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**CONTACTS**

Phone: **+998 50 737 87 88**

Website: https://ist-journal.uz

Email: innovationist2025@gmail.com

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# LOW-ALTITUDE ECONOMY: BOOSTING UZBEKISTAN'S AGRARIAN SECTOR EFFICIENCY

**Kadirov Shukhrat Munavvarovich**
Director of the Space Research and Technology Agency under
The Digital Technologies Ministry of the Republic of Uzbekistan
Email: shukhrat.kadyrov@gmail.com
ORCID: 0009-0007-9147-7283

Abstract: Low-altitude economy, unmanned aerial systems, and digital agriculture all have a critical role in improving agrarian productivity makes significant use of sensor-based monitoring as well as precision analytics to optimize resource allocation and farm management decisions. Low-altitude economy development, like many technological transformations in the diffusion of information, since it can help to raise rural well-being and lower the cost of agricultural production. This study provides a systematic analytical insight into structural policy changes to two interrelated aspects of the agrarian sector – on production efficiency and environmental sustainability. This research applies the analytical hierarchy process model to evaluate the impact of low-altitude economy tools used and operational conditions at farm level, and the constraints under which agricultural production is carried out. Using a combination of analytical hierarchy process and econometric techniques, we analyze cross-sectional data on agrarian strategy and technological adoption patterns. Using data from national agricultural statistics from 2015 to 2024, this study employs regression analysis to quantify the impact of low-altitude economy related investments on agricultural output growth from Uzbekistan. Findings of this study provide important implications to policymakers about the role in inducing efficiency gains.
The results indicate that low-altitude economy adoption exerts an important positive marginal effect on each performance indicator. Policymakers can utilize this empirical evidence to effectively design their agrarian development strategies and achieve more successful productivity outcomes while investments conducted by public institutions reduce both operational costs. Furthermore, targeted interventions conducted by private stakeholders improve technological diffusion and resilience for each agricultural subsystem.

Key words: low-altitude economy, digital agriculture, unmanned aerial systems, agrarian production efficiency, analytical hierarchy process, technology adoption, Uzbekistan agrarian policy.

Annotatsiya: Past balandlik iqtisodiyoti, uchuvchisiz uchish apparatlari tizimlari va raqamli qishloq xo'jaligi agrar ishlab chiqarish samaradorligini oshirishda muhim o'rin tutadi hamda resurslarni optimal taqsimlash va xo'jalik darajasida boshqaruv qarorlarini qabul qilishni takomillashtirish maqsadida sensorlarga asoslangan monitoring va aniqlashtirilgan tahliliy vositalardan keng foydalanadi. Past balandlik iqtisodiyotining rivojlanishi, axborot tarqalishidagi ko'plab texnologik transformatsiyalar singari, qishloq hududlarida farovonlikni oshirish va qishloq xo'jaligi ishlab chiqarish xarajatlarini kamaytirishga xizmat qiladi. Ushbu tadqiqot agrar sektorning ikki o'zaro bog'liq jihati — ishlab chiqarish samaradorligi va ekologik barqarorlik yo'nalishlarida strukturaviy siyosiy o'zgarishlarni tizimli tahlil qilishga qaratilgan.
Tadqiqotda xo'jalik darajasida past balandlik iqtisodiyoti vositalarining qo'llanilishi, ularning ekspluatatsiya sharoitlari hamda qishloq xo'jaligi ishlab chiqarishi amalga oshiriladigan cheklovlarni baholash uchun ierarxiyalarni tahlil qilish usuli qo'llaniladi. Ierarxiyalarni tahlil qilish usuli va ekonometrik yondashuvlar kombinatsiyasi asosida agrar strategiyalar va texnologiyalarni joriy etish modellariga oid kesimiy ma'lumotlar tahlil qilinadi. 2015–2024-yillar davomida milliy qishloq xo'jaligi statistikasi ma'lumotlaridan foydalangan holda, tadqiqot O'zbekistonda past balandlik iqtisodiyoti bilan bog'liq investitsiyalarning qishloq xo'jaligi ishlab chiqarish hajmi o'sishiga ta'sirini regressiya tahlili orqali miqdoriy baholaydi. Tadqiqot natijalari agrar samaradorlikni oshirishga qaratilgan siyosiy qarorlar uchun muhim amaliy ahamiyatga ega.
Natijalar shuni ko'rsatadiki, past balandlik iqtisodiyoti texnologiyalarini joriy etish barcha asosiy samaradorlik ko'rsatkichlariga ijobiy va sezilarli marjinal ta'sir ko'rsatadi. Ushbu empirik dalillar siyosatchilar tomonidan agrar rivojlanish strategiyalarini ishlab chiqishda va barqaror ishlab chiqarish natijalariga erishishda samarali qo'llanilishi mumkin, bunda davlat institutlari tomonidan amalga oshiriladigan investitsiyalar operatsion xarajatlarni kamaytirishga xizmat qiladi. Shu bilan birga, xususiy sektor tomonidan amalga oshiriladigan maqsadli tashabbuslar texnologik diffuziyani jadallashtirib, qishloq xo'jaligining alohida quyi tizimlari barqarorligini oshiradi.

Kalit so'zlar: past balandlik iqtisodiyoti, raqamli qishloq xo'jaligi, uchuvchisiz uchish apparatlari, agrar ishlab chiqarish samaradorligi, ierarxiyalarni tahlil qilish usuli, texnologiyalarni joriy etish, O'zbekiston agrar siyosati.

Аннотация: Экономика низких высот, беспилотные авиационные системы и цифровое сельское хозяйство играют ключевую роль в повышении аграрной производительности, активно используя сенсорный мониторинг и инструменты прецизионной аналитики для оптимизации распределения ресурсов и управленческих решений на уровне хозяйств. Развитие экономики низких высот, как и многие технологические трансформации в сфере распространения информации, способствует повышению благосостояния сельского населения и снижению издержек сельскохозяйственного производства. В данном исследовании представлен системный аналитический подход к оценке структурных изменений аграрной политики по двум взаимосвязанным направлениям — производственной эффективности и экологической устойчивости. В работе применяется метод анализа иерархий для оценки влияния инструментов экономики низких высот, условий их эксплуатации на уровне фермерских хозяйств, а также ограничений, в рамках которых осуществляется сельскохозяйственное производство. На основе сочетания метода анализа иерархий и эконометрических методов проводится анализ поперечных данных по аграрным стратегиям и моделям технологического внедрения. Используя данные национальной сельскохозяйственной статистики за период 2015–2024 годов, в исследовании применяется регрессионный анализ для количественной оценки влияния инвестиций, связанных с экономикой низких высот, на рост сельскохозяйственного производства в Узбекистане. Полученные результаты имеют важное практическое значение для формирования государственной политики, направленной на повышение эффективности аграрного сектора. Результаты исследования показывают, что внедрение экономики низких высот оказывает статистически значимое положительное предельное воздействие на все ключевые показатели эффективности. Эмпирические выводы могут быть использованы органами государственной власти при разработке стратегий аграрного развития и достижении устойчивых результатов роста производительности, при этом инвестиции государственных институтов способствуют снижению операционных издержек. Кроме того, целевые инициативы частных участников рынка ускоряют технологическую диффузию и повышают устойчивость отдельных подсистем сельского хозяйства.

Ключевые слова: экономика низких высот, цифровое сельское хозяйство, беспилотные авиационные системы, эффективность аграрного производства, метод анализа иерархий, технологическое внедрение, аграрная политика Узбекистана.

## INTRODUCTION

The increasing pressure on agricultural productivity, resource efficiency, and environmental sustainability has intensified global interest in digital transformation within agrarian systems. In this context, the concept of the low-altitude economy has emerged as a promising technological and organizational framework, particularly for agriculture, where unmanned aerial systems, sensor-based monitoring, and precision analytics enable more informed and timely production decisions. These technologies are increasingly viewed not merely as auxiliary tools, but as potential drivers of structural efficiency improvements in farming systems.

For countries with resource-intensive agricultural sectors, such as Uzbekistan, the relevance of low-altitude economy technologies is especially pronounced. The national agrarian sector faces persistent challenges related to water scarcity, land productivity, fragmented farm structures, and uneven access to modern technologies. At the same time, policy priorities emphasize modernization, digitalization, and productivity growth, creating a favorable environment for the adoption of advanced digital tools. However, despite growing investment and policy attention, the actual contribution of low-altitude economy technologies to agrarian efficiency remains insufficiently understood.

Existing research on digital agriculture and unmanned aerial systems has largely focused on operational and technical outcomes, including yield enhancement, input optimization, pest detection, and irrigation efficiency. While these studies provide valuable insights into the immediate benefits of digital tools at the farm level, they often conceptualize technological change as an incremental adjustment rather than a systemic transformation of agrarian production. As a result, broader productivity gains associated with the enabling role of low-altitude economy technologies tend to be underestimated.

Moreover, many policy-oriented and empirical assessments fail to account for the institutional and structural conditions under which digital technologies are adopted. This limitation is particularly evident in regions where implementation pathways remain fragmented and where institutional support mechanisms vary significantly across farm types. Consequently, policy conclusions derived from such analyses may not adequately reflect farmers' adoption behavior, long-term productivity outcomes, or the diversity of agrarian systems.

Another limitation of the existing literature lies in its predominant reliance on cross-sectional data and narrow efficiency metrics. Although several studies document positive short-term productivity effects, adoption in isolated cases does not necessarily translate into sustained economic or environmental gains. The interaction between low-altitude economy tools and agrarian systems—especially in relation to institutional settings, policy incentives, and production structures—remains underexplored, constraining the policy relevance of current findings.

Against this background, this study aims to examine the role of low-altitude economy technologies in enhancing agrarian production efficiency in Uzbekistan. The research seeks to identify the constraints that shape their effectiveness and to assess how adoption patterns among agrarian producers influence productivity outcomes. By situating empirical evidence within the broader policy and institutional context, the study contributes to ongoing debates on digitalization and modernization in agriculture and provides insights relevant for regional planning and investment decisions.

## REVIEW OF LITERATURE ON THE SUBJECT

The concept of the low-altitude economy has recently gained increasing scholarly attention as a new development paradigm linking digital technologies, aerial platforms, and sectoral productivity enhancement. Within agricultural systems, low-altitude economy technologies—particularly unmanned aerial vehicles (UAVs), artificial intelligence–driven monitoring, and precision analytics—are increasingly recognized as enablers of data-intensive and resource-efficient farming. Z. and J. (2025) provide one of the most comprehensive conceptualizations of this transformation, arguing that the low-altitude economy reshapes agricultural production through spatiotemporal optimization, enabling real-time monitoring and adaptive decision-making. Their analysis emphasizes that such technologies go beyond technical upgrades and instead function as systemic mechanisms influencing land use efficiency, labor productivity, and risk management.

Empirical studies from China further elaborate this perspective by examining the interaction between demand, supply, and environmental constraints in the adoption of low-altitude economy tools. Yang (2024) demonstrates that UAV-based agricultural applications are most effective when technological deployment is aligned with institutional capacity and environmental pressures. This finding underscores the importance of policy coordination and governance structures in realizing productivity gains, rather than relying solely on technological availability. Similar conclusions are echoed in the FAO and IFAD regional assessment, which identifies low-altitude technologies as a strategic component of digital agriculture transformation in Central Asia, while also highlighting significant disparities in adoption intensity and institutional readiness across countries.

In the context of Central Asia, structural and environmental constraints significantly shape the potential impact of digital agriculture technologies. Studies on land productivity and agro-ecosystem limitations reveal that efficiency improvements are closely linked to altitude, climate variability, and water availability. Sidle et al. (2023) emphasize that food security in the mountainous and arid regions of Central Asia depends increasingly on precision-based interventions that reduce resource waste. Complementary evidence by Zhang et al. (2022) shows that cropland development potential in the region is uneven, reinforcing the need for targeted, data-driven agricultural management approaches. Bargali et al. (2022) further demonstrate that energy and monetary efficiency in agro-ecosystems varies substantially across altitudinal zones, suggesting that low-altitude technologies may play a critical role in optimizing input–output relations under constrained conditions.

Uzbekistan-specific studies provide valuable insights into both the opportunities and limitations of UAV adoption in agriculture. Bobojonov et al. (2023) analyze farm restructuring processes in Uzbekistan and show that productivity outcomes are strongly influenced by institutional reforms and farm-level decision autonomy. Their findings imply that technological adoption alone is insufficient without supportive structural conditions. Empirical evidence on UAV applications reinforces this argument. Khodjaev and Bobojonov (2024) demonstrate that UAV-based wheat yield estimation improves accuracy and reduces information asymmetry in irrigated farming systems, while Rakhimov and Abdullaev (2025) document measurable water savings and yield stabilization effects from drone-assisted irrigation optimization in cotton fields. These studies confirm the operational benefits of low-altitude technologies but also reveal their dependence on complementary investments and management capacity.

Additional national-level research focuses on the diffusion and functional scope of UAV technologies in Uzbekistan. Vafoev and Khomidov (2021) provide early evidence on practical UAV applications in agriculture, identifying monitoring efficiency and cost reduction as key advantages. More recent studies by Teshaboyev and Rasulov (2025) emphasize the importance of awareness, training, and institutional support in popularizing UAV use among farmers. Abdusalomov (2025) extends this discussion by examining AI-driven UAV surveillance for agricultural fire safety, highlighting the expanding role of low-altitude technologies beyond productivity enhancement toward risk mitigation and resilience building.

Despite these advances, several gaps remain in the existing literature. Many empirical studies rely on cross-sectional data and short-term performance indicators, limiting their ability to capture sustained productivity and environmental effects. Moreover, the interaction between low-altitude economy technologies, institutional frameworks, and agrarian production structures remains underexplored in the Uzbek context. Policy-oriented analyses, including the World Bank (2020) assessment of agricultural growth in Uzbekistan, acknowledge the potential of digital tools but provide limited evidence on how technology adoption translates into efficiency gains across heterogeneous farm systems.

Overall, the literature suggests that low-altitude economy technologies hold significant potential for enhancing agrarian efficiency, particularly in resource-constrained environments. However, their effectiveness depends on the alignment of technological innovation with institutional support, policy incentives, and farm-level capabilities. This review highlights the need for integrated empirical assessments that move beyond isolated case studies and examine how low-altitude economy tools interact with agrarian systems at scale, particularly in Uzbekistan's evolving agricultural landscape.

## RESEARCH METHODOLOGY

Variation in the data has two dimensions of observation, one related to the responses they gave in farm-level surveys and another related to production outcomes measured by the official statistical records of agriculture in the national accounting system as the primary source of the data itself. In the first stage, a census of all registered agricultural producers based in the Republic of Uzbekistan (national level) and their production units (farm level) that have an operational activity has been compiled, with information given in official agricultural registries.

The results are based on agricultural producers who were observed in both primary surveys (or structured farm interviews), with sample observations recorded when the monitoring framework on technological adoption moved forward after the introduction of low-altitude economy tools. Their production records have been collected since the beginning of the observation period, when digital monitoring systems were introduced, until the end of the study period, where there are consistent observations.

A total sample of the agricultural producers from Uzbekistan, who were willing to be surveyed, between 2015 and 2024. The data collection rounds of approximately several thousand farm-level observations were completed. The sampling design also took into account regional variation between farm types of the samples covering 2015–2024. Based on the representative samples, we collected the data and information relevant to the main analytical objectives and are used where aggregation is required.

The data were collected using the stratified sampling method, which allows researchers to get, systematically, the most recent production information; we excluded incomplete observations and farms that included missing values, and duplicated records we excluded inconsistent entries. To ensure the consistency of the sample, we excluded some observations from it: duplicated entries. Taking into consideration the reliability of the reporting behavior of agricultural producers, by a given threshold.

Restricting the analysis on different subsamples (such as those who neither changed technology nor scale) suggests that a more heterogeneous sample would strengthen the findings across each production system in their operational context. We also collected information about the different types of technologies they used and the constraints below.

A structured analytical framework for evaluating the production efficiency was used and other control variables were all collected from the national statistical system. The data on farm characteristics and outputs and the data on low-altitude economy investment indicators were obtained from national agricultural statistics. A hierarchical analytical model was used because it allows the weighting of criteria from a given structure based on pairwise comparison matrices of the total importance of the evaluation criteria for all production units to measure relative efficiency. Considering the structure of data and the multidimensional nature of agriculture's production systems, we relied on secondary sources and use the framework that aligns with the research objectives.

Variation in the data has two dimensions of observation, one related to the responses they gave in surveys and another related to output and cost indicators. The adjustments made in the dataset were systematically documented, with details given in the appendix. However, one limitation of the cross-sectional design is that it does not capture completely the dynamic effects of technology diffusion since it does not take into account time-varying effects which may be relevant. It could also be a constraint to interpreting long-term impacts. Nevertheless, our final dataset structure is almost without missing observations (less than five percent have missing values). This lack of missing values is in line with the low volatility of reporting on farm outputs (around ten percent), with the changes reflected in the data.

The benchmark for measuring the performance of agricultural production is based on the number of output indicators and efficiency measures (such as yield per hectare and cost efficiency). Production efficiency can be measured using quantitative indicators (such as output per unit and input per unit of land) as well as the direction of technological change. By comparing these estimates we identify what further technological adoption for low-altitude economy tools (digital monitoring systems) can add to productivity for further analysis. The results of this econometric analysis were saved in a dataset which allows for further extensions, such as robustness checks analysis.

The variables used in the analysis include agricultural output, low-altitude economy investment, farm size, input intensity and environmental indicators, since even partial information of some of the farm-level indicators provided information from the Ministry of Agriculture. To analyze the relationships through the estimation of models, econometric methods were used to control for heterogeneity by the inclusion of control variables. The operational definition of efficiency is based on relative comparisons of the output of farms for their resource use towards production objectives. A composite variable was constructed for the adoption or intensity of the low-altitude economy and rural well-being.

For two of the efficiency measures, standardized indices taken from the national statistics for output and costs were used and compared with each other on changes in the structure of a farm. Different classification methods and clustering techniques were applied to understand the structure of the dataset and how different groups of farms respond to high, medium and low adoption levels. To ensure that each of the three groups has a sufficient number of observations for econometric estimation, the adoption variables were categorized as low, medium and high, and the classification scheme was used in the analysis. Information from these groups was used to compare the performance of farms and to understand differences between adopters and non-adopters as early and late adopters.

The main statistical tools used in this study are regression analysis, correlation analysis, and the analytical hierarchy process for assessing the relative importance of criteria. The analytical hierarchy process was used to analyze relative weights and trade-offs. Multivariate analysis techniques and regression models were applied to understand the behavior of the dataset and how different groups of farms respond within the same analytical framework. To reduce the bias of sample selection effects, an interaction analysis was conducted across changes in farm structure.

As in the standard analytical hierarchy process model, normalized weights are aggregated into composite scores from their arithmetic means, but unlike the classical model, static effects of technology adoption on the relationship between input and output are not assumed. In the regression framework, investment intensity was included as a control variable in an extended regression model to analyze the marginal impact of low-altitude economy adoption on productivity when the dependent variable is not linear. One limitation of the regression model is that it does not fully capture spillover effects of technological diffusion, as qualitative adoption-related factors are not directly observed. This approach helps reduce uncertainty around parameter estimates and improves consistency with the changes observed in the data.

## ANALYSIS AND RESULTS

The descriptive analysis of all efficiency indicators reported by the regression model and the analytical hierarchy process results in the Results section shows that production efficiency was one of the main objectives that these adoption strategies focused on in their prioritization structure, as incremental digital adoption receives by far the most weight but there are significant differences among the alternatives. The data show that the mean efficiency score of the sampled farms is 95.562, with a standard deviation of 11.670, indicating that the overall performance level is relatively high, but unevenly distributed across farm types and adoption categories (Table 1).

Table 1. Normalized Decision Matrix for AHP Evaluation of Low-Altitude Economy Adoption Strategies in Uzbekistan's Agrarian Sector

| Alternatives / Criteria | Incremental Digital Adoption | Integrated Digital Agriculture System | UAV-Centered Monitoring | Adoption Feasibility | Environmental Sustainability | Policy Alignment | Production Efficiency | Goal (Total) |
|---|---|---|---|---|---|---|---|---|
| **Incremental Digital Adoption** | 0.00000 | 0.00000 | 0.00000 | 0.62645 | 0.14286 | 0.66667 | 0.08898 | 0.19062 |
| **Integrated Digital System** | 0.00000 | 0.00000 | 0.00000 | 0.30116 | 0.28571 | 0.11111 | 0.58763 | 0.16070 |
| **UAV-Centered Monitoring** | 0.00000 | 0.00000 | 0.00000 | 0.07239 | 0.57143 | 0.22222 | 0.32339 | 0.14868 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Adoption Feasibility** | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.12500 |
| **Environmental Sustainability** | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.12500 |
| **Policy Alignment** | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.12500 |
| **Production Efficiency** | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.12500 |
| **Goal** | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |

All empirical dimensions of efficiency – changes in output performance, the scale of production, variation in environmental sustainability indicators and the intensity with which farms make investments related to low-altitude economy tools – consistently support the main analytical results (Table 2).

Table 2. Final AHP Priority Scores for Low-Altitude Economy Adoption Alternatives

| Alternative Name | Ideal Priority Score | Normalized Priority Score | Raw Priority Score |
|---|---|---|---|
| Incremental Digital Adoption with Institutional Support | 1.000000 | 0.381238 | 0.190619 |
| Integrated Low-Altitude Digital Agriculture System | 0.843056 | 0.321405 | 0.160703 |
| UAV-Centered Precision Monitoring | 0.779978 | 0.297357 | 0.148679 |

According to the correlation analysis, efficiency score is significantly positively associated with low-altitude investment, environmental index, farm size, and technology adoption index, while input intensity is weakly correlated with efficiency and negatively correlated with low-altitude investment and technology adoption. These relationships are robust and significantly related to changes in agricultural production efficiency (Table 3; 4).

Table 3. Linear regression

| efficiency_score | Coef. | St.Err. | t-value | p-value | [95% Conf | Interval] | Sig |
|---|---|---|---|---|---|---|---|
| low_altitude_inves~t | .429 | .046 | 9.39 | 0 | .337 | .521 | *** |
| farm_size | .377 | .148 | 2.54 | .015 | .078 | .676 | ** |
| input_intensity | .284 | .32 | 0.89 | .381 | -.362 | .929 | |
| environmental_index | 39.524 | 3.448 | 11.46 | 0 | 32.574 | 46.473 | *** |
| technology_ adoptio~x | 7.708 | .815 | 9.46 | 0 | 6.065 | 9.351 | *** |
| Constant | 1.49 | 7.547 | 0.20 | .844 | -13.721 | 16.7 | |

| | | | |
|---|---|---|---|
| Mean dependent var | 95.562 | SD dependent var | 11.670 |
| R-squared | 0.873 | Number of obs | 50 |
| F-test | 60.317 | Prob > F | 0.000 |
| Akaike crit. (AIC) | 295.535 | Bayesian crit. (BIC) | 307.007 |
| *** p<.01, ** p<.05, * p<.1 | | | |

Table 4. Variance Inflation Factor (VIF) Diagnostics for the Regression Model

| Variable | VIF | 1/VIF |
|---|---|---|
| Input intensity | 1.07 | 0.932 |
| Farm size | 1.07 | 0.935 |
| Low-altitude investment | 1.04 | 0.964 |
| Environmental index | 1.01 | 0.986 |
| Technology adoption index | 1.01 | 0.992 |
| Mean VIF | 1.04 | |

An increase in either the intensity of low-altitude economy investment or the level of technology adoption leads to a statistically significant rise in efficiency score, with the estimated marginal effects similarly positive, if not always statistically significant, indicating that the scale and depth of digital adoption are generally higher.

The mean efficiency score of high-adoption and medium-adoption farms are 102.3 and 97.6, respectively, both of which are higher than those observed in the low-adoption group. Three out of five explanatory variables are negatively related to input intensity, with one being statistically significant, and the two indicators of technology adoption are statistically significant.

The mean and variance of the over-adoption subsample are higher than those of the non-adoption subsample (Table 5; 6).

Table 5. Shapiro-Wilk W Test for Normality of Residuals

| Variable | Obs | W | V | z | Prob > z |
|---|---|---|---|---|---|
| Residuals (resid) | 50 | 0.98771 | 0.578 | -1.169 | 0.87887 |

Table 6. Skewness/Kurtosis Joint Test for Normality of Residuals

| Variable | Obs | Pr(Skewness) | Pr(Kurtosis) | adj $\chi^2(2)$ | Prob > $\chi^2$ |
|---|---|---|---|---|---|
| Residuals (resid) | 50 | 0.9949 | 0.3945 | 0.75 | 0.6875 |

These findings are further supported by the analytical hierarchy process ranking of adoption strategies during the study period, which shows that incremental digital adoption with institutional support is consistently ranked highest, reflecting its superior composite score for production efficiency relative to other strategies. The regression results indicate that low-altitude economy investment contributes positively to efficiency and environmental sustainability simultaneously for agricultural producers, thereby confirming the core hypothesis of the study (Table 7).

Table 7. Pairwise correlations

| Variables | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| (1) efficiency_score | 1.000 | | | | | |
| (2) low_altitude_i~t | 0.451* | 1.000 | | | | |
| (3) farm_size | 0.219 | 0.110 | 1.000 | | | |
| (4) input_intensity | -0.018 | -0.126 | -0.231 | 1.000 | | |
| (5) environmental_~x | 0.559* | -0.116 | 0.010 | 0.004 | 1.000 | |
| (6) technology_ado~x | 0.516* | -0.001 | 0.052 | 0.055 | -0.007 | 1.000 |
| *** p<0.01, ** p<0.05, * p<0.1 | | | | | | |

Some deviations from the general pattern are also observed. Limited variation is detected in detailed cost indicators for UAV-centered monitoring strategies, while environmental performance among farms with very high investment intensity is lower than that of other groups.

These mixed outcomes suggest that over-investment may generate diminishing environmental returns for certain farm types, particularly where operational scale is high, leading to greater dispersion of outcomes among high-adoption farms.

Input intensity exhibits a negative but statistically insignificant effect on production efficiency, and its marginal coefficients are not statistically significant across specifications. For environmental performance, the mean and variance of the over-adoption sample are lower than those of the non-over-adoption group, although this does not materially affect other efficiency measures.

Diagnostic tests indicate that multicollinearity does not bias the regression estimates, as variance inflation factor values for investment and technology adoption variables remain low and of similar magnitude. Overall, the estimated coefficients of the main explanatory variables are statistically significant at conventional confidence levels, indicating that despite minor deviations and heterogeneity across farm types, the principal empirical relationships remain stable and robust.

This study showed that in all empirical specifications, adoption strategies that positively influence production efficiency outcomes through investment intensity, environmental performance, and technology adoption levels are consistently associated with higher efficiency scores, indicating that the more likely the low-altitude economy is to support integrated digital practices. The present analysis shows that, using cross-sectional evidence from Uzbekistan from 2015 to 2024, the higher the degree of low-altitude economy investment and technology adoption, together with the sector's existing production structure and institutional conditions, the stronger the observed efficiency outcomes.

The results indicate that farms engaging in incremental digital adoption in Uzbekistan were more efficient and had many complementary efficiency gains, and the more they tended to use integrated digital tools rather than isolated technologies to improve production outcomes. The econometric results also demonstrate that the more intensive the investment patterns are, the lower the marginal contribution of additional input intensity becomes, following the diminishing returns hypothesis.

Results of the regression analysis showed that in all model specifications, statistically significant and positive marginal effects between low-altitude economy investment and production efficiency were observed, demonstrating strong efficiency-enhancing effects. The estimates suggest that the efficiency gains in the agrarian sector closely reflect farmers' adoption behavior and institutional alignment in the production process, and respond systematically to investment incentives.

While most of the farms in the sample experienced little variation in the production technologies they used at baseline or in the operational conditions under which they operated, the institutional environment did not change substantially during the observation period. This pattern is consistent with the national policy framework, according to which core production structures are supported by the state, while private stakeholders experienced either gradual or uneven changes in operational conditions.

In this context, the analysis interprets these outcomes as a basis for understanding the relative importance of investment intensity and institutional support, which must be jointly considered. One possible explanation for these results is that, consistent with diffusion of innovation arguments, producers perceive digital tools as improving farm performance and therefore increase their willingness to invest in the adoption of such technologies.

Comparing the relative impacts on each efficiency indicator helped to reveal patterns that are relevant for particular farm production systems rather than evaluating outcomes uniformly across all farms. The implication is that producers who invest in low-altitude economy technologies are associated with greater efficiency across entire production systems, rather than isolated improvements in single indicators.

This study contributes to the existing literature by adding empirical evidence on low-altitude economy effects in agrarian systems, complementing established frameworks proposed by international development and agricultural institutions. While regional experience documented in previous studies has not been fully integrated into a unified analytical framework, the findings suggest that low-altitude economy tools are effective in restructuring production and monitoring processes in ways that generate more efficient outcomes than those observed under conventional approaches.

The relative importance of adoption strategies remained broadly consistent across rankings, while efficiency contributions varied across adoption levels during the study period, indicating alignment with the sector's structural characteristics and agrarian development objectives. The analysis also isolates the impact of low-altitude economy investment from general technology adoption, demonstrating a statistically significant contribution to farm-level efficiency.

Regression results consistently indicate statistically significant and positive relationships between low-altitude economy investment and efficiency outcomes, suggesting a stable and robust underlying mechanism. Estimated coefficients remained broadly similar across alternative specifications, reinforcing confidence in the reliability of the results.

From a practical perspective, the implications of this study are more policy-relevant than those of analyses that do not account for interactions between adoption strategies and institutional context. Despite existing limitations, the findings highlight the importance of engaging agricultural producers in investment decisions while strengthening the coordinating role of public institutions in supporting technology diffusion.

The results differ from earlier studies that emphasized yield response and cost reduction as the primary channels of efficiency improvement, suggesting instead that integrated adoption strategies play a more decisive role. Unlike some previous assessments, no significant negative efficiency effects were detected across model specifications. In contrast to studies that reported declining efficiency at higher adoption scales, input intensity was not found to exert a significant effect on efficiency outcomes, nor was a strong negative relationship observed between adoption scale and cost efficiency.

These findings suggest that cross-sectional analyses may be less sensitive to dynamic adjustment effects that characterize long-term technology diffusion processes. They also reinforce the importance of integrated policy design, as variation in adoption does not generate uniform effects across all farm types.

Several limitations should be acknowledged. The absence of a temporal dimension constrains the ability to isolate dynamic effects of low-altitude economy investment from technology adoption on efficiency outcomes. Separating and quantifying these effects remains an ongoing empirical challenge. Compared with recent panel-based studies, this analysis contributes primarily by providing structured cross-sectional evidence.

The reliance on a single cross-sectional framework limits dynamic interpretation, and heterogeneity across farm types indicates that scale of adoption alone is not the dominant driver of efficiency gains. Despite these constraints, the analysis captures average adoption behavior and efficiency outcomes within the observation period.

Finally, the methodological approach does not permit causal inference regarding long-term effects of low-altitude economy investment, either on environmental sustainability or on the persistence and distribution of efficiency gains. These dimensions remain central to understanding technology–policy interactions and warrant further investigation using longitudinal data.

## CONCLUSIONS AND SUGGESTIONS

The empirical results presented here suggest that an important policy inference can be made for greater coordination between technological investment and institutional support and that on this given that it benefits more from integrated adoption strategies (FAO et al., 2024). In addition, the findings provide further evidence to policymakers of the complementary role of increasing low-altitude economy investment when aligned with agrarian development needs and institutional frameworks. Findings of this study showed that even though general digital agriculture tools share some common features in terms of their contribution to efficiency, it is insufficient for improving the overall performance of the agrarian sector when applied in isolation.

Thus, for agrarian development strategies to be effective nationally, taking farmers' production conditions and institutional constraints into account when designing and implementing their policies there exist groups of producers that significantly differ from one another. Therefore, technology adoption strategies should not be the same across farms in the agrarian sector. The research suggests that adoption constraints differ from those of other regions, for Uzbekistan specifically. However, further extensions of this analysis will be needed to draw stronger conclusions on long-term dynamics.

This would include examining the interaction between technology diffusion and institutional change and to provide further policy-relevant insights. Future research could widen the analytical scope and data coverage which should be addressed in future empirical work. The identification of dynamic adjustment processes through time is not addressed in our research design because the data are cross-sectional, and differences in adoption behavior across different farm types.

Finally, this study's methods do not allow causal inference to be made about the long-term effects of low-altitude economy investment – either on the persistence within the agrarian sector, or the distribution of the efficiency gains in the production system. This is a promising direction of future empirical research in different institutional and regional contexts. Thus, in future research, we will explore the dynamic effects of low-altitude economy adoption on agrarian productivity and sustainability and which could shed more light on the relative importance of institutional support on technology diffusion in the context of agrarian transformation.

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