustainable practices, as well as their perceptions of land use rights.

**Email: [Tadjiev@iamo.de](mailto:Tadjiev@iamo.de)**

**Boubaker Dhehibi<sup>c</sup>** is an agricultural resource economist at the International Center for Agricultural Research in the Dry Areas (ICARDA) and a principal scientist in the Social, Economy, and Policies Team - Resilient Agricultural Livelihoods Systems (RALS) program. His research portfolios include innovations in partnerships, policies and platforms for the efficient, inclusive and climate-resilient transformation of agrifood systems for the CGIAR initiative on From Fragility to Resilience in Central and West Asia and North Africa (F2R-CWANA) in five countries and CGIAR Science for Impact (S4I) Science Program, inclusive business models and financing strategies for the CGIAR-Agro-ecology initiative on Transformational Agroecology Across Food, Land, and Water Systems (AEi), markets and business models for the CGIAR Multifunctional Landscapes Program, and for the Arabian Peninsula Regional Program in the six GCC countries and Yemen. During the period 2011-2025, he has supported research projects in over 18 countries in North Africa, the Middle East, West Asia, and Arabian Peninsula. His current research interests include production economics; economics of climate change; natural resources management; technology adoption and impact assessment, applied micro-econometrics; economic modelling; and competitiveness and productive analysis of the agricultural sector in the MENA region.

**Email: [B.Dhehibi@cgiar.org](mailto:B.Dhehibi@cgiar.org)**

## AUTHORS

**Akmal Akramkhanov<sup>d</sup>** is a Senior Scientist at ICARDA and leads ICARDA's Regional Office for Central Asia and the Caucasus. Since joining ICARDA in 2013, his work has focused on knowledge management, land degradation, climate resilience, and sustainable agriculture, with a strong emphasis on policy-relevant research, regional platforms, and decision-support tools. He has over 20 years of experience working across Central Asia and selected countries in Eastern Europe, North Africa, and the Middle East. He holds a PhD in Agricultural Sciences from the University of Bonn, Germany.

**Email: [A.Akramkhanov@cgiar.org](mailto:A.Akramkhanov@cgiar.org)**

### Affiliations

<sup>a</sup> Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle (Saale), Germany

<sup>b</sup> Samarkand Agroinnovations and Research University, Amir Temur Street 7, Oqdaryo district, Samarkand region, Uzbekistan;

<sup>c</sup> International Center for Agricultural Research in the Dry Areas (ICARDA), Tunis Office, Tunis, Tunisia

<sup>d</sup> International Center for Agricultural Research in the Dry Areas (ICARDA), Central Asia and the Caucasus Office, Tashkent, Uzbekistan

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## ABSTRACT

Agricultural sector in Uzbekistan is undergoing rapid modernization driven by institutional reforms and mounting pressure to ensure sustainable land and water resource use. This study investigates the adoption and impacts of four sustainable agricultural practices (SAPs) promoted for sustainable intensification: crop rotation, manure application, drip irrigation, and laser levelling.

Using nationally representative survey data from 1,225 farms across four major regions (Andijan, Kashkadarya, Khorezm, and Samarkand) collected in 2024, we employ a multivariate probit model to analyze complex, inter-dependent adoption decisions and their determinants. Subsequently, we apply treatment-effects models to assess the impact of individual practices and selected bundles on three critical outcomes: farm revenue, an agronomic sustainability index, and the gender wage gap among seasonal workers.

Our analysis reveals that SAP adoption patterns are highly practice-specific. Crucially, perceived profitability, benefits and challenges are strong predictors of uptake, while standard structural variables ( education, farm size, and extension contact) are inconsistent determinants across practices. Modern technologies are more strongly linked to institutional arrangements, farm structure, and training than are traditional practices.

Results on impact are nuanced: no single technology improves all three outcomes simultaneously. Drip irrigation emerges as the most promising individual practice, significantly raising both revenue and sustainability. In contrast, laser levelling shows no clear average economic gains. Importantly, SAP bundles consistently outperform single practices on sustainability and sometimes on revenue. Social impacts are mixed: crop rotation tends to widen, while the joint adoption of laser levelling and drip irrigation narrows, the gender wage gap. Overall, the findings underscore the necessity of practice-specific and portfolio-based policy support for sustainable agriculture in reforming transition economies.

## KEYWORDS

Technology adoption; Irrigated farming systems; Multivariate probit; Treatment-effects analysis

## ANNOTATSIYA

O'zbekistonda qishloq xo'jaligi tarmog'i institutsional islohotlar hamda yer va suv resurslaridan oqilona va barqaror foydalanish zaruratining ortib borishi ta'sirida jadal modernizatsiya qilinmoqda. Mazkur tadqiqot qishloq xo'jaligini barqaror intensivlashtirishni qo'llab-quvvatlash maqsadida ilgari surilayotgan to'rtta barqaror qishloq xo'jaligi amaliyotlari (BQXA)ni joriy etilishi va ularning ta'sirini o'rganadi. Bular - almashlab ekish, go'ngdan foydalanish, tomchilatib sug'orish hamda lazerli yer tekislash - amaliyotlaridir.

O'zbekiston miqyosida (Andijon, Qashqadaryo, Xorazm va Samarqand viloyatlaridagi) 2024-yilda 1 225 ta fermer xo'jaligidan to'plangan so'rovnoma ma'lumotlaridan foydalangan holda biz BQXA qo'llashga ta'sir qiluvchi omillarni tahlil qilish uchun ko'p o'lchovli probit (multivariate probit) modelidan foydalandik. Keyingi bosqichda esa, "ta'sirni baholash modeli" (treatment effect modeli)dan foydalangan holda, tanlangan BQXAlarning fermer xo'jaligi faoliyatiga ta'sirini quyidagi uchta ko'rsatkich orqali baholadik. Bular: (1) fermer xo'jaligi daromadi, (2) ekologik barqarorlik indeksi va (3) ayol va erkak mavsumiy ishchilar o'rtasida ish haqi tafovuti (gender tengligi).

Tahlillar BQXAlarni qo'llash tendensiyasi amaliyotlar kesimida keskin farqlanishini ko'rsatdi. Ayniqsa, BQXAlarni joriy etishga ta'sir ko'rsatuvchi asosiy omillar sifatida, texnologiyadan keladigan daromadlilik, foyda va ishlatishdagi qiyinchliklari muhim ekanligi aniqlandi. Aksincha, boshqa muhim deb hisoblangan omillar, (jumladan fermerning ma'lumoti, fermer xo'jaligi hajmi va maslahat xizmatlari bilan hamkorlik ) BQXAlarni joriy etishda amaliyotlar kesimida izchil aniqlovchi omil sifatida namoyon bo'lmadi. Shuningdek, natijalar zamonaviy texnologiyalar (tomchilatib sug'orish va lazerli yer tekislash amaliyotlari) an'anaviy amaliyotlarga (almashlab ekish va go'ngdan foydalanish) nisbatan ko'proq institutsional sharoitlar, xo'jalik tuzilmasi va o'quv-treninglar bilan bog'liq ekanligini ko'rsatdi.

BQXAlarni qo'llashning fermer xo'jaligi faoliyatiga ta'siri natijasi shuni ko'rsatdiki, o'rganilgan to'rtta amaliyot baholangan uchta fermer xo'jaligi faoliyati ko'rsatkichlarining hammasiga bir xilda ta'sir ko'rsatmaydi. Boshqacha qilib aytganda, tanlangan to'rtta amaliyotdan birortasi bir vaqtning o'zida uchala faoliyatni ham yaxshilamadi. Tomchilatib sug'orish texnologiyasi eng istiqbolli yakka amaliyot sifatida ajralib chiqib, daromadni ham, barqarorlik indeksini ham sezilarli darajadi oshishiga olib keldi. Farqli ravishda, lazerli yer tekislashni joriy etish bo'yicha o'rtacha iqtisodiy yutuqlar aniq kuzatilmadi. Muhimi, BQXAlarni birgalikda joriy qilganda ularni fermer xo'jaligining ekologik barqarorligiga va daromadligiga ta'siri, ularni alohida joriy qilishga qaraganda kuchliroq ekanligi aniqlandi. BQXAlarni joriy etishning ijtimoiy ta'siri turlicha namoyon bo'ldi. Almashlab ekishdan foydalanish gender bo'yicha ish haqi tafovutini (gender tengsizligini) kengaytirishga olib kelgan bo'lsa, lazerli yer tekislash va tomchilatib sug'orish texnologiyalarini birgalikda qo'llash ushbu tafovutni qisqartirdi. Umuman olganda, natijalar shuni ko'rsatadiki, tez rivojlanayotgan davlatlarda, xususan O'zbekistonda qishloq xo'jaligini barqaror rivojlanishini ta'minlash uchun

fermerlarning texnologiyalarni joriy qilishini qo'llab-quvvatlovchi islohotlarga, har bir texnologiyaga xos yondashuvga hamda tizimli islohotlarga tayanishi kerak.

## KALIT SO'ZLAR

Texnologiyalarni joriy qilish; Sug'oriladigan dehqonchilik tizimlari; ko'p o'lchovli probit (multivariate probit) modeli; ta'sirni baholash

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## 1 Introduction<sup>1</sup>

Global agrifood systems face unprecedented challenges, particularly in low- and middle-income countries (LMICs), where land degradation, water scarcity, and climate variability directly threaten food security and long-term resilience (Tilman et al., 2002; FAO, 2023). Consequently, the adoption of effective sustainable agricultural practices (SAPs) is increasingly recognized as a critical pathway for aligning essential productivity gains with long-term environmental and social goals. Practices such as crop rotation, zero tillage, and efficient water management technologies have been shown to support soil restoration, conserve water, reduce chemical inputs, and increase farm profitability (Manda et al., 2016; Ogundari and Bolarinwa, 2018; Pretty et al., 2006; Pretty and Hine, 2000; Takahashi et al., 2020). Yet, despite widespread promotion by governments and development partners and the established benefits, the uptake of SAPs across developing regions remains persistently low and uneven (Arslan et al., 2022; Knowler and Bradshaw, 2007; Lee, 2005). This adoption gap is a major constraint to achieving both national agricultural modernization and climate resilience targets (Adamsone-Fiskovica and Grivins, 2024).

A growing body of research has examined factors associated with SAP adoption. This includes field- and farm-level studies, alongside numerous systematic reviews and meta-analyses that consolidate evidence on the determinants of farmer decisions (see, for instance, D'Souza et al. (1993), Foguesatto et al. (2020), Rosario et al. (2022)). Much of this literature has focused on identifying the diverse socioeconomic, human capital, psychological, and institutional factors of SAP adoption worldwide (Addorisio et al., 2025; Begho et al., 2022; Madin et al., 2025; Miriti and Lambarraa-Lehnhardt, 2025; Möhring et al., 2025; Priya and Singh, 2024; Ruzzante et al., 2021). One consistent insight is that there are no universal determinants that explain the adoption of all technologies across all contexts. Instead, adoption is determined by local agroecological conditions, market and institutional environments, the characteristics of specific innovations, and farmers' capabilities and preferences. These reviews emphasize the need for country-specific, context-sensitive empirical evidence that can identify which types of farmers adopt particular practices, under what conditions, and with what consequences. This is especially relevant in settings undergoing structural transformation and agricultural reforms, where institutional changes can substantially alter farmers' incentives, policy frameworks and constraints.

Uzbekistan provides an especially compelling case for such analysis. For much of the post-Soviet period, its agricultural sector was dominated by monoculture production of cotton and

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since the 1990s of wheat. These two crops together accounted for around 80% of arable land in the 2000s (Lerman and Sedik, 2009). These crops were treated as strategic commodities and governed through a centralized system characterized by state procurement, production quotas, subsidized inputs, and strict regulation of farm decisions. While this system ensured stable production, it also discouraged the exploration of alternative crops or sustainable practices. Decades of reliance on flood and furrow irrigation, chemical fertilizers, and labor-intensive cultivation contributed to soil degradation, rising salinity, and inefficient use of scarce water resources. The resulting production system was and is still highly resource-intensive, locked into legacy practices, and slow to adapt to new technologies or sustainability standards.

Over the past decade, Uzbekistan has embarked on a wide-ranging reform programme to modernize the agricultural sector (Djanibekov et al., 2024). A major turning point came in 2020 with the abolition of the state procurement system for cotton. This reform paved the way for privatization in the cotton-textile value chain, the emergence of agro-clusters – vertically coordinated agribusiness organizations that integrate multiple stages of a value chain within a defined territory – and the transition to contract farming (Babadjanov and Petrick, 2025). These institutional changes were accompanied by broader policy efforts aimed at enhancing farm autonomy, improving access to modern machinery, strengthening extension services, and promoting technologies that support more sustainable and diversified production (Kurbanov et al., 2025). The national development strategy for 2020–2030 places agricultural modernization at the center of economic transformation, supported by extensive donor engagement (Djanibekov et al., 2025). Technologies such as drip irrigation, laser leveling, and no-tillage systems have been actively promoted, alongside organic fertilizer use, biological crop protection, more diverse crop rotations designed to restore soil quality and reduce irrigation water use.

Despite this ambitious reform agenda, actual adoption of sustainable practices remains uneven. Many farmers continue to face financial constraints, high upfront investment requirements, limited access to reliable technical information, and persistent gaps in agronomic knowledge (Kurbanov et al., 2025). Even practices with demonstrated potential benefits, such as crop rotation, have not been widely adopted, partly due to entrenched production habits, path dependencies, and the structure of private agro-cluster arrangements (Kurbanov et al., 2022). Drip irrigation and laser leveling are gaining visibility to farmers through the state programmes, their uptake however varies widely across regions and farm types (Hermans et al., 2023). Understanding the drivers and impacts of the SAP adoption is therefore important as public and donor resources are directed toward promoting sustainable agricultural development.

Two key knowledge gaps emerge from the existing literature (see more details on literature review on determinants and impacts of SAP adoption in developing country setting in Section 2). First, despite increasing interest in agricultural modernization in Uzbekistan, there is

limited nationally representative evidence on the adoption of SAPs. Existing studies tend to focus on individual technologies, specific regions, or narrow sets of outcomes, which makes it difficult to derive comprehensive insights for policymakers. There is no systematic analysis that jointly examines traditional natural resource management practices, such as crop rotation and manure application, and modern, equipment-based innovations such as drip irrigation and laser leveling. Understanding how these practices coexist, complement, or substitute one another is particularly important in a context characterized by simultaneous state-led reforms and market experimentation. Second, there is limited empirical evidence linking SAP adoption in Uzbekistan to multiple dimensions of farm performance. Most existing work, both globally and regionally, evaluates economic or environmental impacts in isolation, while social dimensions such as labor requirements or gender wage gaps receive far less attention. A multidimensional assessment could provide more insights about how SAP adoption affects farm performance more broadly and how these effects vary across different types of practices.

Against this backdrop, the present study examines the adoption and impacts of four SAPs in Uzbekistan, representing both traditional practices and modern technologies. Crop rotation and manure application fall under traditional natural resource management practices with which farmers in Uzbekistan are already familiar, whereas drip irrigation and laser land-leveling represent more capital-intensive physical equipment technologies. The study pursues two main objectives. First, it analyses adoption patterns and the determinants of these four SAPs, paying particular attention to technology-specific characteristics, institutional factors, and behavioral preferences such as risk attitudes, time preferences, and openness to experimentation. Second, it assesses how adoption of these practices is associated with farm-level outcomes, focusing on agricultural revenue, agricultural sustainability, and the gender pay gap among hired labor.

The study draws on the UzFarmBarometer dataset coming from a nationally representative survey implemented in 2024 within the German–Uzbek research collaboration. The dataset covers 1,225 farm managers across four regions (Andijan, Kashkadarya, Khorezm, and Samarkand) and includes detailed farm-level information on agronomic practices, access to services, institutional perceptions, market conditions, social networks, and behavioral preferences. This breadth of information makes it possible to examine both the drivers of SAP adoption and the broader economic, environmental, and social implications of using these technologies.

This study makes several contributions. First, it provides a comprehensive, multidimensional assessment of SAP adoption in Uzbekistan, integrating economic, environmental, and social outcomes for both traditional practices and modern technologies on the basis of a nationally representative farm survey collected under the current reform context. Second, it incorporates multiple analytical lenses to investigate adoption determinants, combining technology-specific, institutional, environmental, and behavioral factors, and openness to

experimentation. Third, it models the adoption of four SAPs jointly and links these correlated adoption decisions to farm revenue, an agricultural sustainability index, and the gender pay gap among hired labor.

The remainder of the discussion paper is structured as follows. Section 2 reviews the literature on the determinants and impacts of SAP adoption. Section 3 describes the data, sampling strategy, and key variables. Section 4 outlines the econometric estimation approach. Section 5 presents the empirical results. Section 6 discusses the findings in light of the existing literature, and Section 7 concludes and draws policy implications.

## 2 Determinants and impact of SAPs adoption

Research on the adoption of sustainable agricultural practices in developing countries has grown steadily over the past three decades. This body of work includes meta-analyses of technology adoption and impact, systematic literature maps on SAPs, including ecological and conservation practices, and syntheses of drivers of sustainable agriculture and conservation measures (Arslan et al., 2022; Begho et al., 2022; Foguesatto et al., 2020; Knowler and Bradshaw, 2007; Madin et al., 2025; Ogundari and Bolarinwa, 2018; Ruzzante et al., 2021; Yoder et al., 2019). Further insights come from reviews of sociopsychological and sociotechnical determinants of sustainable practice adoption (Adamsone-Fiskovica and Grivins, 2024; Rosário et al., 2022), as well as global scoping reviews that evaluate the multiple sustainability dimensions of agricultural innovations (Lybbert et al., 2022; Piñeiro et al., 2020). Across these publications, several common themes emerge. There is broad agreement that no single variable explains adoption decisions across contexts, that adoption determinants are highly practice- and context-specific, and that impacts are heterogeneous across economic, environmental, and social domains (Manda et al., 2016; Miriti and Lambarraa-Lehnhardt, 2025). At the same time, the literature reports about persistent gaps regarding social impacts, particularly gendered labor and wage outcomes, and stresses the need to integrate structural, institutional, environmental, and behavioral explanations for SAP adoption in a more systematic way (Rizzo et al., 2024; Takahashi et al., 2020).

### 2.1 Adoption determinants

Studies on SAP adoption determinants commonly begin with **socio-demographic characteristics** of farm managers and households, such as age, education, farming experience. However, reviews and meta-analyses show these are rarely strong or consistent determinants of SAP adoption (Begho et al., 2022; Knowler and Bradshaw, 2007; Madin et al., 2025; Ruzzante et al., 2021). The predictive power of education varies substantially depending on the complexity of the practice, the quality of local training, and the availability of extension support (Madin et al., 2025; Ruzzante et al., 2021). Household size sometimes appears as a positive determinant for labor-intensive practices, including manure application

or residue management, but shows weak or no associations in many other cases, especially for capital-intensive or knowledge-intensive SAPs (Begho et al., 2022; Foguesatto et al., 2020). Farming experience may increase familiarity with certain practices but can also contribute to path dependency, where established routines lower willingness to experiment with new technologies (Manda et al., 2016; Yoder et al., 2019). While early studies suggested a strong role for human capital factors (D'Souza et al., 1993), overall the current literature suggests that socio-demographic variables are rarely central drivers of adoption decisions once economic, institutional, and behavioral factors are considered (Arslan et al., 2022; Madin et al., 2025; Ruzzante et al., 2021).

In contrast **farm size** is among the most frequently cited structural determinants of adoption, especially for innovations requiring substantial capital investment, specialized machinery, or complementary infrastructure. Reviews and empirical studies indicate that larger farms are more likely to adopt capital-intensive SAPs such as improved irrigation systems, mechanization, and precision land levelling, since these technologies exhibit scale economies and require upfront investment that smallholders often cannot afford (Arslan et al., 2022; Ruzzante et al., 2021; Yigezu et al., 2018). Evidence from South Asia suggests that adoption of laser levelling and drip irrigation is concentrated among larger or better-capitalized farms because of the costs of equipment and the need for technical support (Ali et al., 2018; Aryal et al., 2015; Chen et al., 2022; Surendran et al., 2016). Conversely, natural resource management practices that rely primarily on changes in crop management, such as crop rotation or manure application, tend to show weaker or more heterogeneous relationships with farm size (Pretty and Hine, 2000; Yoder et al., 2019). **Land tenure security** also appears repeatedly as a determinant of SAP adoption, particularly for practices with long-term payoffs such as soil fertility management, tree planting, or irrigation infrastructure, since insecure or short-term tenure reduces incentives to invest in measures that pay off only over several seasons (Arslan et al., 2022; Begho et al., 2022; Foguesatto et al., 2020; Madin et al., 2025). These findings suggest that adoption of modern equipment and long-horizon SAPs is more likely under conditions of larger scale and stronger land-use rights, while adoption of low-capital SAPs is less structurally constrained but still defined by local resource endowments and perceived risk (Manda et al., 2016; Rizzo et al., 2024).

**Economic constraints and market access** are consistently mentioned as major determinants of SAP adoption, explaining which practice/technology is adopted and by whom. Liquidity constraints and high opportunity costs of capital, rather than mere access to formal credit institutions, are central barriers to the adoption of SAPs that require significant upfront expenditure, including drip irrigation, pumps, and laser levelling (Arslan et al., 2022; Ogundari and Bolarinwa, 2018; Ruzzante et al., 2021). Studies of irrigation technologies in India and Pakistan indicate that investment and maintenance costs are among the main reasons why potentially profitable drip systems and levelling equipment remain underutilized (Ali et al., 2018; Aryal et al., 2015; Chen et al., 2022; Narayanamoorthy, 2004; Surendran et al., 2016). Market access interacts with these financial constraints by shaping the profitability of SAP adoption. Better access to input markets facilitates timely procurement of seeds, fertilizers,

spare parts, and equipment, while reliable output markets enhance expected returns and reduce risk, particularly important for innovations that increase yields or product quality (Begho et al., 2022; Pretty and Hine, 2000). At the same time, some studies report substitutions toward low-cost practices such as manure application when farmers face financial stress, suggesting that constraints may encourage adoption of certain (cheap) SAPs while discouraging adoption of capital-intensive technologies (Foguesatto et al., 2020; Manda et al., 2016).

**Environmental conditions and agroecological stress** are another central class of determinants. Reviews emphasize that farmers often adopt SAPs in response to increasing pressures on land and water resources, including soil degradation, nutrient depletion, salinity, and variability of climate and irrigation water supply (FAO, 2023; Foguesatto et al., 2020; Pretty and Hine, 2000; Rizzo et al., 2024). For instance, resource-conserving practices have spread most rapidly in regions where environmental stress is most acute, for instance, where soil erosion or water scarcity threatens the viability of traditional practices (Foguesatto et al., 2020; Madin et al., 2025; Pretty and Hine, 2000). Water-saving practices, including drip irrigation and laser levelling, are particularly responsive to water scarcity and irregular canal supplies, which make efficient water use and uniform distribution more valuable (Ali et al., 2018; Aryal et al., 2015; Chen et al., 2022; Narayanamoorthy, 2004; Surendran et al., 2016). At the same time, environmental conditions can act as constraints when degraded soils undermine the potential benefits of certain practices or when unreliable water sources make investments in irrigation technology too risky (Foguesatto et al., 2020; Yoder et al., 2019). The reviewed studies therefore suggest that environmental factors do not operate as simple drivers or barriers but interact with technology attributes and institutional support to shape both incentives and feasibility of SAP adoption across regions and farm types (Arslan et al., 2022; Ruzzante et al., 2021).

**Institutional environments**, including extension services, farmer organizations, and public support schemes, feature prominently as determinants of SAP adoption in both reviews and empirical work. Numerous studies identify contact with extension agents as one of the most consistent predictors of adoption across a wide range of technologies and settings, since extension reduces information asymmetries, supports learning-by-doing, and provides technical guidance (Arslan et al., 2022; Begho et al., 2022; D'Souza et al., 1993; Takahashi et al., 2020). Membership in cooperatives, producer groups, or water user associations also appears as a positive determinant in many studies, reflecting benefits from joint learning, pooling of resources, and improved bargaining power in input and output markets (Pretty and Hine, 2000; Yoder et al., 2019). Policy instruments such as equipment subsidies, credit guarantees, and support for farmer field schools can further facilitate adoption, particularly of modern SAPs that are otherwise financially out of reach (Ali et al., 2018; Narayanamoorthy, 2004; Surendran et al., 2016). Reviews regularly stress that institutional variables are crucial for explaining cross-country differences in adoption patterns and for understanding why similar technologies diffuse at different speeds in different policy and governance environments (Foguesatto et al., 2020; Rizzo et al., 2024; Ruzzante et al., 2021).

**Information access and social learning** processes are closely linked to these institutional factors and constitute another important group of determinants. Farmers rarely adopt new practices without observing or hearing about them through their social networks, including neighbors, relatives, and (in)formal farmer groups. Empirical evidence shows that exposure to peers who have experimented with SAPs substantially increases the likelihood that other farmers will adopt similar practices, in part because peer experiences reduce uncertainty about performance and risks (Foster and Rosenzweig, 2010; Pretty and Hine, 2000; Yoder et al., 2019). Social networks thus act as informal extension channels, particularly in settings where public extension services are understaffed or geographically uneven (Arslan et al., 2022; Ruzzante et al., 2021; Tadjiev et al., 2025). Peer influence within social networks is a primary mechanism for reducing uncertainty and spreading knowledge about SAPs, often acting as an informal extension system (Foster and Rosenzweig, 2010). Reviews point out that the structure of these networks, including density, trust, and heterogeneity, can either facilitate or hinder diffusion, for example, when scepticism or negative experiences with technologies spread through the same channels that spread favorable information (Foguesatto et al., 2020; Madin et al., 2025). While access to information through media and digital platforms is becoming more important, interpersonal networks remain the key information source in many rural settings (Kurbanov et al., 2024; Tadjiev et al., 2025).

**Behavioral and psychological determinants** have gained increasing attention in recent years. These behavioral perspectives help explain why structurally similar farms may respond differently to the same technology and why information and training alone do not always translate into high adoption rates. Reviews of sociopsychological drivers show that attitudes towards environmental sustainability, perceived behavioral control, subjective norms, and innovation orientation frequently emerge as significant predictors of adoption (Rizzo et al., 2024; Rosário et al., 2022). SAPs are often perceived as practices that involve higher management complexity, uncertain outcomes, or delayed benefits, which means that risk and time preferences are particularly relevant (Lee, 2005; D’Souza et al., 1993; Madin et al., 2025; Miriti and Lambarraa-Lehnhardt 2025; Piñeiro et al., 2020). Farmers who are more willing to take risks or who have a stronger orientation towards future benefits may be more willing to experiment with conservation or efficiency-enhancing practices whose payoffs only materialize after several seasons (Miriti and Lambarraa-Lehnhardt, 2025; Piñeiro et al., 2020). Loss aversion and status quo bias can deter adoption when farmers focus more on potential short-term losses from trying a new practice than on possible long-term gains (Dessart et al., 2019; Madin et al., 2025).

**Technology-specific characteristics** form another consistent theme. Reviews note that adoption decisions depend on how farmers perceive the profitability, complexity, compatibility, reversibility, labor requirements, and risk profile of individual SAPs (Begho et al., 2022; Madin et al., 2025; Ruzzante et al., 2021). Practices that require minimal new equipment and fit easily into existing rotations, such as simple crop diversification or manure use, tend to diffuse faster when they are perceived as low risk and low cost (Pretty and Hine, 2000; Rodríguez et al., 2008). By contrast, technologies such as drip irrigation, precision

levelling, or reduced-tillage systems require not only investment but also changes in timing, management, and sometimes in crop choices (Ali et al., 2018; Aryal et al., 2015; Chen et al., 2022; Narayanamoorthy, 2004; Surendran et al., 2016). Evidence on multiple practice adoption shows that farmers frequently adopt bundles of SAPs, and that complementarities or trade-offs between practices influence their decisions (Kassie et al., 2015; Manda et al., 2016; Teklewold et al., 2013). The literature therefore emphasizes that technology attributes cannot be treated as uniform and that heterogeneity across practices must be explicitly considered when analyzing adoption behavior.

## 2.2 Adoption impact

The impacts of SAP adoption have been analyzed across economic, environmental, and, to a lesser extent, social dimensions. On the **economic side**, the literature indicates that SAPs have positive but heterogeneous effects on profits and productivity, and that observed benefits depend on SAP and technology type, input access, environmental conditions, and the degree to which farmers can maintain adopted practice over time (Jaleta et al., 2016; Manda et al., 2016; Ogundari and Bolarinwa, 2018; Pretty and Hine, 2000). The heterogeneity of outcomes is partly explained by differences in the cost structures, resource requirements, and learning needs of specific SAPs. For example, nutrient-management practices such as manure application can generate immediate improvements in soil fertility but require substantial labor inputs that affect short-run profitability (Foguesatto et al., 2020; Manda et al., 2016). Evidence from drip irrigation, land levelling, and related water-saving innovations in India, Pakistan, Tajikistan, and China consistently reports significant gains in water productivity, yield, or revenue per hectare among adopters, thus enhancing both economic performance and resource-use efficiency (Abdullaev et al., 2007; Ali et al., 2018; Aryal et al., 2015; Chen et al., 2022; Narayanamoorthy, 2004; Surendran et al., 2016). In drip irrigation systems, reduced water losses and more uniform distribution contribute to direct productivity gains (Surendran et al., 2016). For laser levelling, reductions in labor efforts during field irrigation and more uniform field irrigation translate into lower labor costs and greater efficiency of irrigation and machinery operations. The adoption of bundles of SAPs, rather than single practices, has been shown to generate higher and more stable returns in several African and Asian contexts (Kassie et al., 2015; Manda et al., 2016; Teklewold et al., 2013). Adoption of bundled SAPs can produce complementarities that amplify economic impacts, although benefits depend on adequate farmer's managerial capacity and received institutional support (Hoover et al., 2019; Ogundari and Bolarinwa, 2018; Takahashi et al., 2020). A growing number of evaluations also report that economic impacts of SAPs are larger in settings characterized by input scarcity or high climate variability, since resource-conserving SAPs mitigate risks that conventional systems cannot manage (Arslan et al., 2022; Rizzo et al., 2024).

**Environmental impacts** of SAP adoption have also been widely documented, with consistent evidence that many SAPs improve soil health, reduce erosion, enhance water-use efficiency,

and limit negative externalities associated with intensive chemical use. Conservation-oriented SAPs are associated with improvements in soil organic matter, reduced erosion, increased water infiltration, and reductions in chemical input use (Foguesatto et al., 2020; Pretty and Hine, 2000). The use of crop rotation contributes to nutrient cycling and suppresses pest and disease pressures, thereby reducing reliance on pesticides and supporting more resilient agroecosystems (Begho et al., 2022; Yoder et al., 2019). Manure management and organic inputs contribute to improved soil structure, greater microbial activity, and increased biodiversity at the field level, although the environmental benefits depend on proper handling and application rates. Efficient irrigation technologies reduce water withdrawals and limit salinization risks in irrigated systems, particularly relevant in areas where excessive irrigation has contributed to widespread soil salinity (Abdullaev et al., 2007; Ali et al., 2018; Chen et al., 2022). Studies across China and South Asia show that drip irrigation and precision land levelling can reduce water use by more than 30% in some systems, lowering pumping costs, reducing energy consumption, and decreasing the risk of waterlogging (Surendran et al., 2016). However, environmental gains from SAP adoption are also context-dependent, with the magnitude and direction of impacts influenced by agroecological conditions, soil fertility status, cropping systems, and the extent of complementary investments, e.g. mulching or green manures (Arslan et al., 2022; FAO, 2023; Ruzzante et al., 2021).

**Social impacts** of SAP adoption receive comparatively less attention in literature, but existing evidence suggests that SAP adoption can have important implications for labor demand, household welfare, equity, and gender relations. Some practices increase labor requirements, particularly for manual operations such as manure spreading, compost preparation, mulching, or hand weeding, and these labor burdens often fall disproportionately on women in smallholder households (Begho et al., 2022; Pretty and Hine, 2000). Practices involving mechanization or efficient irrigation (e.g., drip irrigation) can reduce labor burdens significantly, potentially freeing up time for off-farm income generation or other tasks (Surendran et al., 2016). Reviews note that very few studies systematically examine gender-differentiated impacts, but where evidence exists, it suggests that SAPs can either narrow or widen existing disparities depending on the nature of the practice and the local labor market structure (Madin et al., 2025; Ogundari and Bolarinwa, 2018). Practices that reduce labor burdens may ease time constraints for women, but practices that increase labor may intensify existing inequalities unless accompanied by labor-saving technologies or supportive programmes. There are also possible distributional effects related to wealth or resource endowments. Technologies that require capital investment are often adopted by larger (and wealthier) farms, which may lead to widening income and productivity gaps if poorer farmers cannot access them (Bilal and Jaghdani, 2024; Ruzzante et al., 2021). Social impacts may also arise when SAPs alter the demand for seasonal or hired labor, shifting employment opportunities within communities.

Finally, several studies analyze the impacts of adopting multiple SAPs simultaneously and show that combined practice portfolios can generate synergies that differ from the effects of

individual practices. Adoption of bundles of soil, water, and crop management innovations has been associated with higher yields, reduced risk, and improved resilience to shocks in several African and Asian settings (Jaleta et al., 2016; Kassie et al., 2015; Manda et al., 2016; Teklewold et al., 2013). Combined adoption often improves nutrient-use efficiency, stabilizes production under weather variability, and enhances the long-term sustainability of cropping systems. However, the complexity of managing multiple innovations can increase knowledge and coordination requirements, and in some cases may raise labor demands, particularly for smallholders with limited family labor or hired labor capacity (Begho et al., 2022; Foguesatto et al., 2020). Some practice combinations also introduce trade-offs, for example when reduced tillage increases herbicide reliance or when intensification of irrigation raises energy demand or increases the need for water governance reforms (Ogundari and Bolarinwa, 2018; Takahashi et al., 2020).

### 3 Data

This section presents the data used in the analysis. Section 3.1 describes the sampling strategy and data collection process. Section 3.2 reports descriptive statistics on farm and farmer characteristics, and institutional conditions, and the outcome variables. Section 3.3 examines adoption patterns and farmers' perceptions of the four SAPs.

#### 3.1 Sampling

The farm survey data were collected in Uzbekistan in 2024 under the framework of the UzFarmBarometer research project<sup>2</sup>. The project's main purpose was to understand SAP adoption patterns, identify bottlenecks, and analyze factors influencing technology uptake. The survey, consisting of total between 170-190 questions, targeted farmers specializing in wheat cultivation, cotton cultivation, and mixed crop production (including horticulture). Detailed information was collected on technology use, farm-level characteristics, social and behavioral traits of respondents, economic and environmental farm features, and perceptions of institutional arrangements and weather conditions.

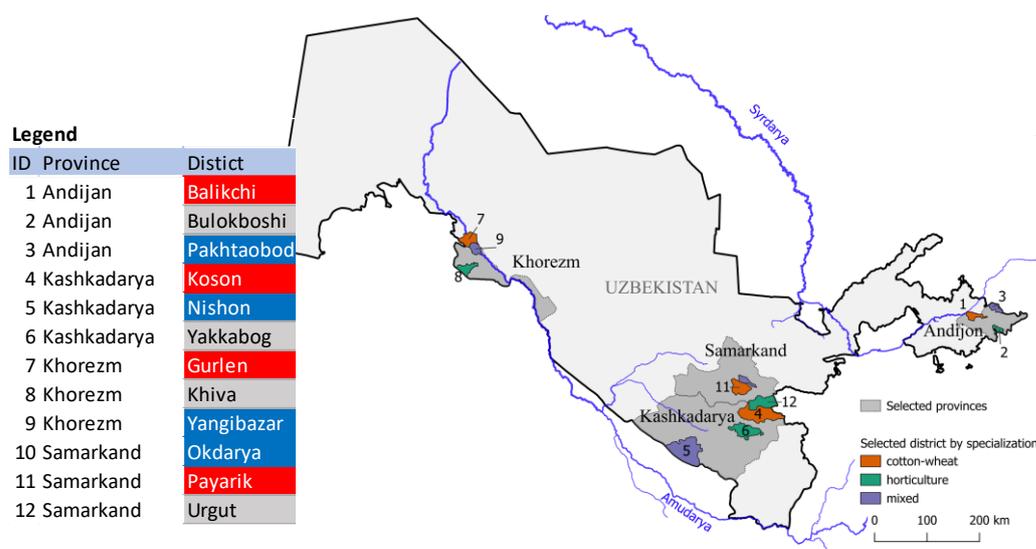
The sampling followed a three-stage procedure. First, four regions were pre-selected: Andijan, Kashkadarya, Khorezm, and Samarkand. Second, within each region, three districts were selected to ensure representation of three key farm specializations: cotton-wheat production, horticulture, and mixed farming. Third, a random selection of farms was made using updated lists of registered farms in the selected districts. Figure 1 presents the location of survey provinces and their districts. Fieldwork took place between November and December 2024. The interviews were conducted using the CAPI (Computer-Assisted Personal Interviewing) platform, which enabled complex logical flows, question routing, and built-in

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<sup>2</sup> Better understanding of the adoption of sustainable agricultural practices in Uzbekistan.  
<https://www.iamo.de/en/research/research-projects/details/uzfarmbarometer/>

checks to minimize input errors. Enumerators were local individuals with prior data collection experience who received two rounds of training to ensure consistency. A pilot survey was conducted beforehand to refine the questionnaire and logistics.

The survey dataset consists of 1,225 interviews with farm managers. The sample is balanced across the four regions: approximately 25% of farm managers come from each region. The primary crops across the sampled regions are cotton, wheat, vegetables, melons, and fruits, with Samarkand and Andijan generally being the more diversified regions. On average, one interview lasted approximately one and a half hours.



**Figure 1:** Map of survey regions

## 3.2 Descriptive statistics

### 3.2.1 Farmer and farm characteristics

**Table 1** reports descriptive statistics on farm and farmer characteristics, first giving general overview and then variables potentially related to technology adoption. To begin with, farms in the sample are medium-sized on average, with about 35 hectares of land, though there is wide variation from less than a hectare to almost 300 hectares. Cotton and wheat is the main crop for more than half of the farms, and around two-thirds own a tractor, indicating a moderate level of mechanization. Farmers reinvest nearly half of their revenues back into the farm, though this varies widely. The average farm manager is 46 years old, with about 40% holding a university degree, and most have substantial farming experience accumulated over their lifetime. Regarding technology-related variables, training participation remains relatively

limited, with farmers attending just over one training on average, and informal channels such as relatives, neighbors, and friends are more common sources of information on sustainable practices than formal media. Among recorded behavioral characteristics, farmers generally report moderate willingness to take risks and to delay gratification, but at the same time a strong concern for potential losses. These characteristics point at a mix of openness and caution in decision-making among the survey respondents, which in our case may define the adoption of modern technologies and sustainable practices.

**Table 1: Description of farm and farmer characteristics**

Variables	Variable description	mean	sd	min	max
<i>Farm characteristics</i>					
Farm size	Total farm land area (ha)	35.574	34.098	0.4	289.3
Cotton specialization	Farm specializes in cotton cultivation (dummy, 1=Yes)	0.572	0.495	0	1
Tractor ownership	Tractor ownership (dummy, 1=Yes)	0.642	0.479	0	1
Technology level	Evaluation of technological level of farm machinery (categorical, 1-5, 5=Outdated, does not meet operational stand)	3.233	1.149	1	5
Revenue reinvested	Share of farm's revenue reinvested back into the farm (%)	46.393	24.709	0	100
Distance to the home	Distance to the house from farm office (km)	3.423	4.214	0	70
Plot location	Location of farm plots to main irrigation source (categorical, 1-5, 5=Very close)	3.440	0.946	1	5
Canal condition	Condition of on-farm irrigation and drainage network (categorical, 1-5, 5=Excellent)	3.435	0.845	1	5
Drought problem severity	Natural drought, lack of water (categorical, 1-5, 5=Very serious problem)	3.071	1.444	1	5
Water availability trend	Locally changed over the last 10 years: availability of irrigation water (categorical, 1-3, 3=Increased)	2.190	0.723	1	3
Heatwave frequency trend	Locally changed over the last 10 years: frequency and severity of heat waves (categorical, 1-3, 3=Increased)	2.507	0.641	1	3
Planned farming horizon	Number of year farmer intend to continue farming business (years)	26.932	21.104	0	100
Succession certainty (1–3)	family or a close relative will manage farm after the retire (categorical, 1-3, 3=100% sure)	2.388	0.701	1	3

<i>Farmer characteristics</i>					
Variables	Variable description	mean	sd	min	max
Age	Age of farm manager (years)	45.929	10.280	22	87
Share of work experience in agriculture	Share of age spent on agricultural production (index, 0-1)	0.336	0.155	0.026	1
Higher education	Farmer has higher university education (dummy, 1=Yes)	0.412	0.492	0	1
Own knowledge	If farmer has own knowledge on agronomy (dummy, 1=Yes)	0.324	0.468	0	1
Trainings attended	Number of participating trainings	1.203	1.420	0	11
Farmer network support size	Number of people to ask for support in solving problems related to the farm management	2.420	2.449	0	20
SAP info: peers/relatives	Source of information on SAP (dummy, 1=from other farmers, relatives, friends and neighbors)	0.296	0.456	0	1
SAP info: media	Source of information on SAP (dummy, 1=from internet, newspaper, radio, TV)	0.162	0.368	0	1
Risk taker	Farmer is willing to take risks (categorical, 1-5, 5=very willing)	3.862	0.915	1	5
Loss aversion	Farmer is concerned more about potential losses in farming business than about potential gains (categorical, 1-5, 5= completely agree)	3.927	1.168	1	5
Future-oriented	Farmer is willing to give up something good today to get something even better in the future (categorical, 1-5, 5=very willing)	3.648	1.031	1	5
Adopt unproven SAPs	Farmer uses SAP even if its benefits are not yet fully proven (categorical, 1-5, 5=completely agree)	3.490	1.236	1	5

Source: UzFarmBarometer survey (2024).

Table 2 presents descriptive statistics of farmers' perceptions of institutional conditions related to access to inputs and credit, decision-making autonomy, and the perceived benefits and challenges of SAP adoption and use. For each domain, cluster analysis distinguishes groups of farmers according to whether they strongly agree with the existence of constraints, take a moderate position, or disagree. For our study we constructed credit rationing variable (credit constrained) following the frameworks proposed by Boucher et al. (2009) and Petrick et al. (2016). This variable is defined as a binary indicator, taking the value of 1 if a farmer experiences any form of credit rationing, specifically quantity rationing, risk rationing, or transaction cost rationing, and 0 otherwise. About 13% of farmers are directly identified as credit constrained. In line with this characteristic, around 17% of farmers strongly agree that

they face difficulties in obtaining credit or subsidies, while 38% moderately agree, and 45% disagree with the existence of such constraints.

**Table 2: Description of perceived institutional conditions and technology attributes**

Variable	Description	mean	sd	min	max
Access to inputs					
Input access difficulty	Farmer has strong concerns about difficulties in accessing credit and subsidies (dummy, 1=Yes)	0.170	0.376	0	1
Input access difficulty	Farmer has moderate concerns about difficulties in accessing credit and subsidies (dummy, 1=Yes)	0.379	0.485	0	1
Input access difficulty (reference group)	Farmer disagrees concerning difficulties in accessing inputs like accessing credit, subsidies etc (dummy, 1=yes)	0.451	0.498	0	1
Credit constrained	Farmer is credit rationed (dummy, 1=Yes)	0.134	0.341	0	1
Decision making autonomy					
Tenure autonomy (reference group)	Farmer strongly disagrees about having free decision making (dummy, 1=yes)	0.313	0.464	0	1
Tenure autonomy	Farmer moderately agrees about free decision making (dummy, 1=Yes)	0.386	0.487	0	1
Tenure autonomy	Farmer strongly agrees about free decision making (dummy, 1=Yes)	0.301	0.459	0	1
Land reallocation experience	Times farm size changed after its establishment through farm optimization	1.380	1.131	0	3
Benefits of using SAPs					
SAP benefits (reference group)	Farmer strongly disagrees concerning benefits of SAP use (dummy, 1=Yes)	0.122	0.328	0	1
SAP benefits	Farmer moderately agrees concerning benefits of SAP use (dummy, 1=Yes)	0.253	0.435	0	1
SAP benefits	Farmer agrees concerning benefits of SAP use (dummy, 1=Yes)	0.624	0.484	0	1
Challenges of using SAPs					
SAP challenges (reference group)	Farmer strongly agrees about challenges of SAP use (dummy, 1=Yes)	0.229	0.420	0	1
SAP challenges	Farmer moderately agrees about challenges of SAP use (dummy, 1=Yes)	0.291	0.454	0	1
SAP challenges	Farmer disagrees about challenges of SAP use (dummy, 1=Yes)	0.481	0.500	0	1

Source: UzFarmBarometer survey (2024).

For decision-making autonomy, perceptions are more evenly distributed across the three groups. About 31% of farmers strongly disagree with having free decision-making power, 39% moderately disagree, and 30% agree that they can decide freely. Turning to the perceived benefits of SAPs, the majority of farmers (62%) agree that such practices are beneficial, while 25% moderately disagree, and only 12% strongly disagree. The distribution here is less variable, showing a more consistent positive perception of SAP benefits among most farmers. Finally, regarding the perceived challenges of SAPs, 23% of farmers strongly agree that challenges are substantial, 29% moderately agree, and nearly half (48%) disagree with the existence of major obstacles. The data reveal distinct patterns across institutional conditions. Perceptions of access to inputs/credit and decision-making autonomy are highly variable, with farmers divided between reporting constraints and perceiving fewer difficulties. By contrast, perceptions of SAP benefits are more strongly positive and consistent, while challenges of adoption are less widely acknowledged. This suggests that institutional conditions are not uniformly enabling: while SAPs are broadly seen as beneficial, access constraints and limited decision-making autonomy remain salient concerns for many farmers.

### 3.2.2 Outcome variables

To assess how the adoption of sustainable agricultural practices is associated with economic, environmental, and social outcomes, this subsection introduces the three outcome variables used in the impact analysis: revenue per hectare, an agronomic sustainability index, and the gender wage gap among seasonal workers.

*Revenue per hectare* serves as a farm-level indicator of economic performance. For each commercial farm, total crop revenue is calculated by multiplying the quantity produced for each crop by the crop-specific prices reported by the farm manager. These values are then summed across all crops to obtain total farm-level crop revenue. This total value is subsequently divided by farm's total sown area across cultivated crops.

To measure farm environmental sustainability performance, we calculated *Sustainability index* variable following Benitez-Altuna et al. (2021) and Rigby et al. (2001). The agricultural sustainability index is composed of four key categories: (1) seed sourcing, (2) soil fertility, (3) pest control, and (4) weed control. The scoring of farming practices within each category is based on four sustainability dimensions: (i) minimization of off-farm inputs, (ii) minimization of non-renewable inputs, (iii) maximization of natural biological processes, and (iv) promotion of local biodiversity. Each practice is evaluated on a scale from -3 to 2, where -1 indicates a negative impact on the specific sustainability dimension, 0 indicates no significant impact, and 2 indicates a strong positive impact. The scores for individual practices are first summed up to produce a total weight for each production stage. These total weights are then aggregated to generate the overall sustainability index. To enhance interpretability, a linear transformation is applied to rescale the index values between 0 and 1, following the

approach of Rigby et al. (2001). [Table A1](#) in Appendix presents the scores used to calculate the index.

*Gender wage gap* variable measures a difference between monthly wages of male and female seasonal workers (US\$/months per person). If it is positive, respondents reported that they pay more to male seasonal workers than to female seasonal workers, and other way around for negative values. Out of 1225 interviewed farm managers, only 713 reported values both for male and female seasonal workers. Thus, in Section 4.2 the model results for impact analysis of SAP adoption on gender wage gap, the number of observations is 713.

Figure 2a illustrates the distribution of farm revenue per hectare across the sample of 1,225 commercial farms. The distribution is right-skewed, with most farms earning between 500 and 2,000 US\$ per hectare. The largest share of respondents (around one-third) falls within the 1,000–1,500 US\$/ha range, while about one-quarter report revenues between 500 and 1,000 US\$/ha. A smaller but notable share of farms achieved revenues between 1,500 and 2,000 US\$/ha.

[Figure 2b](#) shows farm-level sustainability index for all 1,225 commercial farms in the sample. The distribution is broad and relatively dispersed, indicating substantial heterogeneity in the use of sustainable agronomic practices across farms. Most observations fall between 0.15 and 0.65, with no single dominant cluster. The largest concentration of farms lies in the 0.15–0.60 range. Low sustainability scores below 0.15 and high scores above 0.6 are reported by a small share of farm managers.

[Figure 2c](#) shows the distribution of the gender wage gap among seasonal workers for the 713 commercial farms that reported wage information for both male and female workers. The distribution is centered close to zero but exhibits a pronounced right skew. Nearly half of all farms reported equal wages for male and female seasonal workers. A sizeable cluster of farmers reported a wage gap in the 40–120 US\$ range, and a smaller share reports gaps exceeding 120 US\$/month, indicating that male seasonal workers are paid moderately more than female workers. Negative gaps, where female workers are paid more than men, are rare but present.

[Table 3](#) below presents the mean differences in socio-economic outcomes between adopters and non-adopters of four SAPs in our study. Starting with the traditional technologies, adopters of crop rotation and manure application report on average higher revenues per hectare than non-adopters, with the difference particularly large and statistically significant for crop rotation. By contrast, differences in sustainability scores and crop diversification are small and not statistically significant for either technology. In terms of the gender wage gap, adopters of crop rotation show a significantly wider gap compared to non-adopters. Turning to modern technologies, adopters of drip irrigation and laser levelling have significantly higher sustainability scores and crop diversification compared to non-adopters. In contrast, their revenues per hectare are lower on average, with the difference particularly pronounced and significant for laser levelling. For the gender wage gap, adopters of modern technologies

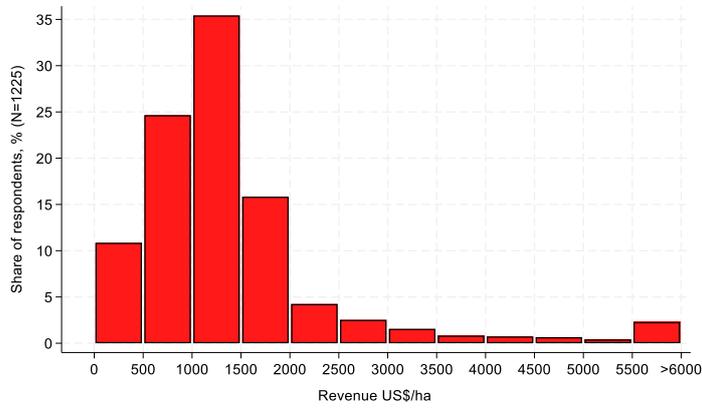
show lower average values than non-adopters, indicating smaller pay disparities against female workers. This pattern is most evident and strongly significant for laser levelling. Lower revenues among adopters of modern technologies is rather surprising. Adopting the modern technologies described here may involve higher upfront and operational costs, which may reduce profitability compared to the traditional practices.

**Table 3: Mean differences of outcome variables between SAP adopters and non-adopters**

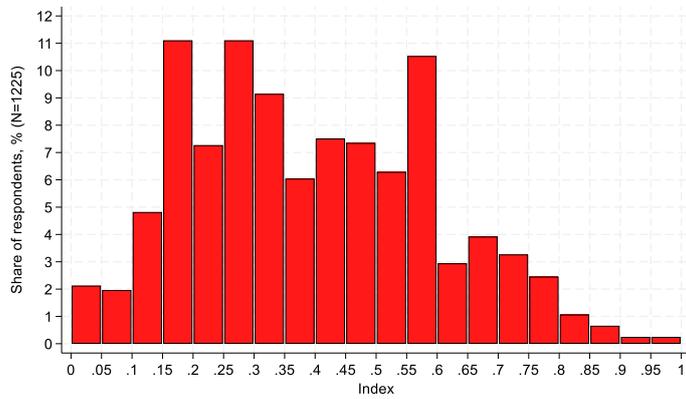
SAPs	Crop revenue (US\$/ha) (N=1225)		Agricultural sustainability index (N=1225)		Wage gap (US\$/month) (N=713)	
	Adopters	Non-adopters	Adopters	Non-adopters	Adopters	Non-adopters
<i>Traditional</i>						
1. Crop rotation	1613.419***	1318.127	0.383	0.402*	47.987***	31.011
2. Manure application	1558.357	1454.822	0.394	0.392	43.714	39.425
<i>Modern</i>						
3. Drip irrigation	1295.389	1507.148	0.431***	0.384	30.749	42.427*
4. Laser levelling	1218.944	1515.492**	0.477***	0.377	26.609	43.822***

Note: Adopters are farmers who reported having ever used the respective technology.  
Source: UzFarmBarometer survey (2024).

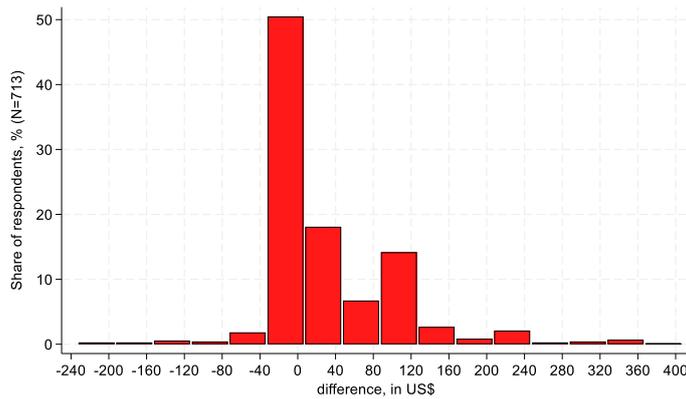
**a) Crop revenue, US\$/ha**



**b) Agricultural sustainability index, 0-1**



**c) Monthly wage difference between male and female seasonal workers (US\$/month)**



**Figure 2: Distribution of key economics (a), environmental (b), and social indicators (c) across surveyed farms**

### 3.3 Patterns and perceptions of SAP adoption

In this sub-section we provide additional information based on the farm survey data about adoption patterns of selected four SAPs among sampled farmers and their perceptions of benefits and challenges related to SAPs. Table 4 presents patterns of SAP adoption. Traditional practices, and crop rotation in particular, stand out as the most widely adopted and longest-practiced SAPs among farmers in Uzbekistan, both in terms of the number of users, the share of land covered, and the years of use. In terms of prevalence, crop rotation has been used by 52% of farmers, followed by manure application (17%), drip irrigation (16%), and laser leveling (14%), with the latter three practices showing relatively similar levels of uptake. Looking at land coverage, manure application is practiced on the largest share of land among adopters (81%), while drip irrigation is applied to the smallest share (47%), with crop rotation and laser leveling falling in between at 73% and 70% respectively.

**Table 4: Adoption patterns of selected agricultural technologies**

	Traditional		Modern	
	Crop rotation	Manure application	Drip irrigation	Laser leveling
Have used this technology (before)	640	208	201	178
Still use this technology	468	197	167	168
Don't use now, but used before	172	11	34	10
Share of land area this technology is used among adopters, in %	73 (3.8, 100)	81 (7.5, 100)	47 (2.4, 100)	70 (9, 100)
How long this technology has been used among adopters, in years <sup>a</sup>	7 (0, 30)	8 (1, 30)	4 (1, 18)	5 (0, 15)

Note: Values in parentheses indicate the minimum and maximum. Adopters are farmers who reported that they are still using the respective technology.

a. "0 years" indicates that the farmer started using the technology recently, i.e., less than one year ago.

Source: UzFarmBarometer survey (2024).

Regarding duration, manure application and crop rotation are the most established practices with an average of 7–8 years of use among adopters, while drip irrigation is recent with only 4 years of experience and laser leveling follows with 5 years. Interestingly, while crop rotation is the most widely adopted technology among sampled farmers, nearly one-third of those who adopted crop rotation have since discontinued the practice. This can indicate that, compared to the other technologies considered, crop rotation has lower persistence in use and a higher rate of dis-adoption over time. Farmers can also be looking for suitable crops to

include in rotation, and hence are trying to explore crops that both fit into existing cropping window (vegetation season) and are profitable.

The subsequent analysis examines the adoption patterns of each technology across the four regions and different types of farm specialization (Tables 5–8). Due to the low adoption rates observed for certain technologies, the regional and specialization-based tables focus exclusively on current adoption status, excluding the 'discontinued' category ('Don't use now, but used before').

Table 5 shows that adoption of crop rotation differs across regions. In Andijan, adoption is both the most widespread (69% ever used, calculated as  $143/206*100$ ) and the most sustained (47% still using), while respondents in the Samarkand region show moderate uptake (55%) but the steepest decline in continued use (only 28%). Kashkadarya and Khorezm fall lower on both indicators, with around 42–43% of respondents having ever used and about 39–40% still using. Land coverage among adopters is especially high in Khorezm (93%), suggesting that when crop rotation is practiced it dominates land use there, while Samarkand (64%) and Andijan (67%) lag behind. Duration of use is relatively stable across regions, at about six years, with only Andijan slightly higher (7 years). Agro-cluster membership further differentiates adoption. Most of cotton agro-cluster members tend to sustain crop rotation (42% vs. 32%), but they devote a smaller share of their land to it (65% vs. 75%). Both groups report similar adoption histories, with around six years of experience.

**Table 5: Adoption patterns of crop rotation across regions and farm specialization**

Variables	All (N=1225)	Regions				Specializes in cotton	
		Andijan (n=302)	Kashkadarya (n=306)	Khorezm (n=301)	Samarkand (n=316)	Yes (n=701)	No (n=524)
Have used this technology (before)	640	206	130	129	175	370	270
Still use this technology	468	143	118	120	87	298	170
Share of land area this technology is used among adopters, in %	73 (3.8, 100)	67 (3.8, 100)	93 (25.5, 100)	64 (8.8, 100)	65 (6.6, 100)	72 (6.1, 100)	75 (3.8, 100)
How long this technology has been used among adopters, in years <sup>a</sup>	6 (0, 30)	7 (1, 25)	6 (1, 20)	6 (1, 30)	6 (0, 26)	6 (1, 30)	6 (0, 25)

Note: Values in parentheses indicate the minimum and maximum. Adopters are farmers who reported that they are still using the respective technology.

a. "0 years" indicates that the farmer started using the technology recently, i.e., less than one year ago.

Source: UzFarmBarometer survey (2024).

**Table 6** below indicates that adoption of manure application varies strongly across regions. It is most common in Kashkadarya (26%) and Andijan (23%), while Khorezm shows lower uptake (13%) and Samarkand very little adoption (6%). Current use closely follows these patterns, with little evidence of discontinuation. Among adopters, land coverage is especially high in Khorezm (95%) and Andijan (83%), compared to more moderate shares in Kashkadarya (63%) and Samarkand (50%). Duration of use is longest in Khorezm (10 years) and Andijan (9 years), while adoption in Samarkand and Kashkadarya is both more recent and less widespread (4–5 years). Agro-cluster membership makes little difference for this technology. Cotton-specialized and non-specialized farms show nearly identical adoption rates (16% vs. 18%) and current use, with only small differences in land share (80% vs. 82%) and average duration (both about 8 years).

**Table 6: Adoption patterns of manure application across regions and farm specialization**

Variables	All (N=1225)	Regions				Specializes in cotton	
		Andijan (N=302)	Kashkadarya (N=306)	Khorezm (N=301)	Samarkand (N=316)	Yes (N=701)	No (N=524)
Have used this technology (before)	208	69	81	39	19	113	95
Still use this technology	197	66	81	37	13	107	90
Share of land area this technology is used among adopters, in %	81 (3.8, 100)	83 (9.6, 100)	95 (12.2, 100)	50 (8.6, 100)	63 (7.5, 100)	80 (8.6, 100)	82 (7.5, 100)
How long this technology has been used among adopters, in years <sup>a</sup>	8 (1, 30)	9 (2, 30)	10 (2, 24)	4 (1, 15)	5 (2, 10)	8 (2, 28)	8 (1, 30)

Note: Values in parentheses indicate the minimum and maximum. Adopters are farmers who reported that they are still using the respective technology.

a. "0 years" indicates that the farmer started using the technology recently, i.e., less than one year ago.

Source: UzFarmBarometer survey (2024).

**Table 7** shows the adoption of drip irrigation. Uptake is highest in Khorezm (26% ever used, 19% still using) and Andijan (20% ever, 16% still), while Kashkadarya and Samarkand show much lower levels (12% and 9% ever used, with only 11% and 8% still using). Discontinuation rates are modest, but overall adoption remains low. Among adopters, land coverage is moderate: about half of land in Khorezm (52%) and Samarkand (52%) is under drip irrigation, compared to lower levels in Andijan (42%). Agro-cluster membership reveals a clear divide. Cotton-specialized farms are more likely to adopt drip irrigation (24% ever, 20% still) than non-specialized farms (10% ever, 4% still). Land coverage among adopters is somewhat lower

for cotton farms (41%) than for non-cotton (54%), but adoption is more sustained among cotton farms.

**Table 7: Adoption patterns of drip irrigation across regions and farm specialization**

Variables	All	Regions				Specializes in cotton	
	(N=1225)	Andijan (N=302)	Kashkadarya (N=306)	Khorezm (N=301)	Samarkand (N=316)	Yes (N=701)	No (N=524)
Have used this technology (before)	201	60	36	78	27	174	27
Still use this technology	167	48	35	58	26	144	23
Share of land area this technology is used among adopters, in %	47 (2.4, 100)	42 (2.3, 100)	52 (12.5, 100)	52 (4.0, 100)	41 (3.6, 100)	46 (2.4, 100)	54 (4.2, 100)
How long this technology has been used among adopters, in years <sup>a</sup>	4 (1, 18)	3 (0, 8)	3 (2, 9)	4 (2, 7)	3 (1, 17)	3 (0, 8)	4 (1, 17)

Note: Values in parentheses indicate the minimum and maximum. Adopters are farmers who reported that they are still using the respective technology.

a. "0 years" indicates that the farmer started using the technology recently, i.e., less than one year ago.

Source: UzFarmBarometer survey (2024).

Table 8 shows that laser leveling adoption is highly concentrated regionally. More than half of farmers in Khorezm report having used the technology (56% ever, 54% still), while adoption is almost absent in Andijan, Kashkadarya, and Samarkand, where only negligible shares of farmers report use. Among adopters, land coverage is extensive, averaging about 70% of cultivated area, and use in Khorezm is relatively well established with an average duration of four years. Agro-cluster membership also shapes adoption. Cotton-specialized farms are more likely to adopt and continue using laser leveling (22% ever, 21% still) than non-specialized farms (10% for both). Land coverage and duration are very similar across groups, at about 70% of land and four years of use.

Overall, three key patterns emerge from the adoption of SAPs in Uzbekistan from Tables 5–8. First, the spread of technologies varies widely across regions, suggesting that local familiarity and agro-ecological conditions, such as land and soil quality, play an important role in shaping adoption choices. Second, farms that are members of cotton agro-clusters show higher adoption rates of modern technologies, yet without corresponding differences in the share of land allocated or the length of experience. This indicates that agro-cluster membership facilitates access to such technologies but does not necessarily translate into more intensive or long-term use. Third, the shorter adoption histories of modern

technologies likely reflect recent policies promoting agro-clusters, which have expanded farmers' access to these practices.

**Table 8: Adoption patterns of laser leveling across regions and farm specialization**

Variables	All	Regions				Specializes in cotton	
	(N=1225)	Andijan (N=302)	Kashkadarya (N=306)	Khorezm (N=301)	Samarkand (N=316)	Yes (N=701)	No (N=524)
Have used this technology (before)	178	9	0	169	0	22	156
Still use this technology	168	4	0	164	0	18	150
Share of land area this technology is used among adopters, in %	70 (9, 100)	71 (22.4, 100)	-	70 (9.0, 100)	-	70 (9.1, 100)	69 (9.1, 100)
How long this technology has been used among adopters, in years <sup>a</sup>	4 (0, 15)	3 (0, 6)	-	4 (2, 15)	-	4 (0, 15)	4 (1, 7)

Note: Values in parentheses indicate the minimum and maximum. Adopters are farmers who reported that they are still using the respective technology.

a. "0 years" indicates that the farmer started using the technology recently, i.e., less than one year ago.

Source: UzFarmBarometer survey (2024).

Table 9 reports the share of farmers who "Agree" or "Strongly Agree" with statements about the benefits and challenges of adopting selected four technologies, split by adopters and non-adopters using the full sample (N=1225). Responses "Agree" and "Strongly Agree" were converted to 1. Regarding perceived benefits, most farmers (68–83%) recognize advantages such as improved water infiltration and storage (83%), increased soil organic matter, profitability, and biodiversity (78–79%), and, to a slightly lesser extent, reduced diseases and pests (68%). Further, the share of farmers reporting benefits from adoption generally increases among adopters than non-adopters across all four technologies. Regarding perceived challenges, around one-third of sampled farmers report issues such as limited decision-making autonomy and lack of necessary equipment to apply SAPs (37–38%), increased weed pressure (35%), insufficient labor for implementing SAPs (29%), and insufficient knowledge about correct application methods and where to purchase required inputs and seeds (26–27%). Furthermore, the share of farmers reporting adoption-related challenges differs between adopters and non-adopters, with perceived challenges being more frequently reported among non-adopters.

**Table 9: Perceived benefits and challenges from the adoption of sustainable agricultural practices among adopters and non-adopters, share of respondents with “Agree & Strongly agree answers”**

SAP characteristics	All (N=1225)	Crop rotation adopted		Manure adopted		Drip irrigation adopted		Laser leveling adopted	
		Yes (N= 640)	No (N=585)	Yes (N= 208)	No (N=1017)	Yes (N= 201)	No (N=1024)	Yes (N= 178)	No (N=1047)
<i>Perceived benefits</i>									
Increases biodiversity	0.78	0.81	0.74	0.94	0.75	0.91	0.75	0.90	0.76
Increases soil organic matter	0.79	0.82	0.75	0.95	0.75	0.90	0.76	0.92	0.76
Reduces soil erosion	0.74	0.77	0.71	0.88	0.71	0.82	0.73	0.92	0.71
Improves water infiltration and storage	0.83	0.80	0.87	0.89	0.82	0.93	0.81	0.94	0.81
Increases profits from crops	0.79	0.85	0.71	0.97	0.75	0.87	0.77	0.94	0.76
Reduces disease and insect pests	0.68	0.75	0.60	0.82	0.65	0.68	0.68	0.93	0.64
<i>Perceived challenges</i>									
Adoption of SAP increases risks of weed growing on fields	0.35	0.36	0.35	0.18	0.39	0.29	0.36	0.35	0.35
I do not have sufficient decision-making autonomy to cultivate SAPs	0.38	0.40	0.37	0.25	0.41	0.26	0.41	0.25	0.40
I do not have enough necessary equipment for applying SAPs	0.37	0.37	0.37	0.26	0.39	0.21	0.40	0.21	0.40
I do not have enough workers for applying SAPs	0.29	0.29	0.30	0.17	0.32	0.12	0.33	0.16	0.32
I do not have enough knowledge about correct application of SAPs	0.27	0.27	0.27	0.13	0.30	0.11	0.30	0.19	0.29
I do not know where to buy inputs and seeds required for SAP	0.26	0.27	0.24	0.14	0.28	0.11	0.29	0.19	0.27

Note: Adopters are farmers who reported having ever used the respective technology.  
Source: UzFarmBarometer survey (2024).

## 4 Econometric estimation

This study applies two econometric approaches. The first is the multivariate probit (MVP) model to account for the possible relationship between SAPs, and a model to estimate probit models for each individual SAP. The MVP model, used to analyze multivariate choice decision problems, is formulated through two interrelated systems of equations following Kassie et al. (2015). First, the model specifies a system of equations in which the dependent variables are latent (unobserved) and are expressed as linear functions of various observed factors, including farm and farmer attributes, institutional arrangements, and locational characteristics of the farm ( $X_i$  – *observed variables of  $i$  th farm  $i = 1 \dots N$* ) and multivariate normally distributed stochastic terms ( $\varepsilon_i$ ). Hence, considering all SAPs, the model can be written as:

$$D_{ik}^* = \delta_k X_{ik} + \varepsilon_{ik} \quad (k=CR, MA, LL, DI) \quad (1)$$

$D_{ik}^*$  denotes the latent dependent variables which can be represented by the level of expected benefit derived from adoption. *CR, MA, LL and DI* indicate crop rotation, sustainable manure application, land laser levelling and drip irrigation respectively. A farm adopts SAPs if the expected benefit from adoption is higher compared with non-adoption. The second set of equations, which characterizes the observed binary choice variables of households, is expressed as follows:

$$D_{ik} = \begin{cases} 1 & \text{if } D_{ik}^* > 0 \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

Within the multivariate framework, where multiple SAP adoption decisions can occur, the error terms are assumed to follow a multivariate normal (MVN) distribution with a conditional mean of zero and a variance standardized to unity. The symmetric covariance matrix  $\Omega$  can thus be given by:

$$\Omega = \begin{bmatrix} 1 & \rho_{CRMA} & \rho_{CRLL} & \rho_{CRDI} \\ \rho_{MACR} & 1 & \rho_{MALL} & \rho_{MADI} \\ \rho_{LLCR} & \rho_{LLMA} & 1 & \rho_{LLDI} \\ \rho_{DICR} & \rho_{DIMA} & \rho_{DILL} & 1 \end{bmatrix} \quad (3)$$

where  $\rho$  (rho) indicates the pairwise correlation coefficient of the error terms corresponding to any two SAP adoption equations to be estimated in the model (Bilal and Jaghdani, 2024; Kassie et al., 2015; Teklewold et al., 2013).

The second goal of this study is to better understand the impact of each SAP on farm outcomes “farm revenue”, “sustainability index”, and “gender wage gap”. We use a two-stage estimation method which is endogenous switching regression (ESR) model following Abdulai and Huffman (2014), Jaleta et al. (2016), and Kurbanov et al. (2024). In the first stage

for each SAP we separately use probit model. In the second stage we used an Ordinary Least Squares (OLS) estimator:

$$y_i = \alpha_0 + \beta X_i + \mu D_{is} + u_i \quad (4)$$

where  $Y_{is}$  is a vector of outcome variables of farmer  $i$ ,  $X_i$  is vectors of determinants of the outcome variables.  $D_{is}$  is  $s$  th SAP of farmer  $i$ , where  $D_{is}$  take a value of 1 if a farmer adopts  $s$  th SAP and 0 otherwise.  $\alpha_0$  is a constant,  $\beta$  and  $\mu$  are vectors of estimated parameters, and  $u_i$  is an error term.

The impact of  $s$ th SAP on outcomes is estimated through the parameter  $\mu$ . However, this method may yield biased estimates since it treats  $s$  th SAP adoption as exogenous, whereas it may actually be endogenous (Di Falco et al., 2011). Farmers' adoption decisions can be influenced by individual self-selection and other factors, such as technology preferences, which might vary among different groups like younger and older farmers. Recognizing that selection bias may arise from both observable and unobservable attributes affecting both adoption decision and outcome variables simultaneously, using Ordinary Least Squares (OLS) could result in biased and inconsistent estimates. From this perspective, to test selection bias, the Inverse Mills Ratio (IMR) can be calculated from the first stage probit model's results (Heckman, 1979) as follows:

$$\lambda_{1is} = \frac{\varphi(\delta X_{is})}{\Phi(\delta X_{is})} \text{ and } \lambda_{2is} = \frac{-\varphi(\delta X_{is})}{1-\Phi(\delta X_{is})} \quad (5)$$

where  $\varphi(\cdot)$  and  $\Phi(\cdot)$  indicate probability density function and cumulative density function of the standard normal distribution respectively.  $\lambda_{1is}$  and  $\lambda_{2is}$  represent IMR for adopters and non-adopters of  $s$ th SAP ( $s= 1$  to 8, 1-crop rotation; 2-sustainable manure application; 3-land laser levelling; 4-drip irrigation; 5-crop rotation with drip irrigation; 6-crop rotation with laser levelling; 7-crop rotation with manure application; and 8-laser levelling with drip irrigation), respectively.  $X_{is}$  is observables for each SAP that used first stage probit model. Thus, in our model the outcome equations in two regimes are:

$$\text{Regime 1 (SAP adopters): } y_{1is} = X_{is1}\beta_{1s} + \sigma_{1\epsilon s}\lambda_{1is} + \eta_{1is} \text{ if } D_{is} = 1 \quad (6a)$$

$$\text{Regime 2 (SAP non-adopters): } y_{2is} = X_{is2}\beta_{2s} + \sigma_{2\epsilon s}\lambda_{2is} + \eta_{2is} \text{ if } D_{is} = 0 \quad (6b)$$

where  $\sigma_{1\epsilon s}$  and  $\sigma_{2\epsilon s}$  are parameters to be estimated,  $\eta_{1is}$  and  $\eta_{2is}$  are normally distributed error terms with mean zero and constant variance.

We select instrumental variables (IV) that affect  $D_{is}$  (adoption decision of  $s$  th SAP of  $i$  th farm) and do not appear in explanatory variables of outcome equation following Abdulai and Huffman (2014), Di Falco et al. (2011), and Jaleta et al. (2016). Technology adoption studies employ information sources as valid IVs (Asfaw et al., 2012; Di Falco et al., 2011; Manda et al., 2016). Furthermore, social learning, peer effects, local learning, and information diffusion explains SAP adoption (Di Falco et al., 2011; Manda et al., 2016; Rogers, 2003). An increase in the number of adopters within a district can further enhance adoption levels, as existing

adopters may share their experiences with their peers (Tadjiev et al., 2025). Farmers often rely on neighbors, relatives, and fellow farmers to form beliefs about the profitability of SAPs. Therefore, we assume that the influence of information sources and the share of adopters on outcomes operates only through the adoption of SAPs. The distance from a farmer's home to the field plays an important role in adoption decisions. For example, the likelihood of adopting drip irrigation may decrease when the field is located farther from the home, due to implementation and supervision challenges. In our study, we thus use information sources such as other farmers, neighbors, relatives and media as IVs. In addition, we employ the "distance from farm fields to the house" and the "share of adopters of particular SAP in district" (share of crop rotation adopters, share of sustainable adopters, share of drip irrigation adopters, and share of laser levelling adopters) as IVs. We checked the suitability of these instruments through a simple falsification test (Di Falco et al., 2011) which showed that the selected variables can be considered as valid instruments: they are jointly statistically significant drivers of the decision to adopt particular SAP, but not of outcome variables of non-adopters. The falsification test is presented in [Table A2](#) of Appendix.

The impact of SAP on farmer's outcomes can be tested through the comparison of expected outcomes of adoption and non-adoption in actual and counterfactual scenarios based on Equations 6a and 6b as follows:

$$E(y_{1is}|X, D_{is} = 1) = X_{1is}\beta_{1s} + \sigma_{1\epsilon s}\lambda_{1is} \quad (7a)$$

$$E(y_{2is}|X, D_{is} = 0) = X_{2is}\beta_{2s} + \sigma_{2\epsilon s}\lambda_{2is} \quad (7b)$$

$$E(y_{2is}|X, D_{is} = 1) = X_{1is}\beta_{2s} + \sigma_{2\epsilon s}\lambda_{1is} \quad (7c)$$

$$E(y_{1is}|X, D_{is} = 0) = X_{2is}\beta_{1s} + \sigma_{1\epsilon s}\lambda_{2is} \quad (7d)$$

Here, Equations 7a and 7b are observed in the sample. In contrast, Equations 7c and 7d consider counterfactuals: Equation 7c is for adopters who would have decided not to adopt the  $s$  th practice, and Equation 7d is for non-adopters who would have decided to adopt.

The differences between Equations 7a and 7c can be formulated as Equation 8 which explains the comparison of the expected outcomes, and allows us to calculate the average treatment effect on the treated (ATT) as follows:

$$\begin{aligned} ATT &= (7a) - (7c) = E(y_{1is} | X, D_{is} = 1) \\ &- E(y_{2is}|X, D_{is} = 1) = X_{1is} (\beta_{1s} - \beta_{2s}) \\ &+ \lambda_{1is}(\sigma_{1\epsilon s} - \sigma_{2\epsilon s}) \end{aligned} \quad (8)$$

The differences between Equations 7b and 7d can be formulated as Equation 9 which is the average treatment effect on the untreated (ATU):

$$\begin{aligned} ATU &= (7b) - (7d) = E(y_{2is}|X, D_{is} = 0) \\ &- E(y_{1is}|X, D_{is} = 0) = X_{2is} (\beta_{1s} - \beta_{2s}) \end{aligned}$$

$$+ \lambda_{2i}(\sigma_{1\epsilon S} - \sigma_{2\epsilon S}) \quad (9)$$

We can use the expected outcomes described in Equations 7a-7d to calculate heterogeneity effects. Farms that chose to adopt might have achieved higher outcomes than those that did not, not necessarily because they adopted SAPs, but possibly due to unobservable factors such as their skills or abilities. This is known as ‘base heterogeneity’ (BH), meaning at baseline there are already differences between two groups other than the role of SAP. Additionally, outcomes for two groups may differ due to unobserved factors, as groups can vary in their responses to stimuli over time. This variability is known as ‘transition heterogeneity’ (TH), meaning post-adoption outcomes differ among groups. We calculate these based on standard methods as presented, for example, by Di Falco et al. (2011) and Jaleta et al. (2016). Accordingly, the difference between Equations 7a and 7d (BH<sub>1</sub>) represents base heterogeneity (BH) for adopters, and the difference between Equations 7c and 7b (BH<sub>2</sub>) represents BH for non-adopters. The difference between Equations (8) and (9) provides transition heterogeneity.

## 5 Results

This section presents the empirical results in two parts. First, we examine the determinants of adoption of four SAPs using a multivariate probit model which accounts for correlations between adoption decisions. The results are interpreted as associations rather than causal effects. Second, we assess the impacts of adoption on three farm-level outcomes, namely revenue per hectare, environmental sustainability index, and the gender wage gap between male and female seasonal workers, using treatment-effects models, which allow us to address potential selection bias in adoption decisions. The main findings are discussed in Section 6.

### 5.1 Determinants of SAP adoption

[Table 10](#) reports the estimates from the multivariate probit model for individual adoption decisions of four SAPs. The determinants of combined adoption decisions of the four SAPs are reported in [Table A3](#) in Appendix. The coefficients indicate the direction and statistical significance of the association between each explanatory variable and the probability of adopting a given practice, while the multivariate specification accounts for correlations across the four adoption equations. To facilitate readability, the explanatory variables are grouped into farmer, behavioral, farm, environmental, institutional, and technology characteristics, and regional dummies. We summarize the main patterns within each group, focusing on the sign and significance of the coefficients.

**Table 10: Multivariate probit model results**

Variables	Crop rotation (1)	Manure application (2)	Laser levelling (3)	Drip irrigation (4)
<i>Farmer characteristics</i>				
Farmer age (years)	-0.0003 (0.004)	0.009* (0.005)	-0.016** (0.008)	-0.003 (0.005)
Share of work experience in agriculture	0.689** (0.295)	-1.312*** (0.387)	0.247 (0.589)	-0.187 (0.394)
Higher education (1/0)	0.105 (0.084)	-0.068 (0.106)	0.139 (0.171)	-0.195* (0.104)
Own knowledge	0.160 (0.100)	-0.216* (0.131)	-0.112 (0.199)	0.114 (0.128)
Trainings attended	0.046 (0.034)	0.244*** (0.039)	0.037 (0.051)	0.201*** (0.036)
Farmer network support size	-0.104*** (0.020)	0.196*** (0.029)	-0.003 (0.028)	-0.090*** (0.030)
SAP info: peers/relatives	0.442*** (0.104)	-0.132 (0.144)	-1.114*** (0.288)	-0.495*** (0.138)
SAP info: media	0.185 (0.121)	0.234 (0.150)	0.060 (0.285)	-0.682*** (0.165)
<i>Behavioral characteristics</i>				
Risk taker (1-5, higher=willing to take more risks)	0.105* (0.063)	-0.108 (0.076)	-0.015 (0.145)	0.087 (0.073)
Loss aversion (1–5, higher=concerned more about gains)	-0.290*** (0.042)	0.050 (0.050)	-0.127 (0.114)	0.040 (0.052)
Future-oriented (1–5, higher =willing to wait for higher future outcome)	-0.018 (0.052)	-0.003 (0.064)	0.194* (0.117)	0.042 (0.067)
Planned farming horizon (years)	0.018*** (0.003)	-0.005 (0.003)	-0.009 (0.006)	-0.016*** (0.003)
Adopt unproven SAPs (1–5, higher=strongly willing)	0.011 (0.042)	-0.013 (0.049)	0.069 (0.092)	0.037 (0.050)
<i>Farm characteristics</i>				
Farm size (ha)	-0.003* (0.002)	-0.002 (0.002)	0.004 (0.004)	0.007*** (0.002)
Cotton/wheat specialization	0.179 (0.119)	-0.366*** (0.140)	0.832*** (0.316)	0.534*** (0.159)
Tractor ownership	0.130 (0.107)	0.231* (0.135)	0.864*** (0.277)	0.026 (0.164)
Technology level (1–5, higher = outdated)	0.141*** (0.040)	0.031 (0.053)	-0.012 (0.115)	-0.216*** (0.055)
Revenue reinvested (%)	-0.004* (0.002)	-0.003 (0.003)	0.008* (0.005)	0.001 (0.003)
Succession certainty (1–3, higher = more certain)	-0.227*** (0.068)	0.191** (0.093)	-0.203 (0.131)	-0.078 (0.092)
Distance to home (km)	-0.005 (0.009)	0.038*** (0.011)	0.029 (0.021)	-0.048*** (0.018)

Variables	Crop rotation (1)	Manure application (2)	Laser levelling (3)	Drip irrigation (4)
<i>Environmental characteristics</i>				
Plot location (1–5, higher=very near water)	0.073 (0.047)	-0.027 (0.063)	-0.083 (0.107)	-0.142** (0.067)
Canal condition (1–5, higher=excellent)	0.084 (0.051)	0.109 (0.071)	-0.086 (0.107)	0.016 (0.071)
Drought problem severity (1–5, higher =very serious)	-0.098** (0.039)	-0.058 (0.048)	-0.098 (0.082)	0.010 (0.046)
Water availability trend (1–3, higher=increased)	-0.031 (0.064)	-0.271*** (0.081)	-0.080 (0.156)	0.042 (0.083)
Heatwave frequency trend (1–3, higher=increased)	0.201** (0.082)	-0.182 (0.112)	0.571*** (0.183)	0.112 (0.113)
<i>Institutional characteristics</i>				
Input access difficulty (strongly agree)	0.574*** (0.124)	-0.177 (0.151)	0.522** (0.259)	0.015 (0.155)
Input access difficulty (moderately agree)	0.115 (0.118)	-0.083 (0.135)	0.410* (0.238)	-0.059 (0.140)
Credit constrained (1=yes)	0.117 (0.122)	0.219 (0.143)	-0.087 (0.264)	-0.324* (0.191)
Tenure autonomy (moderately agree)	-0.088 (0.125)	-0.072 (0.155)	-0.730*** (0.212)	-0.315** (0.144)
Tenure autonomy (strongly agree)	-0.009 (0.124)	-0.215 (0.144)	-0.680** (0.268)	-0.376** (0.156)
Land reallocation experience (times)	-0.082* (0.042)	0.187*** (0.054)	-0.086 (0.097)	0.049 (0.054)
<i>Technology characteristics</i>				
SAP benefits (moderately agree)	0.613*** (0.157)	1.344*** (0.389)	0.330 (0.827)	0.528** (0.232)
SAP benefits (strongly agree)	0.797*** (0.156)	1.623*** (0.398)	0.165 (0.818)	0.368 (0.240)
SAP challenges (strongly agree)	0.115 (0.123)	-0.356* (0.184)	-0.780*** (0.244)	-0.714*** (0.175)
SAP challenges (moderately agree)	0.283*** (0.099)	0.0003 (0.122)	-0.124 (0.217)	-0.258** (0.128)
<i>Regional dummies</i>				
Khorezm	-0.230 (0.149)	-1.175*** (0.210)	2.599*** (0.342)	-0.483*** (0.187)
Kashkadarya	-0.264 (0.173)	0.838*** (0.206)	-5.570*** (0.501)	-0.947*** (0.216)
Samarkand	-0.128 (0.168)	-0.453** (0.221)	-4.884*** (0.461)	-0.426* (0.219)
_cons	-1.155* (0.607)	-2.244*** (0.863)	-3.055** (1.511)	-0.221 (0.845)

$\rho_{21}$	-0.413*** (0.062)
$\rho_{31}$	-0.021 (0.101)
$\rho_{41}$	-0.412*** (0.061)
$\rho_{32}$	0.082 (0.149)
$\rho_{42}$	-0.050 (0.089)
$\rho_{43}$	0.038 (0.125)
Log pseudolikelihood	-1497.165***
Wald $\chi^2$ (152)	4254.03***
Likelihood ratio test of $\rho_{21} = \rho_{31} = \rho_{41} = \rho_{32} = \rho_{42} = \rho_{43} = 0$ $\chi^2$ (6)	73.213***
N	1225

Note: Standard errors in parentheses. \*\*\*, \*\* and \* indicate significant at  $p < 0.01$ ,  $p < 0.05$  and  $p < 0.1$  level, respectively. number of random draws (R = 150). Adopters are farmers who reported having ever used the respective technology.

Among **farmer characteristics**, several variables are clearly related to one or more practices. Age is weakly positively associated with manure application and negatively associated with laser levelling, while it is not significantly related to crop rotation or drip irrigation. The share of work experience in agriculture is positively associated with crop rotation and negatively associated with manure application and does not show significant coefficients for laser levelling or drip irrigation. Higher education is not significantly associated with crop rotation, manure application, or laser levelling, but is negatively and significantly associated with drip irrigation. Agronomic knowledge is significantly and negatively related to manure application and not to the other practices. Training attendance stands out with positive and significant coefficients for manure application and drip irrigation, and positive but insignificant coefficients for crop rotation and laser levelling. Network support size is negatively and significantly associated with crop rotation and drip irrigation, and positively and significantly associated with manure application. Information received from peers and relatives is positively and significantly associated with crop rotation, and negatively and significantly associated with laser levelling and drip irrigation; it is not significantly related to manure application. Information obtained from media is not significantly associated with crop rotation, manure application, or laser levelling, but shows a negative and significant coefficient for drip irrigation. Altogether, farmer characteristics indicate that crop rotation is more common among farmers with longer agricultural experience, smaller support networks, and stronger reliance on peer information, whereas manure application and drip irrigation are more frequently adopted by farmers who have attended trainings and, in the case of manure, who have larger support networks.

**Behavioral characteristics** display distinct, practice-specific patterns. A higher willingness to take risks is positively and significantly associated with crop rotation, while its coefficients for the other three practices are not significant. Loss aversion is strongly and negatively associated with crop rotation and is not significantly related to the adoption of the other technologies. Future orientation is positively and significantly associated with laser levelling, and not significantly associated with crop rotation, manure application, or drip irrigation. The planned farming horizon is positively and significantly associated with crop rotation and negatively and significantly associated with drip irrigation and shows no significant association with manure application or laser levelling. The indicator for adopting unproven SAPs, capturing openness to experimentation, is not significantly associated with any of the four practices. These results indicate that crop rotation is the practice most clearly linked to behavioral traits, particularly higher risk tolerance, lower loss aversion, and a longer planned farming horizon, while laser levelling is related to a future-oriented outlook, and manure application shows no strong behavioral correlates in the model.

**Farm characteristics** also show differentiated associations. Farm size has a small but negative and significant coefficient for crop rotation and a positive and significant coefficient for drip irrigation, indicating that drip irrigation is more common on larger farms, while crop rotation is slightly less frequent there. Cotton–wheat specialization is positively and significantly associated with laser levelling and drip irrigation and negatively and significantly associated with manure application, and is not significantly related to crop rotation. Tractor ownership is positively and significantly related to laser levelling and positively (at 10% level) related to manure application, and not significantly related to crop rotation or drip irrigation. The technology level index, where higher values indicate more outdated equipment, is positively and significantly associated with crop rotation and negatively and significantly associated with drip irrigation, while its coefficients for manure application and laser levelling are not significant. The share of revenue reinvested in the farm is positively associated with crop rotation and laser levelling and not significantly related to manure application or drip irrigation. Succession certainty is negatively and significantly associated with crop rotation and positively and significantly associated with manure application, with no significant coefficients for laser levelling or drip irrigation. Distance from home to field is positively and significantly associated with manure application and not significantly related to the other three practices. Overall, these farm-level patterns suggest that laser levelling and drip irrigation are more prevalent on cotton–wheat specialized, tractor-equipped farms, while crop rotation is more common on farms with older machinery and lower succession certainty, and manure application is more frequent where tractors are available, succession is perceived as secure, and plots are located further from the homestead.

**Environmental characteristics** show selective associations with adoption. Plot location relative to irrigation water, where higher values indicate fields nearer to water sources, is not significantly related to crop rotation, manure application, or laser levelling, but has a negative and significant coefficient for drip irrigation, so plots closer to water are less likely to be equipped with drip systems. Canal condition, capturing perceived quality of canal

infrastructure, is not significantly associated with any of the four practices. Drought problem severity is negatively and significantly associated with crop rotation and not significantly related to the other technologies. Perceived increases in water availability are positively and significantly associated with manure application and not significantly associated with crop rotation, laser levelling, or drip irrigation. The perceived trend in heatwave frequency is positively and significantly associated with crop rotation and laser levelling, and not significantly related to manure application or drip irrigation. In sum, drought concerns are linked to reduced crop rotation, increasing water availability is linked to more manure application, and more frequent heatwaves are associated with higher adoption of crop rotation and laser levelling.

**Institutional characteristics** also display several clear patterns. Strong agreement that input access is difficult is positively and significantly associated with crop rotation and laser levelling, while moderate agreement is positively and significantly associated with laser levelling and not with the other practices. For manure application and drip irrigation, the coefficients for input access difficulty are not statistically significant. Credit constraints do not show significant coefficients for crop rotation, manure application, or laser levelling, but are negatively and significantly associated with drip irrigation. Moderate and strong tenure autonomy are negatively and significantly associated with laser levelling and drip irrigation but not with crop rotation or manure application. Land reallocation experience is negatively and significantly associated with crop rotation and positively and significantly associated with manure application, and is not significantly related to the two modern technologies. The findings for institutional factors show that input access difficulties, tenure perceptions, credit constraints, and land reallocation experiences are related to adoption in technology-specific ways.

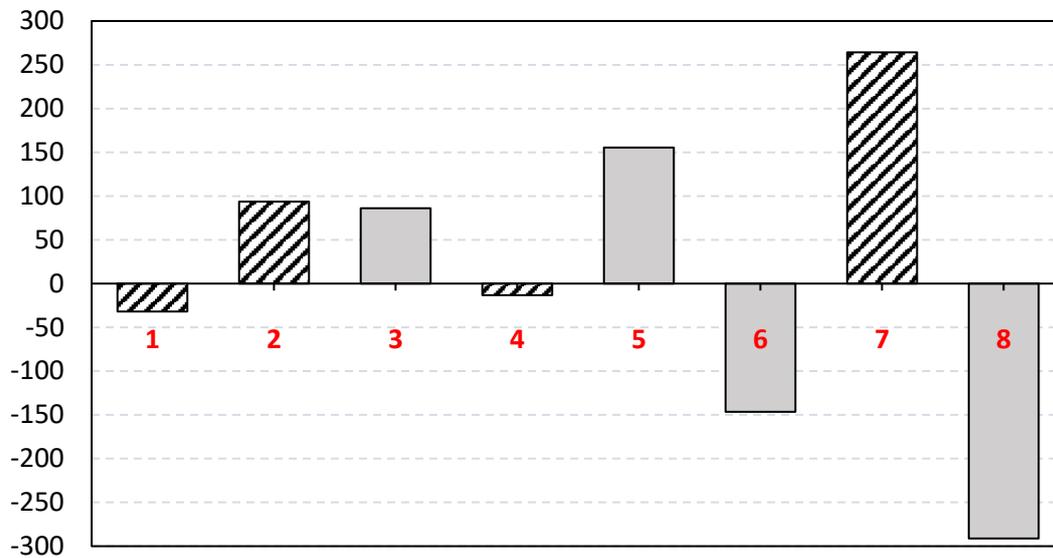
**Technology characteristics**, measured through perceived benefits and challenges of SAPs, are strongly related to adoption. For crop rotation, both moderate and strong agreement with SAP benefits have positive and highly significant coefficients. The same holds for manure application, where agreement with benefits is strongly and positively associated with adoption. For drip irrigation, moderate agreement with benefits is positively and significantly related to adoption, while strong agreement shows a positive but statistically insignificant coefficient. For laser levelling, perceived benefits are not significantly associated with adoption. Perceived challenges show the opposite pattern for most practices. Strong agreement with challenges is negatively and significantly associated with manure application, laser levelling, and drip irrigation, and is not significant for crop rotation. Moderate agreement with challenges is positively and significantly associated with crop rotation, not significant for manure application and laser levelling, and negatively and significantly associated with drip irrigation. Overall, perceived benefits are positively related to adoption of crop rotation, manure application, and drip irrigation, whereas perceived challenges are more often negatively related to adoption, particularly for manure application, laser levelling and drip irrigation.

Finally, the **regional dummies** indicate that adoption is strongly region-specific. Compared to the omitted reference region, farms in Khorezm are significantly less likely to adopt manure application and drip irrigation and significantly more likely to adopt laser levelling, while there is no significant difference for crop rotation. Farms in Kashkadarya are significantly more likely to adopt manure application and significantly less likely to adopt laser levelling and drip irrigation, again with no significant difference for crop rotation. Farms in Samarkand are significantly less likely to adopt manure application, laser levelling, and drip irrigation and do not differ significantly from the reference region in terms of crop rotation. These spatial patterns underline that diffusion of the four practices is uneven across regions.

## 5.2 Impact of SAP adoption

We now turn to the estimated impacts of SAP adoption on farm revenue, environmental sustainability, and the gender wage gap, drawing on the estimated average treatment effects on the treated (ATT) reported in Figures 3–5. The figures show the ATTs for the four individual and (joint) bundled SAPs on three outcome variables: farm revenue per hectare, the farm-level environmental sustainability index, and the gender wage gap among seasonal workers. In all three figures, full-colored bars indicate statistically significant effects at the 10% level, while dashed bars indicate effects that are not statistically different from zero. Treatments 1–4 refer to the single adoption of crop rotation, manure application, drip irrigation, and laser levelling. Treatments 5–8 refer to bundled adoption of crop rotation with drip irrigation, crop rotation with laser levelling, crop rotation with manure application, and laser levelling with drip irrigation.

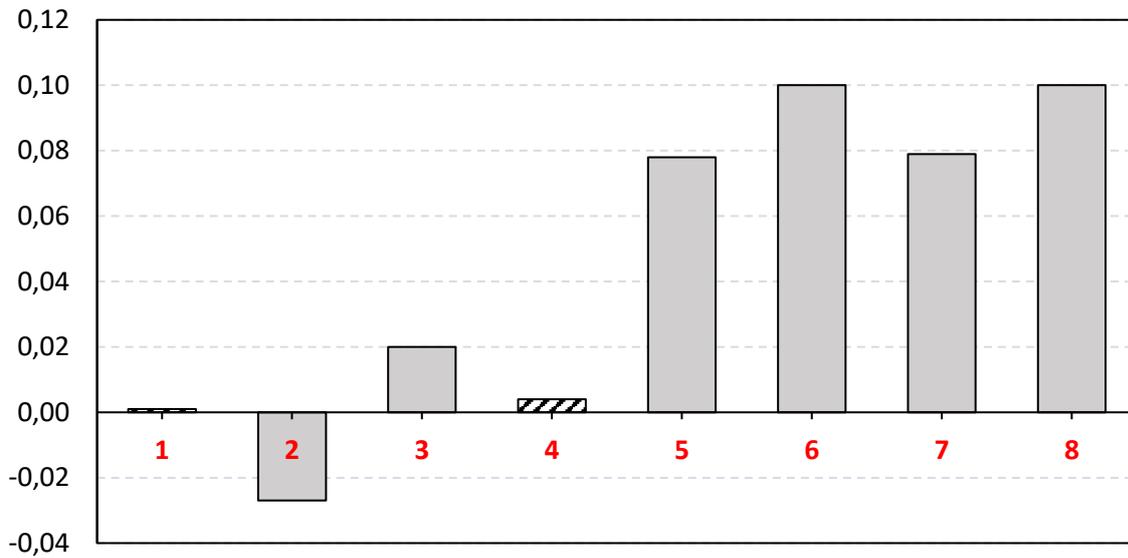
For **farm revenue** (Figure 3), the clearest pattern concerns drip irrigation and its combination with crop rotation. Drip irrigation on its own (3) is associated with a statistically significant increase in revenue per hectare of around 80 US dollars for adopters. Crop rotation alone (1) has a small negative ATT of about 30 US dollars, which is not statistically significant. Manure application (2) and the combination of crop rotation and manure application (7) are associated with positive but statistically insignificant revenue gains of around 90 and 260 US dollars per hectare, respectively. The combination of crop rotation and drip irrigation (5) shows the largest and statistically significant revenue effect, with an increase of about 150 US dollars per hectare relative to the matched non-adopters. In contrast, laser levelling alone (4) and its combinations with crop rotation (6) and with drip irrigation (8) are associated with revenue losses. These effects are sizeable for the two combinations, particularly for laser levelling with drip irrigation (8), where the ATT is roughly minus 280 US dollars per hectare and statistically significant.



**Figure 3: Average treatment effects on the treated (ATT) of SAPs on farm revenue (US\$ per ha)**

Note: Full-colored bars indicate statistically significant results at  $p < 0.1$ ; dashed bars indicate non-significant results. 1=Crop rotation; 2=Manure application; 3=Drip irrigation; 4=Laser levelling; 5=Crop rotation + Drip irrigation; 6=Crop rotation + Laser levelling; 7=Crop rotation + Manure application; 8=Laser Levelling + Drip Irrigation. Adopters are farmers who reported having ever used the respective technology.

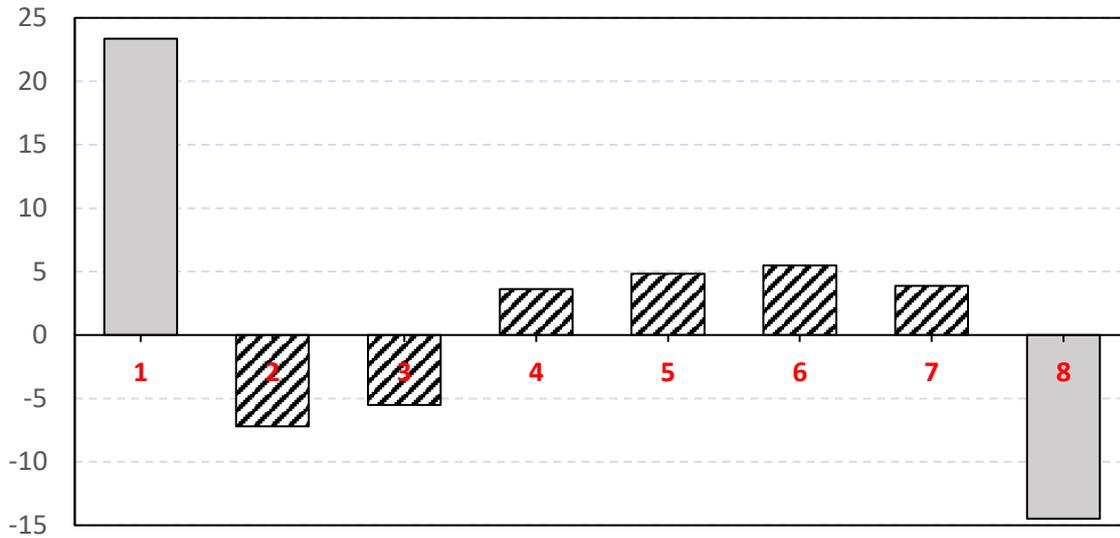
For the **agricultural sustainability index** (Figure 4), the pattern is more consistently positive, especially for SAP bundles. Manure application on its own (2) is associated with a small but statistically significant reduction in the sustainability index of about 0.025 points. Crop rotation (1) has a very small positive but insignificant effect. Drip irrigation (3) is associated with a statistically significant improvement in the sustainability index of about 0.02 points, whereas laser levelling alone (4) has a small, positive and statistically insignificant effect. All four combinations (5–8) show clear and statistically significant gains in sustainability. The joint adoption of crop rotation and drip irrigation (5) increases the index by about 0.08 points, while crop rotation with laser levelling (6) and laser levelling with drip irrigation (8) both increase the index by about 0.10 points. The combination of crop rotation and manure application (7) also shows a positive and significant effect of roughly 0.08 points. Overall, the ATT estimates indicate that combined adoption of SAPs is associated with markedly higher sustainability scores than adoption of individual practices, with particularly strong effects for bundles that include one or both modern technologies.



**Figure 4: Average treatment effects on the treated (ATT) of SAPs on environmental sustainability (index 0-1)**

Note: Full-colored bars indicate statistically significant results at  $p < 0.1$ ; dashed bars indicate non-significant results. 1=Crop rotation; 2=Manure application; 3=Drip irrigation; 4=Laser levelling; 5=Crop rotation + Drip irrigation; 6=Crop rotation + Laser levelling; 7=Crop rotation + Manure application; 8=Laser Levelling + Drip Irrigation. Adopters are farmers who reported having ever used the respective technology.

For the **gender wage gap** among seasonal workers (Figure 5), the estimated effects are more mixed and only two treatments show statistically significant coefficients. Note that an increase in gender wage gap is assumed to reflect more gender discriminatory labor compensation against female laborers, suggesting unequitable pay. Crop rotation alone (1) is associated with an increase in the gender wage gap of around 23 US dollars per month, and this effect is statistically significant. Manure application (2) and drip irrigation (3) are associated with reductions in the wage gap of around 7 and 6 US dollars per month, respectively, but these effects are not statistically significant. Laser levelling on its own (4) and the three combinations that include crop rotation (5–7) are associated with positive, but statistically insignificant, wage gap changes of about 3 to 5 US dollars per month. In contrast, the joint adoption of laser levelling and drip irrigation (8) is associated with a statistically significant reduction in the gender wage gap of roughly 14 US dollars per month. Hence, among all treatments, crop rotation alone is the only one that significantly widens the wage gap, while the bundle of modern technologies (laser levelling with drip irrigation) is the only one that significantly narrows it.



**Figure 5: Average treatment effects on the treated (ATT) of SAPs on gender wage gap among seasonal workers (US\$ per month)**

Note: Full-colored bars indicate statistically significant results at  $p < 0.1$ ; dashed bars indicate non-significant results. 1=Crop rotation; 2=Manure application; 3=Drip irrigation; 4=Laser levelling; 5=Crop rotation + Drip irrigation; 6=Crop rotation + Laser levelling; 7=Crop rotation + Manure application; 8=Laser Levelling + Drip Irrigation. Adopters are farmers who reported having ever used the respective technology.

In addition to estimating the ATT, we also examine heterogeneity effects, specifically base heterogeneity (BH) and transition heterogeneity (TH) (the detailed results are presented in [Table A4](#) and [Table A5](#) in Appendix). While several ATT estimates are statistically insignificant or even negative, the TH results often show the opposite pattern and are statistically significant. For instance, as illustrated in [Figure 3](#), the ATT for the adoption of sustainable manure application on crop revenue is positive but statistically insignificant. In contrast, the corresponding TH estimate is both positive and statistically significant. This suggests that, overall, farmers benefit from adopting sustainable manure application in terms of increased crop revenue. A similar pattern emerges for laser leveling adoption. The ATT for the isolated adoption of laser leveling on farm revenue is negative and statistically insignificant. However, the TH estimate for this practice is positive and statistically significant, indicating that, on average, farmers experience revenue gains from adopting laser leveling.

By and large, no technology in the sample improves all three outcomes (revenue, sustainability, and gender wage gap) in a statistically significant way. However, drip irrigation stands out as the only technology that shows statistically significant improvements in two of the three dimensions. It is associated with higher revenue and better sustainability outcomes among adopters, while also showing a favorable, though not statistically significant, reduction in the gender wage gap. This suggests that drip irrigation may offer a relatively balanced contribution across economic, environmental, and social goals. In contrast, laser

levelling does not lead to statistically significant improvements in any of the three outcomes. Moreover, the direction of change in gender wage inequality appears unfavorable. These results show that drip irrigation technology is the most promising technology overall, while suggesting that the current adoption of laser levelling has delivered limited measurable benefits. By comparison, traditional practices such as crop rotation and manure application show a more uneven pattern of effects, with limited or no realized revenue gains and trade-offs in either agricultural sustainability or social outcomes.

## 6 Discussion

This section discusses the main findings of the analysis in light of the existing literature and crucially, within the specific institutional and economic context of Uzbekistan's ongoing agricultural reforms. Section 6.1 reflects on the adoption patterns of the four SAPs, considering how the interplay of structural conditions, institutional arrangements, and behavioral factors help explain the differences between traditional and modern practices. Section 6.2 turns to the estimated associations between SAP adoption and farm revenue, environmental sustainability, and the gender pay gap among hired labor, with particular attention to complementarities and trade-offs across practices and their implications for equity. Throughout the discussion, we compare our results with previous evidence on SAP adoption in developing countries, and explain what these patterns imply for the design of policies and donor programmes that seek to promote more sustainable and inclusive agricultural production in Uzbekistan.

### 6.1 Interpreting adoption patterns in a reforming agricultural sector

Taken together, the multivariate probit results confirm that adoption of the four SAPs in Uzbekistan is highly technology specific and strongly conditioned by the broader enabling policy context. The significant correlations in the MVP model, particularly the negative correlations between crop rotation and both manure application and drip irrigation, suggest farmers perceive these practices as strategic substitutes within their technology portfolio, likely due to differing resource demands or contrasting institutional linkages. This pattern is broadly in line with large-sample syntheses which show that once technology type, institutional setting, and agroecological conditions are considered, only a few variables display consistent associations with adoption across studies (Madin et al., 2025; Ruzzante et al., 2021). Our findings underscore that in transitional economies, macro-level institutional shifts can override or reshape the influence of typical farm-level determinants. Meta-analytical evidence indicates that education, land size, access to credit and extension, tenure security, and membership in organizations are on average positively associated with the uptake of agricultural innovations, while at the same time their effect and even their signs vary widely across technology classes and regions (Ruzzante et al., 2021). Scoping reviews similarly emphasize that climatic, economic, and socio-cultural factors rarely operate in the

same way across practices and contexts, and therefore call for empirical models that allow for heterogeneity and interdependencies in adoption behavior (Madin et al., 2025). Our results fit this picture: neither socio-demographic nor structural variables emerge as universal predictors across the four SAPs, while perceptions of technologies, institutional incentives, and behavioral characteristics show practice-specific associations.

Across all four practices, the clearest and most consistent pattern concerns perceived benefits and challenges of SAPs. Farmers who report stronger agreement with the benefits of SAPs are more likely to adopt crop rotation, manure application, and drip irrigation, whereas stronger agreement with statements about challenges is associated with lower adoption probabilities, particularly for laser levelling and drip irrigation. This is consistent with the adopter-perception perspective in adoption theory, which stresses that perceived relative advantage, compatibility, and complexity are central determinants of technology uptake (Pannell et al., 2006; Rosário et al., 2022; Ruzzante et al., 2021). In Uzbekistan's context, where information about long-term sustainability benefits remains limited and where many modern technologies have been introduced relatively recently, it is plausible that farmers rely heavily on their own assessments of short- and medium-term economic benefits and management demands. The strong role of perceived benefits for both a low-capital practice (manure application) and a high-capital practice (drip irrigation) suggests that farmers differentiate carefully between technologies rather than reacting uniformly to generic "sustainability" messages, which is in line with findings from other settings where adoption is more responsive to perceived profitability than to abstract environmental arguments (Begho et al., 2022; Pretty and Hine, 2000).

Institutional and land-related variables show more unexpected patterns, particularly for the modern, capital-intensive technologies. In contrast to evidence from many other developing countries, where more secure tenure and greater decision-making autonomy tend to support long-term investments in land-improving practices (Foguesatto et al., 2020; Ruzzante et al., 2021), we find that higher perceived tenure autonomy is negatively associated with the adoption of both laser levelling and drip irrigation. This counterintuitive result is a key illustration of how Uzbekistan's unique reform trajectory shapes micro-level decisions. This result can be understood against the background of Uzbekistan's recent agricultural reforms. Since 2020 the state procurement system for cotton has been abolished and cotton production has been reorganized into private cotton-textile agro-clusters, within which farmers contract with a single agro-cluster and receive inputs, credit, and marketing services through that intermediary (Babadjanov and Petrick, 2025). Although formal quotas have been removed, agro-clusters and local authorities still play an important role in steering technology choices and providing access to subsidized equipment and water-saving technologies.

At the same time, the government has launched several subsidy schemes for water-saving irrigation technologies, including drip irrigation and laser levelling, which cover part of the investment costs and offer tax exemptions on irrigated land equipped with these

technologies (Liutin and Dower, 2023; World Bank, 2022). These programmes are often channeled through larger farms and agro-cluster arrangements that already cooperate closely with state agencies. It is therefore plausible that farmers who perceive less autonomy in land-use decisions are precisely those more embedded in agro-clusters and state programmes and thus more exposed to incentives and pressure to adopt modern equipment. Farmers who feel more autonomous may also be those who diversify away from cotton and wheat and therefore face weaker incentives to invest in agro-cluster-supported technologies whose profitability is closely tied to these crops. The recent evidence from Uzbekistan indicates that, under current institutional and economic conditions, the production of key state-regulated crops such as cotton and wheat can be economically unattractive to farmers (Kurbanov et al., 2025). When profitability is low, farmers are less inclined to channel institutional support, such as decision-making autonomy or access to credit, into fixed productive investments like modern technologies. Instead, they may redirect these resources toward alternative income-generating activities, which appear more promising than adopting practices with high upfront costs and uncertain returns.

The role of training, information channels, and social networks further illustrate how institutional support and social capital shape adoption in a system undergoing reforms. Training attendance is strongly and positively related to the adoption of manure application and drip irrigation, confirming evidence that extension, demonstrations, and targeted training can facilitate both low-capital and high-capital SAPs (Arslan et al., 2022; Aryal et al., 2015; Kassie et al., 2015). In contrast, the size of informal support networks and the reliance on peers and media for SAP information show mixed and sometimes negative associations, particularly for modern technologies. This pattern suggests that the diffusion of drip irrigation and laser levelling in Uzbekistan is driven more by formal channels, including agro-clusters, water authorities, and equipment suppliers, rather than by horizontal learning among neighbors. Recent qualitative work on water-saving technologies in Uzbekistan reports that many farmers remain skeptical about drip irrigation, in part because of high upfront costs, unclear profitability, and limited successful local examples, and that they often “wait and see” until credible success stories emerge in their own networks (Liutin and Dower, 2023). Our negative coefficients for peer and media information on drip adoption are consistent with this observation: in the current stage of diffusion, informal discussions may transmit more caution and mixed experiences than enthusiastic endorsements. However, this does not imply social networks are irrelevant. Recent evidence shows that greater peer engagement on specific topics like water management issues can increase adoption of SAPs (Tadjiev et al., 2025).

Farmer characteristics, including behavioral ones, help explain the distinct profiles of adopters of traditional versus modern practices. For crop rotation, higher willingness to take risks, lower loss aversion, and a longer planned farming horizon are all positively associated with adoption, whereas higher shares of lifetime agricultural experience and greater succession certainty reduce the probability of rotating crops. This combination suggests that crop rotation is more common among farmers who are willing to alter established routines

and to plan over a longer horizon, while more “settled” farmers with strong path dependence and established successor plans may be more inclined to stick to familiar monoculture patterns, especially in cotton-dominated areas. For manure application, behavioral variables are less prominent, but training, network support, tractor ownership, and succession certainty matter, which fits the idea that manure use is both labor intensive and knowledge intensive and is more likely where farmers anticipate continued family farming and have access to basic machinery. For laser levelling, future-oriented farmers are more likely to adopt, while older farmers are less likely, suggesting that younger or more forward-looking managers are more willing to engage with precision technologies that require new forms of management. These differentiated patterns mirror findings from behavioral studies that highlight the importance of risk and time preferences, innovation orientation, and status quo bias for conservation and efficiency-enhancing practices (Dessart et al., 2019; Shaub et al., 2023; Swart et al., 2023).

Environmental variables are not uniformly strong predictors in our models, yet several associations are informative in light of Uzbekistan’s water and climate challenges. Farms that report more severe drought problems are less likely to adopt crop rotation, while higher frequency of heatwaves is associated with greater uptake of laser levelling. Difficulties in water access and deteriorating canal conditions are central concerns in many irrigated areas of the country, and national strategies explicitly promote water-saving technologies as a response to growing water scarcity and the legacy of Aral Sea desiccation (Liutin and Dower, 2023). At the same time, irrigation service fees continue to be charged mostly per hectare rather than per volume, and much of the cost of water delivery and pumping is borne by the state rather than by farmers, which weakens direct financial incentives to save water (Liutin and Dower, 2023). In this setting, farmers’ responses to environmental stress may depend more on perceived risks to yields and on local support for specific technologies than on direct water-price signals, which could explain why environmental variables show selective rather than universal effects in our models.

Finally, the estimated error correlations of the multivariate probit model and the adoption patterns across individual and joint practices indicate that farmers treat SAPs as elements of broader technology portfolios rather than as isolated choices. Positive and significant correlations between adoption of manure and drip irrigation, and between crop rotation and drip irrigation, point to complementarities between soil fertility management and water-saving technologies, consistent with evidence from other regions where bundles of conservation measures and improved varieties yield higher and more stable returns than single practices (Manda et al., 2016; Teklewold et al., 2013). At the same time, the lack of a single determinant that explains adoption across all four SAPs, even within the class of modern physical technologies, underscores the importance of tailoring policy instruments to specific practices and local institutional conditions. In the context of Uzbekistan’s ongoing agricultural reforms, this implies that generic support to “sustainable agriculture” is unlikely to be sufficient; instead, targeted combinations of subsidies, training, and institutional

arrangements are needed that take both technology attributes and farmers' perceived benefits and constraints into account.

## 6.2 Impacts of SAP adoption: Bundles, trade-offs, and social outcomes

The impact estimates provide first insights into how individual and combined SAPs shape farm revenue, agricultural sustainability, and gender wage gaps in Uzbekistan's irrigated farming systems. A central finding is that no single practice in our sample simultaneously improves the outcome variables. Rather, the outcomes respond differently to individual and combined adoption decisions, revealing clear trade-offs and synergies. This pattern is consistent with the literature on trade-offs and complementarities in smallholder systems, which shows that sustainable intensification rarely delivers uniform gains across all dimensions and that effects depend on practice combinations, farming systems, and policy environments (Kassie et al., 2015; Manda et al., 2016; Teklewold et al., 2013; Wainaina et al., 2016). In our case, drip irrigation on its own raises both revenue and the farm-level sustainability index, whereas manure application is revenue-enhancing but reduces the sustainability index. Crop rotation alone slightly reduces revenue and has only a modest, statistically insignificant sustainability effect. The strongest and most robust gains in revenue appear when crop rotation is combined with drip irrigation, while all tested practice bundles deliver significantly higher sustainability scores than non-adoption. These results closely mirror evidence from Eastern and Southern Africa where portfolios of conservation agriculture components and improved varieties yield higher and more stable returns than their single components (Kassie et al., 2015; Manda et al., 2016; Teklewold et al., 2013).

Our least favorable result concerns laser levelling as a single treatment, which shows no measurable improvement in revenue, sustainability, or the gender wage gap for adopters, and even negative revenue effects when combined with drip irrigation. This contrasts with experimental and farm-level evidence from the Indo-Gangetic Plains and from several pilot projects in Uzbekistan that document substantial water savings, yield increases, and higher net returns when laser levelling is implemented under suitable conditions and with adequate service provision (Ali et al., 2018; Aryal et al., 2015; Bekchanov et al., 2010; Oberkircher, 2010). In Khorezm, for example, trials reported water savings of 1,500–2,000 m<sup>3</sup> per hectare and yield gains for wheat and cotton of around 0.4 t/ha compared with traditional levelling, together with higher irrigation application efficiency (Bekchanov et al., 2010; Oberkircher, 2010). More recent scaling study by Hermans et al. (2023) indicates that laser levelling has been rolled out widely, with particularly high uptake in flat region such as Khorezm and increasing domestic production of laser planners.

Several contextual factors can help reconcile this positive evidence with our null and sometimes negative average treatment effects. First, our impact estimates pooled farms across diverse regions and hydrological settings. Khorezm and parts of Kashkadarya are relatively low-lying, flat and saline, rely on salt leaching for cropping and technically well

suited for precision levelling, whereas landscapes in other regions are heterogeneous, shaped by favorable conditions for mixed cropping and horticulture. Existing experiments and case studies that demonstrate strong benefits of laser levelling in Khorezm are precisely from such flat, gravity-fed systems (Bekchanov et al., 2010; Hermans et al., 2023). It is therefore plausible that our estimates understate region-specific benefits and that separate evaluation for Khorezm and Kashkadarya, would reveal clearer positive effects where topography and infrastructure are most favorable. Second, the structure of irrigation costs in Uzbekistan weakens the private financial incentive to save water and electricity. Pumped irrigation from the Amu Darya and other water sources supply a large share of water in regions such as Kashkadarya and Bukhara, and the electricity costs of these pumping stations account for a very high share of the irrigation sector's operating budget, which is largely financed from the state budget rather than through volumetric water charges to farmers (Hamidov et al., 2022). When farmers do not face the full marginal cost of water and energy, efficiency gains from technologies like laser levelling translate only weakly into private revenue gains, even if they generate substantial fiscal and environmental benefits at system level. This creates a critical policy misalignment between private adoption incentives and social benefits.

Third, adoption channels and implementation quality matter. In India and Pakistan, positive impacts of laser levelling are often observed where the technology is delivered through specialized service providers or cooperatives that ensure proper field preparation, well-calibrated equipment, and regular maintenance (Ali et al., 2018; Aryal et al., 2015). In Uzbekistan, the rapid diffusion of laser levelling has been promoted through subsidies for equipment purchases, concessional credit lines, and agro-cluster-based initiatives, but field reports and scaling-readiness assessments note variation in operator skills, equipment quality, and after-sales service, as well as difficulties in accessing repairs in remote areas (Hamidov et al., 2022; Hermans et al., 2023). Under such conditions, early adopters may not yet realize the full potential of the technology, and observed yields and revenues may lag behind the gains documented in controlled experiments. The fact that laser levelling appears more beneficial in combination with other practices in our sustainability results, and that it contributes to a reduction in the gender wage gap when paired with drip irrigation, suggests that its advantages may currently materialize more clearly in labor organization and water management than in short-run revenue.

On social outcomes, our analysis adds to a relatively small body of research on gendered labor impacts of SAPs. Much of the adoption literature still focuses on productivity and environmental indicators and pays limited attention to how new technologies reshape labor demand, task allocation, and bargaining power within households and labor markets (Malapit et al., 2020; Manda et al., 2016). In our case, single adoption of crop rotation appears to widen the gender wage gap among seasonal workers, whereas the combined adoption of laser levelling and drip irrigation substantially narrows it. These contrasting patterns suggest that different SAPs reconfigure seasonal labor in distinct ways. A plausible mechanism is that crop rotation raises labor demand for soil preparation, and crop-specific

tasks, e.g. weeding, that are more often undertaken by daily-hired female workers with very low pay. For male workers this hired daily field work could be not attractive or male workers are simply not available, i.e. migrated. By contrast, mechanized and water-saving technologies such as laser levelling and drip irrigation reduce the physical intensity and timing constraints of irrigation jobs, which may allow more women to participate in better remunerated or more regular field tasks and may reduce scope for discretionary wage setting that disadvantages women. This interpretation is consistent with qualitative accounts that link mechanization and improved irrigation scheduling to more formalized employment relations and less reliance on casual, male-dominated irrigation labor (Hamidov, 2022; FAO, 2023). While these mechanisms remain tentative, the evidence underscores that SAP adoption can have redistributive effects within rural labor markets, and that inclusive policy design needs to consider gendered labor implications alongside economic and environmental outcomes (Doss and Quisumbing, 2020; Malapit et al., 2020).

More broadly, our findings show that the impacts of SAPs are multidimensional and context-dependent. In a reforming agricultural sector like Uzbekistan's, where agro-clusters, subsidies, and centrally financed energy costs define farmers' incentives, impacts cannot be inferred from technology attributes alone. Policymakers should therefore consider the institutional fit of technologies, not just their agronomic potential. Integrating gender-disaggregated indicators and labor outcomes into future evaluations is crucial for understanding whether sustainable technologies reinforce or mitigate existing inequalities. Finally, our cross-sectional design, the "ever-used" adoption definition, and the use of matching-based treatment-effects models limit the strength of causal claims and likely attenuate measured effects. These limitations echo calls in recent reviews to move beyond static, binary adoption models towards analytical frameworks that incorporate dynamic portfolios, discontinuation, and re-adoption (Madin et al., 2025). In Uzbekistan's context, panel data from future rounds of the UzFarmBarometer survey, event history models that track the sequencing of technologies, and experimental or quasi-experimental designs around subsidy and service programmes for drip irrigation and laser levelling would provide a more precise assessment of how sustainable practices affect productivity, sustainability, and equity in the medium and long run. Ultimately, promoting sustainable agriculture in Uzbekistan requires moving beyond a focus on adoption per se to a deeper understanding of how practices perform within the nation's evolving institutional landscape, and for whom.

## 7 Conclusions and policy implications

This study has provided nationally representative evidence on the adoption and impacts of four SAPs in Uzbekistan. By analyzing both determinants and farm-level outcomes, our results reveal how practice-specific and institutional factors, and farmers' behavioral characteristics shape the adoption of different sustainable practices and how these choices translate into economic, environmental, and social outcomes. Taken together, the findings highlight that transitioning to sustainable agriculture is not merely a technical challenge but a complex socio-institutional process.

**First, adoption is strongly driven by farmers' perceptions of the benefits and challenges of specific practices, while standard structural characteristics such as education or farm size are not consistent predictors.** The determinants are clearly practice specific. Traditional practices like crop rotation respond most strongly to farmers' behavioral characteristics and perceived advantages of SAP use, whereas adoption of modern technologies such as drip irrigation and laser levelling are also related to institutional arrangements, farm structure, and training. This confirms that promoting "sustainable agriculture" as a broad category is unlikely to be effective unless policies are tailored to the characteristics of individual practices and to the specific institutional environment in which farmers operate.

**Second, the impact analysis demonstrates that practice bundles matter more than isolated technologies.** Individual practices rarely improve all outcomes at once, but combinations of selected traditional and modern SAPs generate more robust gains, especially for environmental sustainability and, in some cases, for revenue. In particular, the joint adoption of crop rotation and drip irrigation, and other paired adoptions, delivers stronger and more consistent improvements than single practices. This suggests that policies should think in terms of SAP bundles/portfolios rather than isolated technologies, and that the design of support instruments needs to reflect complementarities between soil, water, and crop management decisions.

**Third, the effects of modern technologies depend on how they are introduced, financed, organized, and supported on the ground, not just on the technology itself or the biophysical conditions.** Laser levelling, which is widely promoted as a water-saving and productivity-enhancing technology, does not show clear average benefits in our sample and even appears to reduce revenue when combined with drip irrigation. At the same time, evidence from pilot interventions and regional patterns within the data suggest that positive effects may be concentrated in specific locations, particularly in flatter areas with more favorable canal and drainage conditions and in settings where service provision works well. This indicates that the profitability of modern technologies cannot be taken for granted and depends on how they are introduced, financed, and supported in practice.

**These conclusions translate into several implications for policy. The first implication is that farmers' perceptions of profitability and risk need to be at the center of SAP promotion.** Since perceived benefits and challenges are closely aligned with adoption behavior, it is

important to make the economic performance of practices visible and testable. Policy instruments that provide clear information about expected costs and returns, support on-farm demonstrations, and allow farmers to try new practices at a limited scale can help reduce uncertainty and encourage experimentation. For labor-intensive practices such as manure application, this includes transparent communication about labor needs and yield effects. For capital-intensive technologies such as drip irrigation and laser levelling, farmers need realistic guidance on payback periods under different crop choices and water regimes.

**A second policy implication is the importance of targeted training and advisory services.**

Our model results show that practice-specific training is positively associated with adoption of manure application and drip irrigation, indicating that well-designed trainings can make a difference for both low-capital and high-capital SAPs. This suggests that initiatives such as irrigators' schools, farmer field schools, and agro-cluster-based training programmes should focus not only on general agronomic topics but also on the concrete management requirements and potential pitfalls of each SAP. Involving agro-clusters, and farmer organizations in curriculum design and delivery can make training more relevant and more closely linked to actual services and input supply.

**Third, access to modern equipment requires attention not only to investment subsidies but also to service markets.** Experience from other regions and field evidence from Uzbekistan indicate that the performance of technologies like laser levelling depends heavily on farmer-operators' skills, equipment quality, and access to repairs. Developing private and cooperative service providers, machinery pools, or agro-cluster-level service units can reduce fixed costs for individual farms and help maintain implementation quality. In regions where irrigation water is pumped at high public expense, such as Kashkadarya, aligning incentives so that water-saving technologies also generate private gains for farmers will be crucial. Gradual adjustments in irrigation service arrangements, or performance-based support that reward actual efficiency improvements, could contribute even further.

**Fourth, policy should explicitly support the adoption of SAP portfolios rather than single technologies.** The results show that combinations of practices can generate synergies in terms of sustainability and revenue, while also revealing trade-offs for labor and equity outcomes. Intervention packages that combine soil fertility management, diversified rotations, and efficient irrigation in agronomically suitable areas are likely to be more effective than programmes that promote only one component. Given the capital intensity of many modern SAPs, risk-mitigation instruments such as crop insurance linked to sustainable technologies, input guarantee schemes, or subsidized pilot plots can reduce downside risks for farmers and make bundled adoption more attractive.

**Fifth, institutional and equity dimensions require explicit attention of policy-making towards wider adoption of SAP.** While perceived land-use autonomy does not emerge as a straightforward driver of adoption in this study, predictable and transparent land-use rights remain important for long-term investment decisions and planning. In a context where land reallocation has been frequent and where cotton and wheat agro-clusters still exert strong

influence, continued efforts to clarify lease conditions and to ensure fair treatment across farms can create a more stable environment for investment in sustainable practices. At the same time, the concentration of capital-intensive technologies on better-endowed farms and the divergent effects of different practices on the gender wage gap suggest that SAP promotion can either reduce or reinforce existing inequalities. Targeted support for smaller farms and for women, including inclusive advisory services, improved access to credit and equipment, and attention to legal and social barriers to resource ownership, is therefore essential if sustainable intensification is to be socially inclusive.

**Finally, investments in information and behavioral tools can complement structural reforms.** Strengthening agro-environmental monitoring systems, for example through soil and water data and geospatial mapping of degradation and irrigation performance, would help target practices to locations where they are most likely to be beneficial. Behaviorally informed interventions, such as structured peer learning, the use of credible lead farmers, and communication that address common misperceptions and psychological barriers, can improve uptake without substantial additional financial costs.

**Future adoption studies in Uzbekistan should follow farmers and agro-clusters over time in order to capture the dynamics of adoption, discontinuation, and re-adoption of SAP portfolios.** Panel data, combined with qualitative work on perceived risks, service quality, and labor arrangements, will be particularly valuable for understanding how reforms reshape incentives and constraints. Building this longitudinal evidence base will help design policy instruments that not only increase adoption rates, but also support more cost-effective, productive, environmentally sustainable, and socially equitable farming systems.

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## Appendices

**Table A1: Farm-level agricultural sustainability scores**

Farm practice	Dimension of sustainability				Total
	Minimizes off-farm input use	Minimizes non-renewable input use	Maximizes natural biological processes	Promotes local biodiversity	
<b>I. Seed sourcing</b>					
Conventional					0
Organic		1			1
Own (farm saved)	1				1
<b>II. Soil fertility</b>					
Chemical fertilizers (Synthetic)	-1	-1	-1		-3
Organic fertilizers	1			1	2
Composted fertilizers	1	1		2	4
Green manure	1	1	1		3
Biofertilizers			1	1	2
Natural fertilizers	-1	-1			-2
<b>III. Pests and diseases control</b>					
Synthetic chemical pesticides	-1	-1	-3	-3	-8
Natural predators		0.5	1	1	2.5
Manual or mechanical methods		0.5	1	1	2.5
Crop rotation, intercropping, or planting resistant crop varieties for pests and disease control	1	1	1	1	4
Combine various methods, such as chemical, biological, manual/mechanical practices	1	1.5			2.5
<b>IV. Weed control</b>					
Hand tools or manual labor, and machinery such as tractors	1	0.5	1	0.5	3
Chemical herbicides	-1	-1	-1	-1	-4
Organic or synthetic mulch materials			1	1	2
Crop rotations for weed control	1	1	1	1	4
Plant cover crops	1	1	1	1	4

Source: Authors following Rigby et al. (2001).

**Table A2: Falsification test to check validity of instrument**

a)

Instrumental variables	Model 1	Model 2		
	<b>Adoption of crop rotation (1/0)</b>	<b>Farm revenue of non-adopters</b>	<b>Wage gap of non-adopters</b>	<b>Sustainability index of non-adopters</b>
Share of crop rotation adopters in district	3.230*** (0.539)	x	-17.662 (40.984)	0.056 (0.099)
Source of information about SAP from other farmers	0.437*** (0.105)	0.596 (136.938)	-0.830 (8.797)	-0.017 (0.019)
Wald test on selected IVs	$\chi^2 = 17.12^{***}$	F-Stat.=0.00	F-Stat.=0.12	F-Stat.=0.57
N	<b>1225</b>	<b>585</b>	<b>325</b>	<b>585</b>

b)

Instrumental variables	Model 1	Model 2		
	<b>Adoption of sustainable manure (1/0)</b>	<b>Farm revenue of non-adopters</b>	<b>Wage gap of non-adopters</b>	<b>Sustainability index of non-adopters</b>
Share of sustainable manure adopters in district	2.367*** (0.512)	-301.083 (691.351)	x	0.027 (0.069)
Distance from farm field home (km)	0.038*** (0.011)	-6.344 (11.110)	0.664 (0.762)	x
Wald test on selected IVs	$\chi^2 = 30.14^{***}$	F-Stat.=0.33	F-Stat.=0.76	F-Stat.=0.15
N	1225	1017	576	1017

c)

Instrumental variables	Model 1	Model 2		
	<b>Adoption of drip irrigation (DI) (1/0)</b>	<b>Farm revenue of non-adopters</b>	<b>Wage gap of non-adopters</b>	<b>Sustainability index of non-adopters</b>
Distance from farm field home (km)	-0.414** (0.017)	-3.693 (8.104)	0.858 (0.574)	x
Share of DI adopters in district	3.418*** (0.851)	-1168.486 (755.017)	34.444 (39.023)	x
Source of information about SAP from other farmers	-0.498*** (0.145)	-164.325 (144.933)	2.126 (5.761)	x
Wald test on selected IVs	$\chi^2 = 33.17^{***}$	F-Stat.=1.35	F-Stat.=0.96	x
Source of information about SAP from media	-0.704*** (0.177)	x	x	-0.018 (0.017)
Wald test on selected IV	$\chi^2 = 15.87^{***}$	x	x	F-Stat.=1.14
N	1225	1024	580	1024

d)

Instrumental variables	Model 1		Model 2	
	<b>Adoption of Laser Levelling (LL) (1/0)</b>	<b>Farm revenue of non-adopters</b>	<b>Wage gap of non-adopters</b>	<b>Sustainability index of non-adopters</b>
Share of LL adopters in district	3.730*** (0.801)	741.222 (1160.581)	2.015 (38.668)	-0.138
Source of information about SAP from other farmers	-0.972*** (0.292)	-109.132 (147.482)	2.358 (5.983)	x
Wald test on selected IVs	$\chi^2 = 33.06***$	F-Stat.=0.48	F-Stat.=0.08	F-Stat.=1.57
N	1225	1047	565	1047

Note: Model1: Probit model; Model 2: Ordinary least squares. Standard errors are reported in parentheses. \*\*\*, \*\* and \* are significant at  $p < 0.01$ ,  $p < 0.05$  and  $p < 0.1$  level, respectively. The coefficients for all other variables are not presented.

**Table A3: Determinants of combined SAP adoption decisions**

Variables	Crop rotation + Drip irrigation	Crop rotation + Laser levelling	Crop rotation + Manure application	Drip Irrigation + Laser Levelling
Age	-0.007 (0.008)	-0.017** (0.008)	0.007 (0.007)	-0.002 (0.011)
Share of work experience in agriculture	-0.028 (0.546)	1.341** (0.652)	-1.255** (0.570)	-0.524 (0.753)
Higher education	-0.101 (0.146)	0.346** (0.168)	0.035 (0.150)	-0.133 (0.221)
Farmer network support size	-0.172*** (0.041)	-0.203*** (0.053)	0.052** (0.024)	-0.084** (0.041)
Own knowledge	0.784*** (0.163)	-0.013 (0.189)	-0.011 (0.192)	0.524** (0.250)
Farm size	0.009*** (0.003)	0.008*** (0.003)	-0.006 (0.004)	0.013*** (0.004)
Cotton specialization	0.427* (0.250)	0.537* (0.299)	-0.033 (0.233)	0.944** (0.398)
Plot location	-0.119 (0.113)	-0.039 (0.136)	0.071 (0.083)	-0.616*** (0.176)
Canal condition	0.100 (0.123)	-0.052 (0.112)	0.100 (0.107)	-0.146 (0.170)
Drought problem severity	-0.057 (0.061)	-0.331*** (0.083)	-0.051 (0.077)	-0.089 (0.104)
Tractor ownership	0.315 (0.256)	0.339 (0.261)	0.342* (0.194)	0.328 (0.359)
Technology level	-0.205** (0.087)	0.006 (0.102)	0.054 (0.078)	-0.127 (0.131)
Input access difficulty (strongly agree)	0.555** (0.228)	0.937*** (0.251)	0.223 (0.248)	0.179 (0.309)
Input access difficulty (moderately agree)	-0.169 (0.223)	0.262 (0.256)	0.203 (0.225)	0.193 (0.329)

Variables	Crop rotation + Drip irrigation	Crop rotation + Laser levelling	Crop rotation + Manure application	Drip Irrigation + Laser Levelling
Decision-making autonomy (strongly agree)	-0.245 (0.225)	-0.258 (0.271)	0.091 (0.201)	-0.635* (0.328)
Decision-making autonomy (moderately agree)	-0.194 (0.219)	0.052 (0.216)	0.123 (0.218)	-0.559** (0.277)
SAP benefits (strongly agree)	0.572 (0.403)	-0.070 (0.301)	4.617*** (0.581)	0.760 (0.803)
SAP benefits (moderately agree)	0.302 (0.394)	0.240 (0.293)	4.407*** (0.538)	0.937 (0.824)
SAP challenges (strongly agree)	-0.574* (0.305)	0.279 (0.270)	-0.304 (0.304)	-1.191** (0.513)
SAP challenges (moderately agree)	0.180 (0.177)	0.865*** (0.218)	0.054 (0.179)	-0.639** (0.277)
Credit constrained (1=yes)	0.307 (0.229)	0.463 (0.289)	0.525*** (0.181)	-0.070 (0.343)
Land reallocation experience (times)	-0.069 (0.081)	-0.196** (0.090)	0.135 (0.086)	0.013 (0.106)
Planned farming horizon (years)	-0.005 (0.004)	0.008 (0.005)	0.002 (0.004)	-0.016* (0.009)
Succession certainty (1–3)	-0.149 (0.144)	-0.189 (0.125)	0.125 (0.124)	-0.037 (0.206)
Revenue reinvested	-0.005 (0.004)	-0.008* (0.005)	0.000 (0.005)	0.007 (0.005)
Trainings attended	0.229*** (0.048)	0.092 (0.061)	0.274*** (0.050)	0.312*** (0.075)
Risk taker	0.052 (0.122)	0.220 (0.163)	0.169 (0.129)	0.262 (0.181)
Future-oriented	0.154 (0.114)	0.028 (0.118)	-0.068 (0.102)	0.220 (0.155)
Loss aversion	-0.044 (0.077)	-0.076 (0.083)	-0.299*** (0.060)	-0.425*** (0.110)

Variables	Crop rotation + Drip irrigation	Crop rotation + Laser levelling	Crop rotation + Manure application	Drip Irrigation + Laser Levelling
Adopt unproven SAPs	0.013 (0.075)	-0.030 (0.086)	-0.117* (0.064)	0.333*** (0.125)
Water availability trend	0.047 (0.124)	-0.217 (0.137)	-0.312** (0.126)	0.022 (0.168)
Heatwave frequency trend	0.308** (0.154)	0.445*** (0.172)	-0.008 (0.159)	0.538** (0.218)
Distance to the home	-0.066** (0.028)	-0.016 (0.022)	0.052*** (0.015)	-0.036 (0.025)
share_Dri	2.497** (1.188)			8.948*** (2.965)
SAP info: media	-0.359* (0.210)	-0.248 (0.259)	0.359* (0.198)	0.090 (0.329)
SAP info: peers/relatives	-0.146 (0.207)	-0.104 (0.277)	-0.038 (0.211)	-0.341 (0.517)
Khorezm	-0.572** (0.273)	0.755 (0.469)	0.775 (0.496)	2.735*** (0.882)
Kashkadarya	-1.371*** (0.428)		1.620*** (0.470)	
Samarkand	0.223 (0.350)		0.773 (0.502)	
Share of drip irrigation adopters in the district	2.497** (1.188)			8.948*** (2.965)
Share of laser levelling in the district		2.517*** (0.678)		-2.956* (1.638)
Share of sustainable manure adopters in the district			2.070** (0.987)	
share of crop rotation adopters in the district			4.416*** (1.124)	
_cons	-2.818* (1.466)	-3.382*** (1.243)	-10.256*** (1.919)	-6.190*** (2.219)
<b>N</b>	<b>1225</b>	<b>1225</b>	<b>1225</b>	<b>1225</b>

Note: Standard errors in parentheses \* p < 0.1, \*\* p < 0.05, \*\*\* p < 0.01.

**Table A4: Treatment effect results based on ESR model for isolated SAP adoption**

a)

Outcome	Decisions in crop rotation			
	Category	Adopters (N=640)	Non-adopters (N=585)	Adoption effect
Crop revenue (\$/ha)	ATT	(a) 1613.419 (27.279)	(c) 1645.325 (25.027)	-31.906 (37.020)
	ATU	(d) 1490.444 (28.191)	(b) 1318.127 (19.949)	172.318*** (34.536)
	HE	BH1= 122.975	BH2= 327.199	TH = -204.224***
Sustainability (index 0-1)	ATT	(a) 0.383 (0.004)	(c) 0.382 (0.005)	0.001 (0.006)
	ATU	(d) 0.447 (0.006)	(b) 0.402 (0.005)	0.045*** (0.005)
	HE	BH1= - 0.064	BH2= -0.020	TH =-0.044***
	Category	Adopters (N=388)	Non-adopters (N=325)	Adoption effect
Gender wage gap (USD/month)	ATT	(a) 47.987 (2.183)	(c) 24.628 (1.868)	23.359*** (2.873)
	ATU	(d) 49.846 (2.275)	(b) 31.011 (1.998)	18.836*** (3.028)
	HE	BH1=-1.859	BH2= -6.382	TH = 4.523*

b)

Outcome	Decisions in sustainable manure application			
	Category	Adopters (N=208)	Non-adopters (N=1017)	Adoption effect
Crop revenue (\$/ha)	ATT	(a) 1558.357 (82.880)	(c) 1464.719 (29.344)	93.638 (87.922)
	ATU	(d) 1299.569 (39.405)	(b) 1454.822 (14.377)	-155.253*** (41.946)
	HE	BH1= 258.788	BH2= 9.897	TH = 248.891***
Sustainability (index 0-1)	ATT	(a) 0.393 (0.010)	(c) 0.420 (0.007)	- 0.027** (0.012)
	ATU	(d) 0.432 (0.004)	(b) 0.392 (0.003)	0.041*** (0.005)
	HE	BH1= - 0.039	BH2= 0.028	TH =-0.068***
	Category	Adopters (N=137)	Non-adopters (N=576)	Adoption effect
Gender wage gap (USD/month)	ATT	(a) 43.714 (4.061)	(c) 50.924 (2.995)	- 7.210 (5.046)
	ATU	(d) 73.838 (2.502)	(b) 39.424 (1.592)	34.413*** (2.966)
	HE	BH1=-30.124	BH2= 11.500	TH = -41.624***

c)

Outcome	Decisions in Drip irrigation			
	Category	Adopters (N=201)	Non-adopters (N=1024)	Adoption effect
Crop revenue (\$/ha)	ATT	(a) 1295.389 (19.319)	(c) 1209.298 (42.712)	86.091* (46.878)
	ATU	(d) 1223.247 (11.253)	(b) 1507.148 (19.276)	-283.901*** (22.320)
	HE	BH1= 72.142	BH2= - 297.850	TH = 369.992***
Sustainability (index 0-1)	ATT	(a) 0.431 (0.009)	(c) 0.411 (0.006)	0.020* (0.011)
	ATU	(d) 0.369 (0.005)	(b) 0.384 (0.003)	- 0.015** (0.006)
	HE	BH1=0.062	BH2= 0.027	TH =0.035***
	Category	Adopters (N=133)	Non-adopters (N=580)	Adoption effect
Gender wage gap (USD/month)	ATT	(a) 30.749 (3.513)	(c) 36.249 (2.634)	- 5.501 (4.391)
	ATU	(d) -10.084 (2.921)	(b) 42.427 (1.672)	- 52.511*** (3.365)
	HE	BH1=40.833	BH2= - 6.178	TH = 47.010***

d)

Outcome	Decisions in Laser levelling			
	Category	Adopters (N=178)	Non-adopters (N=1047)	Adoption effect
Crop revenue (\$/ha)	ATT	(a) 1218.944 (17.999)	(c) 1232.170 (33.547)	-13.226 (38.070)
	ATU	(d) 940.189 (11.972)	(b) 1515.492 (17.715)	-575.303*** (21.381)
	HE	BH1= 278.755	BH2= - 283.322	TH = 562.077***
Sustainability (index 0-1)	ATT	(a) 0.477 (0.008)	(c) 0.473 (0.005)	0.004 (0.010)
	ATU	(d) 0.555 (0.005)	(b) 0.377 (0.003)	0.178*** (0.006)
	HE	BH1=-0.078	BH2= 0.095	TH =-0.174***
	Category	Adopters (N=148)	Non-adopters (N=565)	Adoption effect
Gender wage gap (USD/month)	ATT	(a) 26.609 (2.210)	(c) 22.997 (2.494)	3.612 (3.332)
	ATU	(d) -2.510 (1.465)	(b) 43.822 (1.647)	- 46.332*** (3.383)
	HE	BH1=29.120	BH2= - 20.825	TH = 49.945***

Note: \*\*\*, \*\* and \* indicate significant at  $p < 0.01$ ,  $p < 0.05$  and  $p < 0.1$  level, respectively. Standard error in parenthesis.

**Table A5: Treatment effect results based on ESR model for combined SAP adoption**

a)

Outcome	Decisions in Crop rotation + Drip irrigation			
	Category	Adopters (N=64)	Non-adopters (N=1161)	Adoption effect
Crop revenue (\$/ha)	ATT	(a) 1422.699 (58.370)	(c) 1267.269 (65.628)	155.430* (87.831)
	ATU	(d) 980.490 (23.642)	(b) 1475.142 (16.709)	-494.652*** (28.834)
	HE	BH1= 442.209	BH2= -207.873	TH = 650.081***
Sustainability (index 0-1)	ATT	(a) 0.488 (0.020)	(c) 0.410 (0.012)	0.078*** (0.024)
	ATU	(d) 0.372 (0.006)	(b) 0.387 (0.003)	-0.015** (0.007)
	HE	BH1= 0.116	BH2= 0.024	TH = 0.062***
	Category	Adopters (N=48)	Non-adopters (N=665)	Adoption effect
Gender wage gap (USD/month)	ATT	(a) 29.614 (11.555)	(c) 24.781 (3.743)	4.833 (12.146)
	ATU	(d) -120.089 (11.738)	(b) 41.016 (1.468)	- 161.105*** (3.383)
	HE	BH1=149.703	BH2= - 16.235	TH = 165.938***

b)

Outcome	Decisions in Crop rotation + Laser levelling			
	Category	Adopters (N=72)	Non-adopters (N=1153)	Adoption effect
Crop revenue (\$/ha)	ATT	(a) 1251.636 (37.181)	(c) 1381.762 (58.004)	-130.126* (68.934)
	ATU	(d) 1071.706 (16.076)	(b) 1486.188 (15.700)	-414.482*** (22.471)
	HE	BH1= 179.930	BH2= -104.426	TH =284.355***
Sustainability (index 0-1)	ATT	(a) 0.521 (0.017)	(c) 0.419 (0.008)	0.102*** (0.018)
	ATU	(d) 0.515 (0.006)	(b) 0.384 (0.003)	0.131*** (0.007)
	HE	BH1= 0.006	BH2= 0.035	TH = -0.029
	Category	Adopters (N=58)	Non-adopters (N=655)	Adoption effect
Gender wage gap (USD/month)	ATT	(a) 30.133 (5.387)	(c) 24.393 (3.972)	5.740 (6.693)
	ATU	(d) 12.106 (3.415)	(b) 41.144 (1.423)	- 29.038*** (3.699)
	HE	BH1=18.027	BH2= -16.751	TH = 34.778***

c)

Outcome	Decisions in Crop rotation + Manure Application			
	Category	Adopters (N=79)	Non-adopters (N=1146)	Adoption effect
Crop revenue (\$/ha)	ATT	(a) 2024.930 (198.600)	(c) 1760.732 (76.592)	264.199 (212.858)
	ATU	(d) 94.681 (75.033)	(b) 1434.313 (13.893)	-1339.632*** (72.137)
	HE	BH1=1930.249	BH2=326.418	TH =1603.831***
Sustainability (index 0-1)	ATT	(a) 0.432 (0.017)	(c) 0.353 (0.009)	0.079*** (0.019)
	ATU	(d) 0.392 (0.009)	(b) 0.389 (0.003)	0.003 (0.009)
	HE	BH1=0.040	BH2= -0.036	TH = 0.076**
	Category	Adopters (N=55)	Non-adopters (N=658)	Adoption effect
Gender wage gap (USD/month)	ATT	(a) 66.095 (9.168)	(c) 62.208 (4.262)	3.887 (10.110)
	ATU	(d) 27.246 (6.209)	(b) 38.088 (1.456)	-10.842 (6.377)
	HE	BH1=38.849	BH2= 24.120	TH = 14.729

d)

Outcome	Decisions in Drip Irrigation + Laser levelling			
	Category	Adopters (N=71)	Non-adopters (N=1154)	Adoption effect
Crop revenue (\$/ha)	ATT	(a) 1245.533 (21.883)	(c) 1536.72 (59.973)	-291.187** (63.840)
	ATU	(d) 1479.215 (18.037)	(b) 1486.360 (15.833)	-7.145 (24.001)
	HE	BH1=-233.682	BH2=50.360	TH =-282.042***
Sustainability (index 0-1)	ATT	(a) 0.519 (0.016)	(c) 0.419 (0.010)	0.100*** (0.018)
	ATU	(d) 0.507 (0.007)	(b) 0.384 (0.003)	0.123*** (0.008)
	HE	BH1= 0.012	BH2= 0.035	TH = -0.023**
	Category	Adopters (N=64)	Non-adopters (N=649)	Adoption effect
Gender wage gap (USD/month)	ATT	(a) 33.680 (4.605)	(c) 48.156 (5.148)	-14.476** (6.907)
	ATU	(d) -27.829 (5.963)	(b) 40.896 (1.468)	-68.725*** (6.142)
	HE	BH1= 61.509	BH2= 7.259	TH = 54.249**

Note: \*\*\*, \*\* and \* indicate significant at  $p < 0.01$ ,  $p < 0.05$  and  $p < 0.1$  level, respectively. Standard error in parenthesis.

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**Leibniz Institute of Agricultural Development  
in Transition Economies (IAMO)**

Theodor-Lieser-Str. 2  
06120 Halle (Saale), Germany

 +49 345 2928-0

 [iamo@iamo.de](mailto:iamo@iamo.de)

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