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RELATIONSHIP BETWEEN ENVIRONMENTAL SUSTAINABILITY INDEX AND TECHNICAL EFFICIENCY: CASE STUDY OF WHEAT-GROWING FARMERS IN SAMARKAND REGION

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Abstract. In this study, the relationship between environmental sustainability level and technical efficiency of farmers in Samarkand region was investigated. The Environmental Sustainability Index (ESI) was constructed using primary data from 300 wheat-producing farmers. Utilizing the Cobb-Douglas stochastic frontier model, technical efficiency of farmers was estimated, and Tobit regression was used to learn their determinants. A marginally negative relationship between farmers ESI and technical efficiency was identified based on the results. The findings highlight that sustainability strategies based on local context and supporting sustainable intensification are important for sustainable growth in agriculture sector.

Keywords: technical efficiency, environmental sustainability, SFA, Tobit model, sustainable agriculture.

Introduction.

In the world, producing and providing people with agricultural products and in the meantime preserving natural resources has brought the sustainability of agricultural systems to the forefront of policy and research agendas (FAO, 2020; Van Cauwenbergh et al., 2007). When rural livelihoods face a number of problems such as climate change, environmental degradation and input inefficiencies a critical question emerges: can sustainable agricultural practices improve, or at least not compromise, farm-level productivity? In regions like Central Asia, where agriculture is both economically vital and ecologically vulnerable, this question bears significant weight (FAO, 2022).

Positioned at the intersection of Central Asia, Uzbekistan grapples with a dual challenge of increasing production so as to meet the exploding food demand of its citizens while concurrently adopting sustainability-enhancing agriculture practices as a measure of preventing further degradation of the environment. Despite the country’s impressive achievement of modernizing agricultural practices, persistent inefficiencies, high chemical fertilizer dependency and pesticide use as well as poor soil health remain key issues (ADB, 2021). Wheat as one of the crucial staple crops of Uzbekistan has a crucial national food security ensuring role. For this reason, wheat production presents a valuable template of analyzing the sustainability-technical efficiency conflict or complementarity (Devkota et al., 2025).

Concept of technical efficiency - here defined as a farm’s capacity to bring out the best possible output from a specific input set - is vital to an explanation of agricultural performance (Kumbhakar & Lovell, 2003). Although a volume of research has looked at determinants of efficiency during developing nations (Coelli et al., 2005; Bravo-Ureta & Pinheiro, 1997; Golib & Kim, K., 2017; Sherzod B. et al., 2018), comparatively few of those studies took into consideration the aspect of environmental sustainability as part of their model. And the empirical sustainability - efficiency connection remains uncertain as well: some of the research proposes that environmentally friendly practices could cut input wastage and make a farm more efficient (Lansink & Silva, 2003; Solis et al., 2009; Khanal et al., 2018), while others assert that environmentally friendly practice-performing farms are less technically efficient (Sidhoum et al., 2022; Minviel et al., 2024).

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This study adds to the current literature base through an exploration of the interrelationship between technical efficiency and environmental sustainability among a purposive sample of 300 wheat growers from the Samarkand region of Uzbekistan. Using primary farm-level data and a stochastic frontier approach alongside a Tobit regression model, this study aims to shed light on two core queries: (i) How widespread are technical inefficiencies among the wheat growers of the demarcated region?, and (ii) How does a measure of environmental sustainability positively or negatively impact technical efficiency?, through the incorporation of sustainability indicators in an efficiency context. Providing evidence-based recommendations for policy developers who seek to align productivity outcomes with sustainability outcomes are the aims of this exploratory study. Impacting the creation of context-specific interventions supporting yields growth while encouraging ecological resilience of Uzbekistan's agriculture are expected outcomes.

The nexus of technical efficiency and sustainability has attracted more interest over the last couple of years as an indication of the mutual needs of both agricultural production and environmental protection. Initial studies of efficiency were largely concerned with economic and structural variables like farm size, accessibility of capital, and utilization of labor (Coelli et al., 2005; Battese & Coelli, 1995; Golib & Kim K., 2017). Nevertheless, the unification of ecological variables with technical efficiency frameworks has offered a more holistic approach with which agricultural performance could be evaluated. Rigby et al. (2001) were first amongst others to derive indicators of sustainability under farming systems with a consideration of the multi-dimensional nature of sustainability - which incorporates seed sources, pest regulation practices, and fertilizer use techniques. Lansink and Silva (2003), thereafter, utilized frontier analysis with a consideration of gauging the ramifications of integrated system implementation of crops upon productivity and discovered that sustainability practices could heighten technical efficiency under specific situations.

More recent studies carried out by Khanal et al. (2018) applied data envelopment analysis to analyze smallholder farms in Nepal and showed that resource-conserving practices like the use of organic fertilizers and crop rotations produced mixed effects on efficiency depending on contextual variables and implementation intensity. Similarly, Baksh et al. (2020) noted that efficiency outcomes vary depending on the specific sustainability practices applied and the current support system. On the contrary, Reddy (2024) maintains that farmers practicing sustainability agriculture in Fiji are more efficient and produce at higher outputs. Balasubramanian (2012), further posits that technical efficiency can potentially rise through adopting sustainability agriculture through improved resource use and controlled environmentally related effects. In contrast, Minviel and coauthors (2024) established that higher technical efficiency levels are also related to lower levels of environment efficiency among French suckler sheep farms and suggest therefore that technical efficiency gains could have negative effects on the environmental sustainability of farming activities.

Within the context of Central Asia, studies of agricultural efficiency are lacking. Karimov (2014), for example, examined the productivity of Uzbekistan's cotton sector and pointed out long-lasting inefficiencies owed to institutional and marketplace constraints. Golib & Kim (2017), similarly, pointed out unsatisfactory technical efficiency of tomato farms in the Samarkand region. Nevertheless, few studies exist that have examined the sustainability-efficiency interrelation and conducted this with primary micro-level data. This research plugs that gap using a Rigby-type sustainability index and a stochastic frontier approach to estimate the interrelation.

Overall, the research presents the promise and nuance of balancing sustainability and efficiency. Whereas some practices are possible as both environmentally friendly and yield-improving practices, results are frequently dependent on site conditions, farmer capabilities, and extension support. What becomes crucial are locally comparative empirical evaluations, of the type conducted in this study in Samarkand, as a starting point for balanced developmental initiatives.

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Materials and methods.

3.1. Study site.

This study investigates the nexus of technical efficiency and environmental sustainability at the farm level using a two-stage empirical approach. First, a composite Environmental Sustainability Index (ESI) was created. Then technical efficiency used a Cobb-Douglas stochastic frontier function with a Tobit regression used to describe the efficiency scores. The empirical study was conducted in the Samarkand region of Uzbekistan, one of the country's most productive and climatically diverse agricultural areas. Samarkand is situated in the southeastern part of the nation and has a semi-arid continental climate with hot summers and cold winters. Average precipitation is between 310 and 360 mm per annum and occurs mostly during spring, making irrigation a critical component of agriculture (Babakholov et al., 2022).

Agriculture is a vital part of the local economy, employing a major share of the rural population while also adding considerably to household income and food security. Amongst the major crops produced locally, wheat predominates with an assortment of fruits, vegetables, and cotton. Most of the wheat production takes place at private farms of a medium and large size with varying degrees of access to agricultural input supplies, technology, and institutional support. The region has been selected for the present study because of its critical status in the nation's wheat production and because of its capacity to represent mixed-input agriculture systems widespread in Uzbekistan. Samarkand presents a unique mix of both modern and traditional agriculture with environmentally friendly methods and conventional input-intensive practices. For this reason, it becomes an excellent choice as a study location with a view of understanding the interaction of environmental sustainability and technical efficiency.

3.2. Data collection.

To investigate our research questions, we collected data via face-to-face interviews with wheat growing farmers in Samarkand region. We visited most farmers in the field and at their homes. We selected these farmers randomly from contact lists provided by Samarkand districts' agricultural departments. Field survey was implemented from June to August 2024 in 5 districts of Samarkand region: Bulungur, Payarik, Akdarya, Toylok and Jomboy. Data were collected across multiple districts within the region, ensuring variation in agro-ecological conditions, farm size, and management practices. This provides a robust foundation for analyzing sustainability-efficiency dynamics in a real-world, policy-relevant setting.

3.3. Environmental Sustainability Index.

The ESI was constructed based on the framework proposed by Rigby et al. (2001), incorporating four key stages in production process: seed source, soil fertility management, pest and weed control, and crop management. Each production stage then evaluated according to 4 sustainability dimensions: the minimization of off-farm inputs, the minimization of non-renewable inputs, the maximization of natural biological processes and the promotion of local biodiversity. Each component was assigned a score between -6 and 4, with higher scores indicating more sustainable level of farmers.

Seed Source (Weight: 0.07): Organic seed use was scored as 3; conventional seed use as 0.

Soil Fertility Management (Weight: 0.31): Categorized based on the share of organic fertilizer in total fertilizer use (organic + chemical). Four groups were formed:

- <40% organic: -3
- 40.1-60% organic: 0
- ≥60.1% organic: 3

Pest and Weed Control (Weight: 0.31): Averaged scores from two sub-components:
Chemical use: -6
Mechanical/biological methods: 4
Crop Management (Weight: 0.31)**:** Average score of three practices:

- Crop rotation: 4
- Use of improved varieties: 3
- Monoculture (planting the same crop more than 2 years in the same field): -1

The final ESI index was calculated as a weighted average of the four dimensions. After obtaining ESI indices for each farmer, linear transformation method is used to modify ESI indices to 0 and 1 with the help of min-max approach.

3.4. Technical efficiency estimation.

The study employed stochastic frontier production function approach with Cobb-Douglas functional form to measure technical efficiency of farms. Technical efficiency measures how well individual farm transform inputs to a set of outputs based on a given set of technology and economic factors (Golib & Kim, 2017). The two most widely used methods for calculation of technical efficiency are stochastic frontier analysis (SFA) and nonparametric Data Envelopment Analysis (DEA). The weakness of DEA model is the most of the statistical noise and measurement errors are not taken into account. SFA model solve this problem and take into account technical inefficiency and statistical noise.

The model included five inputs: seed (kg), fuel (liters), chemical fertilizer (kg), organic fertilizer (kg), land (ha) and labor (man-hours). The dependent variable was wheat yield (kg). The production function is specified as:

$$ln(Y_i) = \beta_0 + \sum_{k=1}^{6} (\beta_k * ln(X_{ki})) + v_i - u_i$$

Where:

- Y_i = output (total wheat production in kg) of the i-th farm
- X_{ki} = quantity of the k-th input used by the i-th farm
- β_k = parameters to be estimated
- v_i = two-sided random error term, $v_i \sim N(0, \sigma_v^2)$
- u_i = non-negative inefficiency term, $u_i \sim N^+(0, \sigma_u^2)$

The inefficiency component u_i captures the shortfall of actual output from the potential frontier output, given the input levels. Technical efficiency (TE) for each farm is calculated as:

$$TE_i = \frac{Y_i}{Y_{i^*}} = exp(-u_i)$$

Where:

- Y_i = observed output
- Y_{i^*} = frontier (maximum possible) output given inputs
- $TE_i \in [0,1]$, with values closer to 1 indicating higher efficiency.

3.5. Determinants of inefficiency (Tobit Model)

After calculating technical efficiency scores obtained from SFA model, Tobit regression model is used to examine the determinants of farm-level technical efficiency scores, which are bounded between 0 and 1. Since the dependent variable – technical efficiency estimated from SFA model – is censored at these limits, the Tobit model provides an appropriate estimation framework that accounts for this restricted range (Wooldridge, 2010).

The latent Tobit model as specified as:

$$TE_i^* = \gamma_0 + \gamma_1 ESI_i + \gamma_2 X_1 + \gamma_3 X_2 + \gamma_4 X_3 + \gamma_5 X_4 + \gamma_6 X_5 + \gamma_7 X_6 + \gamma_8 X_7 + \gamma_9 X_8 + \varepsilon_i \qquad \varepsilon_i \sim N(0, \sigma^2)$$

Where:

TE_i^* = latent (unobserved) technical efficiency score for the i-th farm

$TE_i = TE_i^*$ IF $0 < TE_i^* < 1$; otherwise, it is censored at the bounds

ESI_i=Environmental sustainability index for the i-th farm

X_1=Age

X_2=Age squared

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X_3=Household size
X_4=Access to credit
X_5=Cluster membership
X_6=Climate change awareness
X_7=Tree planting
X_8=Access to fertilizer.
i = 1, 2, ….., 300

Results and discussion

4.1 Descriptive Statistics.

This section presents descriptive statistics of the main variables used in the analysis. Table 1 reports summary statistics for a sample of 300 wheat farmers from the Samarkand region. The data show substantial variation in land size, input use, and labor allocation, reflecting the heterogeneity of production systems in the region.

Table 1. Descriptive statistics of key variables

Variable	Mean	Std. Dev.	Min	Max
Wheat Yield (kg)	4,246.87	910.90	2,000	8,500
Wheat Land (ha)	22.94	17.52	2	120
Seed Used (kg)	241.30	20.24	180	400
Fuel Consumption (liters)	108.30	34.57	30	350
Organic Fertilizer (kg)	7,782.3	7,023.14	200	40,000
Chemical Fertilizer (kg)	644.40	151.55	200	1,000
Labor (man-hours)	3,604.3	2,661.71	360	16,800
Farmer Age (years)	45.76	11.27	24	74
Household Size	6.38	2.17	2	16
Farming Experience (years)	12.35	6.47	1	28
Cluster Membership (binary)	0.44	0.50	0	1
Fertilizer Access (binary)	0.58	0.50	0	1
Climate Awareness (binary)	0.73	0.44	0	1
Tree Planting (binary)	0.39	0.49	0	1

These figures suggest that while the average yield per hectare is around 4.2 tons, some farmers achieve yields over 8 tons, potentially due to differences in input efficiency, management, and resource access. Farmers average land size is 23 hectare and varies between 2 and 120 hectares, which shows there is big differences among farms. Farmers average age is 46 years and average experience of farmers is 12 years (standard deviation 6 years). 50 % of farmers is cluster members in the sample and 73% of them feel climate change is occurring. Notably, organic fertilizer application and tree planting practice is highly variable, reflecting the diversity in sustainability practices across the sample.

4.2. Determinants of technical efficiency: Tobit model results

To assess the relationship between farm-level environmental sustainability and technical efficiency, a Tobit regression model was estimated. Technical efficiency scores, computed from a Cobb-Douglas stochastic frontier model, served as the dependent variable. Given that efficiency scores are bounded between 0 and 1, the Tobit model is appropriate for this analysis. Table 2 summarizes the estimation results.

The coefficient of the Environmental Sustainability Index (ESI) is negative and statistically significant at the 10% level, suggesting a marginal trade-off between environmental

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sustainability and technical efficiency. This finding aligns with theoretical expectations that environmentally friendly practices may, in the short term, reduce efficiency due to input substitution or adaptation costs. However, several sustainability-aligned practices—such as tree planting and climate awareness—were found to positively influence technical efficiency, implying that specific sustainable behaviors may enhance productivity. Other significant determinants include farmer age and its squared term, which together suggest a concave relationship: efficiency rises with age up to a certain point, then declines. Larger households, likely reflecting greater labor availability, were associated with higher efficiency.

Table 2. Tobit model estimating technical efficiency determinants

Variable	**Coefficient**	**Std. Error**
Environmental Sustainability Index	-0.018*	0.011
Age	0.004**	0.0018
Age squared	-0.00038**	0.000019
Household size	0.0025**	0.0012
Access to credit	0.048*	0.0253
Cluster membership	-0.011**	0.005
Climate change awareness	0.011*	0.0056
Tree planting	0.012**	0.005
Fertilizer access	0.01**	0.005
Constant	0.7	0.049

Note: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Model statistics: LR $chi^2(9) = 35.33$, Pseudo $R^2 = 0.0351$, Observations = 300

Access to credit and fertilizer both have positive effects, while cluster membership had a negative association, possibly indicating inefficiencies in collective decision-making or resource sharing within clusters.

These results underscore the complexity of the sustainability-efficiency nexus, indicating that while full sustainability may involve trade-offs, specific targeted practices can simultaneously improve environmental performance and technical efficiency.

The empirical findings of this study contribute important insights into the nuanced relationship between environmental sustainability and technical efficiency in the context of smallholder wheat farming in Uzbekistan. The slightly negative and statistically weak coefficient of the Environmental Sustainability Index (ESI) suggests that adopting sustainable agricultural practices may, in the short term, involve marginal efficiency trade-offs. This result is similar to Pourzand and Bakhshoodeh (2014) which identified in order to increase technical efficiency, farmers sometimes used unsustainable practices such as excessive use of fertilizers and pesticides in Far province, Iran. This could stem from reduced reliance on synthetic inputs, the learning curve associated with organic practices, or the relatively higher labor demands of sustainable techniques. However, the small magnitude of the effect and the positive impact of specific sustainable practices indicate that the relationship is not unidirectional or uniform.

For instance, practices such as tree planting and climate change awareness were positively associated with technical efficiency. These findings align with literature suggesting that sustainable land management and climate-smart agriculture can improve input use efficiency and farm resilience (Khanal et al., 2018; Baksh et al., 2020). They also reinforce the importance of farmer education and awareness in translating sustainable intentions into productive outcomes.

The observed non-linear relationship between age and technical efficiency points to the dynamic role of farmer experience. Younger farmers may lack experience, while older farmers may be less inclined to adopt innovations. This result is in line with Liu et al. (2019) and Xia-bo et al.

(2009) findings. Additionally, household size was positively correlated with efficiency, underscoring the continued importance of family labor in contexts with low mechanization levels. Unexpectedly, cluster membership had a negative association with technical efficiency. This may reflect coordination failures, weak governance structures, or inefficiencies in input distribution among farmer organizations. Similarly, Babakholov and Hasanov (2024) identified negative association between climate adaptation practices and membership in agro-clusters and suggested lack of mutual understanding and low level of cooperation between farmers and agro-clusters could be the reason. This result suggests that while clusters have the potential to improve input access and knowledge dissemination, their actual impact depends heavily on institutional design and capacity.

Access to credit and fertilizers emerged as key enablers of higher efficiency, supporting the notion that liquidity and input constraints remain significant barriers for smallholders. The role of financial inclusion and supply chain access in supporting efficient and sustainable intensification cannot be overstated.

In sum, while full-spectrum sustainability may pose initial productivity trade-offs, this study underscores that carefully selected and supported sustainable practices can enhance both ecological and economic performance at the farm level. Agricultural policy in Uzbekistan should move toward integrated frameworks that account for farm heterogeneity and promote the co-optimization of sustainability and efficiency.

Conclusion.

This study investigated the empirical relationship between environmental sustainability and technical efficiency in wheat farming, drawing on micro-level data from wheat-growing farmers in Uzbekistan's Samarkand region. Employing a stochastic frontier approach and a Tobit regression model, the analysis provides novel insights into how farm-level adoption of environmentally sustainable practices influences production efficiency.

The results reveal a marginally negative association between the composite Environmental Sustainability Index (ESI) and technical efficiency, suggesting that broad-based sustainability efforts may, in the short term, involve trade-offs in productivity. The analysis also highlights the influence of socio-economic characteristics, such as age, household size, and access to credit and inputs, on technical efficiency. The negative association between cluster membership and efficiency raises important questions about the functioning and governance of collective farming arrangements.

Overall, the study reinforces the idea that environmental sustainability and technical efficiency are not inherently incompatible. With appropriate institutional support and policy design, it is possible to identify and promote synergies between ecological stewardship and economic performance. Policymakers are thus encouraged to design nuanced, evidence-based interventions that reward specific sustainable behaviors while minimizing transitional costs to productivity.

Despite its contributions, the study is subject to several limitations. First, the reliance on cross-sectional data limits the ability to establish causality or examine dynamic changes over time. Second, the construction of the ESI, while grounded in literature, involves subjective decisions on indicator selection and weighting. Third, the geographic focus on the Samarkand region restricts the generalizability of the findings to other parts of Uzbekistan.

Future research should explore these relationships using panel data and consider incorporating biophysical indicators of sustainability. Comparative studies across crop types and agro-ecological zones would also be valuable in advancing context-specific sustainable intensification strategies in the region.

Conflicts of interest

None.

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