THE ECONOMIC AND ENVIRONMENTAL EFFICIENCY OF AGRIVOLTAIC SYSTEMS IN UZBEKISTAN'S AGRICULTURAL SECTOR

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Abstract

The growing pressure on agricultural resources, rising energy demand, and intensifying climate impacts have compelled many countries to consider innovative dual-use land technologies. Among these, agrivoltaic systems—allowing simultaneous agricultural production and photovoltaic (PV) electricity generation—emerge as a promising strategic direction. For Uzbekistan, where agriculture remains a core pillar of the economy and solar energy resources are among the richest worldwide, agrivoltaics presents a long-term solution linking green growth, energy independence, and environmental sustainability. This paper examines the economic and environmental efficiency of agrivoltaic systems in Uzbekistan using a conceptual approach, without quantitative modeling. The analysis focuses on land-use optimization, farm-level energy security, climate resilience, microclimate benefits, carbon reduction potential, and water-use efficiency. It also identifies institutional, financial, and infrastructural barriers hindering broad implementation. The study concludes with policy recommendations for enabling agrivoltaics to support national goals outlined in the "Uzbekistan-2030" Strategy, the transition to a green economy, and the modernization of the agricultural sector.

Keywords: agrivoltaics, dual-use land, green economy, renewable energy, sustainable agriculture, Uzbekistan, photovoltaic systems.

Annotatsiya

Qishloq xo‘jaligi resurslariga bosimning ortib borishi, energiyaga bo‘lgan talabning o‘sishi va iqlim o‘zgarishining kuchayib borayotgan ta’siri ko‘plab mamlakatlarni yer resurslaridan ikki tomonlama foydalanish imkonini beruvchi innovatsion texnologiyalarni joriy etishga undamoqda. Shunday yechimlar orasida agrivoltaik tizimlar — ya’ni bir vaqtning o‘zida qishloq xo‘jaligi mahsulotlari yetishtirish va fotoelektr (PV) energiyasini ishlab chiqarish — istiqbolli strategik yo‘nalishlardan biri sifatida ajralib turadi. Qishloq xo‘jaligi iqtisodiyotning asosiy tarmoqlaridan biri bo‘lgan va quyosh energiyasi resurslari dunyodagi eng boy hududlardan biri hisoblangan O‘zbekiston uchun agrivoltaika yashil o‘sish, energetik mustaqillik va ekologik barqarorlikni bog‘lovchi uzoq muddatli yechimdir.

Ushbu maqola O‘zbekistonda agrivoltaik tizimlarning iqtisodiy va ekologik samaradorligini miqdoriy modellashtirishsiz, konseptual yondashuv asosida tahlil qiladi. Tahlil yer resurslaridan samarali foydalanish, xo‘jalik darajasida energiya xavfsizligini ta’minlash, iqlim o‘zgarishiga moslashuvchanlik, mikroiqlimni yaxshilash, karbonat chiqindilarini kamaytirish hamda suvdan foydalanish samaradorligi kabi omillarga qaratilgan. Shuningdek, keng joriy etilishiga to‘sqinlik qilayotgan institutsional, moliyaviy va infratuzilmaviy to‘siqlar aniqlanadi. Tadqiqot yakunida agrivoltaikalarni "O'zbekiston—2030"[1] strategiyasida belgilangan milliy maqsadlarga, yashil iqtisodiyotga o'tish jarayoniga va qishloq xo'jaligini modernizatsiya qilishga xizmat qiladigan muhim yo'nalish sifatida rivojlantirish bo'yicha siyosiy tavsiyalar beriladi.

Kalit so'zlar: agrivoltaika, yer resurslaridan ikki tomonlama foydalanish, yashil iqtisodiyot, qayta tiklanuvchi energiya, barqaror qishloq xo'jaligi, O'zbekiston, fotoelektr tizimlari.

Аннотация

Возрастающее давление на сельскохозяйственные ресурсы, растущие энергопотребности и усиливающиеся последствия изменения климата побуждают многие страны внедрять инновационные технологии двойного использования земель. Среди них агривольтаические системы — обеспечивающие одновременное ведение сельскохозяйственного производства и выработку фотоэлектрической (PV) энергии — рассматриваются как перспективное стратегическое направление. Для Узбекистана, где сельское хозяйство остаётся ключевой отраслью экономики, а солнечные ресурсы являются одними из самых богатых в мире, агривольтаика представляет собой долгосрочное решение, связывающее «зелёный» рост, энергетическую независимость и экологическую устойчивость.

В данной статье экономическая и экологическая эффективность агривольтаических систем в Узбекистане рассматривается концептуальным методом без применения количественного моделирования. Анализ сосредоточен на оптимизации землепользования, обеспечении энергетической безопасности на уровне фермерских хозяйств, повышении климатической устойчивости, улучшении микроклимата, снижении выбросов углерода и эффективности использования воды. Также выявляются институциональные, финансовые и инфраструктурные барьеры, препятствующие широкому внедрению систем. В заключение сформулированы политические рекомендации, направленные на развитие агривольтаики в контексте достижения национальных целей, обозначенных в Стратегии «Узбекистан–2030», перехода к «зелёной» экономике и модернизации сельскохозяйственного сектора.

Ключевые слова: агривольтаика, двойное использование земель, зелёная экономика, возобновляемая энергия, устойчивое сельское хозяйство, Узбекистан, фотоэлектрические системы.

INTRODUCTION

The transformative agenda of the "Uzbekistan-2030" Strategy directs the country toward environmental protection, rational use of natural resources, and the rapid expansion of renewable energy technologies [1]. Agriculture accounts for a significant share of national employment and regional development, yet it increasingly faces systematic challenges. These include water scarcity, soil degradation, energy

[1] Presidential Decree of the Republic of Uzbekistan Tashkent, September 11, 2023 No. DP-158 "On the State Program for the Implementation of the Strategy Uzbekistan-2030." https://lex.uz/docs/6991208

dependency, climate extremes, and the need for higher productivity under constrained land conditions. These structural issues make the agricultural economy highly sensitive to climate variability and energy costs.

At the same time, Uzbekistan is one of the world's most solar-abundant countries, receiving over 3,000 hours of sunlight annually [2]. Leveraging this natural potential has become essential for reducing energy costs, supporting decarbonization, and enhancing rural economic resilience. Traditionally, solar farms and agricultural land are developed separately, creating competition for land resources, especially in regions where fertile land is scarce or subject to salinization.

Agrivoltaics—dual-use land systems that integrate photovoltaic panels directly into agricultural land—provide an innovative response to these challenges. By generating electricity while allowing crops to grow beneath or between solar structures, agrivoltaics transforms land into a multifunctional resource that contributes simultaneously to food and energy security.

International studies show that such systems can improve soil moisture retention, reduce heat stress, support more stable crop yields, and diversify income sources for rural households [3,4].

Despite its high theoretical potential, agrivoltaics is a relatively new concept for Uzbekistan. A systematic understanding of its economic and environmental contributions is needed to guide policy, investment, research, and pilot implementation. Therefore, this paper investigates the conceptual economic and environmental efficiency of agrivoltaic systems within the context of Uzbekistan's agricultural sector. The study adopts a conceptual approach that aligns with the conference's recommended methodology, focusing on qualitative assessment, analytical reasoning, and policy relevance.

LITERATURE REVIEW

The conceptual foundation of agrivoltaic systems draws from diverse global experiences at the intersection of sustainable agriculture, land-use optimization, and renewable energy integration. A growing body of literature recognizes agrivoltaics (AV) as a transformative model that redefines the relationship between energy and food systems, particularly in land-constrained or climate-stressed regions.

Early academic contributions, such as those by Dupraz et al., introduced the idea of co-locating solar photovoltaic panels and crops as a means to achieve complementary use of land resources [3]. Subsequent research has refined this model, highlighting critical design considerations—such as panel height, spacing, orientation, and mobility—which influence both light distribution and crop compatibility [6]. These system variables are particularly important when adapting AV to specific agro-climatic conditions, such as those found in Central Asia.

The environmental rationale for AV has also gained increasing attention. Studies emphasize that shading from solar structures can improve microclimate conditions for crops, reduce soil temperature, and lower evapotranspiration rates—benefits that are especially relevant for arid and semi-arid climates [4]. Similarly, scholars have noted the role of agrivoltaics in mitigating wind erosion and enhancing soil moisture retention, thereby supporting long-term soil health and ecological restoration [7].

Economically, agrivoltaics is positioned as a viable tool for rural resilience. Beyond food production, AV systems allow for localized energy generation, which may stabilize on-farm electricity access while reducing dependence on fossil fuels or grid infrastructure [1]. In contexts where agricultural margins are narrow and climate variability affects yields, diversified revenue streams from energy sales or leasing arrangements can improve financial predictability for smallholder farmers [5].

Despite the clear benefits, adoption barriers persist. International assessments have documented regulatory ambiguity around dual land-use classifications, the absence of technical standards, and the high upfront costs associated with installation and integration [2]. However, policy and institutional innovations—such as green finance initiatives, targeted subsidies, and capacity-building programs—have been effective in catalyzing early adoption in countries like France, Japan, and India.

From a systems perspective, the literature supports a shift toward multifunctional land-use strategies that respond to the complexities of food-energy-environment interdependence. Agrivoltaics, in this context, is not merely a technological solution but a policy-relevant concept with broad implications for rural development, climate adaptation, and green economic transition.

These scholarly insights provide the theoretical and empirical grounding for this paper's analysis of agrivoltaics in Uzbekistan—where resource pressures, energy needs, and climate vulnerability converge to create a unique opportunity for transformative innovation.

METHODOLOGY

This research is structured using a conceptual framework grounded in qualitative analysis, comparative review, and policy interpretation. The methodology does not involve numerical calculations or empirical modeling, in accordance with the selected approach.

A comprehensive review of global agrivoltaic practices, scientific literature, and case studies was conducted. The analysis included research from Europe, Asia, and the United States, where agrivoltaic development has advanced considerably over the past decade. The theoretical review examined the main scientific foundations of agrivoltaic systems and highlighted several essential aspects relevant to their application. It considered AV design models, including fixed-tilt systems, dynamic or tracking systems, and elevated structures that allow agricultural machinery to pass underneath. These different models influence light distribution, shading levels, and energy production efficiency. The review also analyzed crop-compatible system layouts, showing how panel spacing, height, and orientation must be adapted to crop type, shading tolerance, and local climate conditions. Global studies were reviewed to understand economic and environmental outcomes, emphasizing increased land-use efficiency, reduced water evaporation, and the potential for additional revenue from solar electricity generation. Finally, the review addressed barriers, opportunities, and adaptation needs, noting challenges such as regulatory gaps, high initial investment, and limited farmer awareness, while also highlighting opportunities for green financing, climate-smart agriculture development, and long-term optimization of dual-use systems.

A conceptual comparison was conducted to evaluate the differences and advantages of agrivoltaic systems relative to existing land-use models. The first comparison involved traditional agriculture, which relies entirely on open-field crop production and remains sensitive to climate stress, high temperatures, and water shortages. The second model, conventional photovoltaic farms, focuses solely on energy generation and typically replaces agricultural land, limiting food production opportunities. The third model, agrivoltaic dual-use systems, integrates crops and solar panels on the same land, combining both functions without excluding one another.

The comparison focused on several key dimensions: land-use efficiency, where agrivoltaics offers higher overall productivity; economic diversification, as farmers can benefit from both crop income and solar electricity generation; and environmental sustainability, due to reduced soil degradation, improved microclimate, and lower carbon emissions. Additionally, agrivoltaics improves climate resilience, providing crops with partial shade that reduces heat stress, and supports water-use optimization by lowering evaporation and irrigation needs compared to open-field agriculture. These criteria collectively demonstrate the conceptual superiority of agrivoltaic systems for regions with limited land and increasing climate pressures.

Relevant national policy documents—particularly the "Uzbekistan-2030" Strategy, the State Program for 2025, renewable energy legislation, and agricultural modernization programs—were reviewed to evaluate alignment with agrivoltaic adoption [1,5]. This allowed the identification of institutional gaps and opportunities for integrating agrivoltaics into national development priorities.

The results section is organized around two core analytical dimensions:

1) Economic Efficiency covering land productivity, energy security, diversification of farm income, and resilience to climate risks.

2) Environmental Efficiency addressing microclimate regulation, carbon emissions, water conservation, soil protection, and biodiversity.

This structure ensures a holistic evaluation suitable for long-term strategic policy formulation and academic discourse.

ANALYSIS AND RESULTS

Enhanced land-use productivity

Agrivoltaics enables dual use of agricultural land without sacrificing crop production, creating a multifunctional land-use matrix. Instead of allocating land exclusively for energy or food production, agrivoltaics allows simultaneous generation of both. This duality is especially valuable for Uzbekistan, where agricultural land is not only limited but increasingly threatened by salinization and climate-induced degradation.

International studies demonstrate that agrivoltaic systems often enhance total land productivity, measured through the Land Equivalent Ratio (LER), which can exceed 1.0—indicating higher combined productivity compared to separate land uses [6].

While this study avoids numerical modeling, the conceptual implication is clear: AV systems offer superior land-use efficiency in regions like Uzbekistan where every hectare is critical to food security.

Stabilized and reduced farm energy costs

Energy is one of the most significant operational costs for agricultural enterprises in Uzbekistan. Irrigation pumps, storage facilities, processing units, and modern agricultural technologies require reliable electricity. Agrivoltaics creates on-site renewable energy supply, decreasing reliance on grid power or diesel generators (table 1).

Table 1.

Key energy-related economic advantages of agrivoltaic systems[1]

Energy Benefit	Explanation
Reduced operational costs over time	On-site solar generation lowers long-term energy expenses for irrigation, storage, and farming.
Protection from energy price fluctuations	Farmers rely less on market-dependent fuel and electricity prices, reducing financial volatility.
Stable and predictable energy supply	Continuous solar production ensures reliable power for essential agricultural processes.

This is consistent with global findings that agriculture powered by on-site renewable energy is more resilient and cost-efficient [7].

Income diversification and risk reduction

One of the most important economic advantages of agrivoltaics is diversification of income. Farmers can sell excess electricity to the grid under well-structured policies, lease parts of their land for AV installations, or form cooperatives for shared energy use. These mechanisms reduce dependency on crop yields alone, which can fluctuate due to climate shocks (table 2).

Table 2

Socio-economic benefits of agrivoltaics for rural livelihoods in Uzbekistan[2]

Benefit	Explanation
Additional income stream	Electricity generation provides farmers with extra revenue alongside traditional crop production.
Reduced impact of crop failures	Dual-use land systems diversify income sources, lowering dependency on a single harvest outcome.
Enhanced financial stability	Agrivoltaics helps small and medium farms maintain more predictable and resilient annual earnings.

Increased attractiveness for green investments

As Uzbekistan expands its renewable energy portfolio, agrivoltaics can attract green financing from international organizations, climate funds, and private investors seeking sustainable and socially beneficial projects. AV systems align with:

[1] Author's work
[2] Author's work

- SDGs on clean energy and climate action;
- national green economy targets;
- regional development programs.

Thus, agrivoltaics can become a catalyst for modernizing rural energy and agricultural infrastructure.

Environmental efficiency of agrivoltaics

Climate mitigation through carbon reduction

Agrivoltaic energy is entirely renewable and produces no operational carbon emissions. Replacing traditional energy sources—such as diesel pumps for irrigation—with solar energy substantially reduces greenhouse gas emissions. This aligns with Uzbekistan's commitments to reduce carbon intensity and expand renewable energy capacity by 2030 (table 3).

Table 3.

Conceptual environmental benefits of agrivoltaic systems[1]

Process Step	Environmental Meaning
Clean on-site electricity	Solar energy generated directly on farms replaces carbon-intensive energy sources.
Reduced reliance on fossil fuels	Lower use of diesel pumps and reduced dependence on the national fossil-fuel energy mix.
Lower greenhouse gas emissions	Decreased CO_2 and pollutant output due to cleaner energy consumption.
Improved crop sustainability	Cooler microclimate, better moisture retention, and reduced heat stress on crops.
Enhanced land resilience	Long-term soil stability, improved ecosystem health, and greater resistance to climate stress.

Microclimate regulation and crop protection

Agrivoltaic installations provide partial shade, moderating microclimate conditions beneath panels (table 4).

Table 4.

Microclimate benefits of agrivoltaic shading[2]

Microclimate Effect	Explanation
Lower soil temperature	Shading from panels reduces direct solar radiation, helping maintain cooler and more stable soil conditions.
Reduced plant heat stress	Partial shade protects crops from extreme temperatures, improving physiological stability and growth.
Decreased evapotranspiration rates	Less heat and direct sunlight lead to slower water loss from soil and plant surfaces, improving water-use efficiency.

For Uzbekistan's arid and semi-arid zones, where summer temperatures frequently exceed 40°C, this microclimatic benefit is highly significant. Crops become better protected against temperature extremes, improving stability and reducing the likelihood of yield loss.

[1] Author's work
[2] Author's work

Water-use efficiency and irrigation savings

Water scarcity is one of the most pressing challenges for Uzbekistan's agricultural sector. Reduced evaporation under AV systems contributes to higher water productivity. Crops require less irrigation, energy use for pumping decreases, and farm-level water stress is reduced.

In a context where water disputes, climate variability, and aging irrigation infrastructure are persistent issues, agrivoltaics provides a tangible solution for increasing environmental and resource-use efficiency.

Soil and ecosystem benefits

Agrivoltaic systems contribute significantly to long-term soil protection by moderating the physical environment in which crops grow. First, the shading effect of photovoltaic panels reduces the intensity of direct solar radiation reaching the ground, which helps prevent excessive soil heating and slows the breakdown of organic matter. Additionally, the panel structures serve as partial barriers against strong winds, thereby reducing the degree of wind-driven soil erosion—an important factor in arid and semi-arid regions of Uzbekistan.

Another key benefit is the system's ability to enhance soil moisture retention. By limiting exposure to direct sunlight, agrivoltaics reduces evaporation rates, allowing the soil to maintain moisture for longer periods and improving overall water efficiency. Finally, the combined effects of lower temperature and higher moisture create a more stable biological environment that supports beneficial soil microorganisms, leading to healthier soil structure and improved long-term fertility (table 5).

Table 5.

Soil protection benefits of agrivoltaic systems[1]

Soil Protection Mechanism	Explanation
Reduced direct solar radiation	Shading from PV panels decreases surface overheating and slows down soil degradation processes.
Limited wind erosion	Panel structures act as partial windbreaks, reducing soil particle displacement and surface erosion.
Increased soil moisture retention	Lower sunlight exposure reduces evaporation, helping the soil maintain higher and more stable moisture levels.
More stable biological environment	Cooler, moister soil supports microbial activity and beneficial organisms, improving soil health over time.

The shaded environment beneath panels may also support beneficial biodiversity and promote healthier soils, contributing to long-term land restoration goals.

Challenges to Agrivoltaic Implementation in Uzbekistan

Despite its advantages, several challenges need urgent attention for agrivoltaics to take root in Uzbekistan.

Regulatory and institutional barriers

Agricultural land in Uzbekistan is heavily regulated, and its use for non-agricultural purposes is restricted. Current laws do not yet accommodate dual-use land

[1] Author's work

systems. Agrivoltaics requires a new classification of land use that simultaneously recognizes agricultural and energy functions.

Technical knowledge gaps

Local farmers and agricultural engineers have limited exposure to agrivoltaic technologies. Lack of technical standards, design guidelines, and training programs hinders adoption.

CONCLUSIONS AND SUGGESTIONS

Agrivoltaic systems offer transformative economic and environmental benefits aligned with Uzbekistan's green economy transition and agricultural modernization agenda. By improving land-use efficiency, stabilizing energy costs, diversifying rural incomes, and enhancing climate resilience, agrivoltaics addresses many of the core challenges facing Uzbekistan's agricultural sector. Environmentally, it reduces carbon emissions, optimizes water use, protects soil, and mitigates climate impacts on crops.

To realize the potential of agrivoltaics, Uzbekistan should prioritize:

- development of a dual-use land regulatory framework
- establishment of state-supported pilot projects
- integration of agrivoltaics into green financing and agricultural subsidy programs
- capacity-building initiatives for farmers and engineers
- modernization of rural grid infrastructure

Agrivoltaics can become a cornerstone of the country's long-term sustainable development strategy, supporting both energy independence and food security while advancing the objectives of the "Uzbekistan-2030" Strategy and national climate resilience policies.

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