

AGRIVOLTAICS THROUGH AN ESG LENS: ENVIRONMENTAL, SOCIAL AND GOVERNANCE DIMENSIONS FOR SUSTAINABLE AGRICULTURAL SYSTEMS: IMPLICATIONS FOR UZBEKISTAN

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Abstract

The article examined agrivoltaics for sustainable agriculture through environmental, social and governance criteria. A structured narrative review and synthesis of official information on Uzbekistan informed a conceptual assessment framework. Relationships involving land use, water consumption, electricity generation, crop productivity, farmer income and stakeholder participation were analysed. Eighteen monitoring indicators were proposed across three dimensions. Outcomes were shown to depend on crops, local climate, technical design and governance arrangements. Priorities for Uzbekistan included pilot trials, irrigation metering, agreed benefit sharing and institutional coordination. The need to validate the framework using local observations and comparisons with appropriate agricultural control plots was acknowledged.

Keywords: agrivoltaics, ESG criteria, sustainable agriculture, water efficiency, solar energy, farmer participation, benefit sharing, Uzbekistan.

Annotatsiya

Maqolada agrivoltaik tizimlarning barqaror qishloq xo'jaligidagi imkoniyatlari ekologik, ijtimoiy va boshqaruv mezonlari asosida o'rganildi. Ilmiy adabiyotlarning tuzilmali sharhi hamda O'zbekistonga oid rasmiy ma'lumotlarni umumlashtirish orqali konseptual baholash modeli ishlab chiqildi. Yer va suvdan foydalanish, elektr energiyasi ishlab chiqarish, hosildorlik, fermerlar daromadi va manfaatdor tomonlar ishtiroki o'rtasidagi bog'liqliklar tahlil qilindi. Uch yo'nalish bo'yicha jami o'n sakkizta monitoring ko'rsatkichi taklif etildi. Agrivoltaik loyihalar natijalarining ekin turi, mahalliy iqlim, texnik yechim va boshqaruv sharoitlariga bog'liqligi ko'rsatildi. O'zbekiston uchun tajriba maydonlari, suv sarfini o'lchash, manfaatlarni kelishilgan tartibda taqsimlash va idoralararo hamkorlik yo'nalishlari belgilandi. Modelni bir necha mavsumdagi mahalliy kuzatuvlar bilan tekshirish zarurati qayd etildi.

Kalit so'zlar: agrivoltaika, ESG mezonlari, barqaror qishloq xo'jaligi, suv samaradorligi, quyosh energetikasi, fermerlar ishtiroki, manfaatlar taqsimoti, O'zbekiston.

Аннотация

В статье были рассмотрены возможности агровольтаики для устойчивого сельского хозяйства с учётом экологических, социальных и управленческих критериев. На основе структурированного обзора литературы и обобщения официальных сведений об Узбекистане была разработана концептуальная модель оценки. Проанализированы взаимосвязи землепользования,

водопотребления, производства электроэнергии, урожайности, доходов фермеров и участия заинтересованных сторон. Предложены восемнадцать показателей мониторинга по трём направлениям. Показана зависимость результатов проектов от культур, местного климата, технических решений и организации управления. Для Узбекистана были определены направления пилотных испытаний, измерения расхода воды, согласованного распределения выгод и межведомственного взаимодействия. Отмечена необходимость проверки модели на основе местных наблюдений и сопоставления результатов с контрольными участками в течение нескольких сезонов.

Ключевые слова: агровольтаика, критерии ESG, устойчивое сельское хозяйство, водоэффективность, солнечная энергетика, участие фермеров, распределение выгод, Узбекистан.

INTRODUCTION

Agriculture, energy and water systems are becoming increasingly interconnected under conditions of climate change. Growing electricity demand and the transition toward renewable energy require additional land for energy infrastructure, while the agricultural sector must simultaneously maintain food production, adapt to heat and drought, and use increasingly scarce water resources more efficiently. Conventional ground-mounted solar photovoltaic systems may contribute to energy decarbonization but can also compete with agriculture for suitable land. Agrivoltaics offers an alternative by combining photovoltaic electricity production and agricultural activity on the same area of land [4]; [5].

The basic concept of agrivoltaics is relatively simple, but its performance is highly context-dependent. Solar modules influence the amount and spatial distribution of radiation reaching crops, while module height, spacing, orientation and density affect machinery access, crop management and electricity output. In turn, vegetation underneath and between modules may influence ground temperature and the local microclimate. Agrivoltaics should therefore be understood not merely as the physical co-location of photovoltaic panels and crops, but as an integrated land-management system in which energy, agriculture and resource management interact [17].

Research has demonstrated several potential advantages. Agrivoltaic systems can increase combined land productivity by producing agricultural output and electricity from the same land, create additional revenue streams for farmers, moderate crop exposure to high temperatures, and under some conditions improve soil moisture retention and water-use efficiency [1]; [14]; [17]. Nevertheless, these benefits should not be assumed. Excessive shading can reduce photosynthetically active radiation and crop productivity; structural infrastructure can interfere with agricultural machinery; project development can create land-use conflicts; and benefits may accrue disproportionately to landowners, investors or large farms rather than to local farmers and communities [12]; [13].

This distinction between potential sustainability and demonstrated sustainability is important. Much of the early agrivoltaic literature concentrated on energy output, crop responses, system configuration and land-use efficiency. More recent studies have

increasingly examined economic feasibility, public acceptance, farmer adoption, institutional conditions, justice and policy design [3]; [9]; [12]; [16]. Chen and Shaw [3], reviewing 66 peer-reviewed studies, conclude that agrivoltaic research still gives insufficient attention to fairness, socio-ecological implications, stakeholder governance and interdisciplinary policy innovation. This suggests that an integrated framework is necessary for assessing whether agrivoltaics genuinely contributes to sustainable agricultural development.

Environmental, Social and Governance (ESG) analysis offers such a framework [3]. Within agrivoltaics, the environmental dimension concerns renewable-energy generation, water, soils, biodiversity, crop resilience, land-use efficiency and lifecycle impacts. The social dimension concerns farmer livelihoods, employment, acceptance, food security, occupational safety, inclusion and the distribution of benefits. Governance concerns land rights, permitting, contracts, institutional coordination, accountability, benefit-sharing rules, monitoring, grievance mechanisms and decommissioning responsibilities. Applying these three dimensions together makes it possible to evaluate not simply whether an agrivoltaic system produces electricity, but whether it creates durable environmental and agricultural value, distributes benefits fairly and operates through credible governance arrangements.

The relevance of this perspective is particularly strong in Uzbekistan. The country combines high solar potential with an arid climate and an irrigation-dependent agricultural system. The World Bank [19] estimates that agriculture accounts for approximately 90% of national water consumption. Approximately 2.4 million hectares, equivalent to around 56% of irrigated agricultural land, depend on pumping systems, while approximately 1,700 irrigation pumping stations consume about 7.2 billion kWh of electricity annually [19]. Climate change is expected to place further pressure on this system: available water resources may fall by approximately 30-40%, while irrigation demand may rise by about 25% [19]. These conditions make Uzbekistan an important case for examining technologies that connect agricultural resilience, water management and renewable energy.

At the same time, Uzbekistan is rapidly expanding renewable energy. Official national plans announced in 2025 envisage more than 17 GW of additional renewable-energy capacity by 2030 and an increase in the share of green electricity generation to approximately 54% [7]. Agrivoltaics is also beginning to move from a theoretical concept toward local experimentation. A planned Agri-PV installation at the Scientific Research Institute of Vegetable Crops, Melons and Potatoes in Tashkent District covers a total project area of 1.5 hectares, with 819 photovoltaic panels planned on one hectare and an indicated capacity of approximately 507.78 kW [6].

Against this background, the aim of this paper is to examine agrivoltaics through an integrated ESG perspective and develop a conceptual framework for sustainable agrivoltaic development in water-stressed agricultural systems. Particular emphasis is placed on the implications for Uzbekistan. The central argument is that agrivoltaics should not be classified as sustainable merely because renewable energy and farming occupy the same land. Sustainability must be demonstrated through measurable

environmental performance, socially legitimate benefit distribution and accountable governance.

LITERATURE REVIEW

The scientific foundations of agrivoltaics were laid by studies that demonstrated the land-use advantage of combining crops and photovoltaic modules on the same area. Dupraz et al. [5] applied the land equivalent ratio to show that mixed systems of food crops and solar panels could increase overall land productivity compared with separate land allocation. Dinesh and Pearce [4] extended this argument by assessing the economic value of agrivoltaic systems, while Malu et al. [8] demonstrated the relevance of crop-specific assessment for grape farms in India. Weselek et al. [17] reviewed the applications, challenges and opportunities of agrophotovoltaic systems and emphasised that crop responses to shading depend on species, climate and system design.

A second stream of research examines the food-energy-water nexus in drylands. Barron-Gafford et al. [1] showed that agrivoltaic shading can moderate microclimatic conditions, reduce plant water stress and support crop performance under arid conditions. Recent field studies, however, report mixed outcomes: Senturk et al. [11] observed higher soil moisture together with a substantial reduction of photosynthetically active radiation in Türkiye, whereas Ukwu et al. [15] found genotype-specific responses of mung bean under agrivoltaic shading in Nigeria. These studies indicate that environmental benefits must be verified under local conditions.

A third stream addresses social acceptance and farmer adoption. Pascaris et al. [9] found that industry actors regard visible agricultural activity and tangible community benefits as key conditions for local support. Torma and Aschemann-Witzel [13] identified perceived advantages, compatibility, complexity and social acceptance as drivers and barriers of diffusion in Europe, and Wagner et al. [16] showed that perceived usefulness and additional income shape German farmers' willingness to adopt agrivoltaics. Trommsdorff et al. [14] and Tomasi et al. [12] drew attention to the distribution of benefits among farmers, landowners and investors, placing questions of justice on the research agenda.

The fourth stream concerns governance and policy. Carrausse and Arnauld de Sartre [2] analysed how energy companies, agricultural institutions and public authorities interact in French agrivoltaic deployment, while Pascaris et al. [10] showed that policy in Massachusetts can both enable and constrain adoption. Chen and Shaw [3], reviewing 66 peer-reviewed studies, concluded that fairness, stakeholder governance and socio-ecological implications remain underexplored and recommended multi-criteria decision tools.

For Uzbekistan, the evidence base is formed mainly by official and international sources. World Bank publications describe high water stress, the dependence of irrigation on electricity and growing climate risks [18; 19]. National policy documents on the transition to a green economy set the direction for renewable-energy development and efficient resource use [20; 21], and recent official statements confirm ambitious renewable-energy targets [7]. However, peer-reviewed studies that assess

agrivoltaics in Uzbekistan through an integrated ESG lens are still lacking. This gap defines the contribution of the present paper.

METHODOLOGY

This study adopts a structured narrative review and conceptual-framework approach. It synthesizes peer-reviewed research on agrivoltaic technology, environmental performance, agricultural productivity, socio-economic impacts, farmer acceptance, stakeholder participation, policy and governance. Particular attention is given to publications that move beyond purely technical assessment and examine interactions among environmental, economic and social objectives.

The conceptual organization of the literature follows three categories corresponding to ESG. Environmental evidence includes land-use efficiency, solar-energy generation, water use, microclimate, soil conditions, biodiversity and crop performance. Social evidence includes farmer income, livelihood diversification, employment, acceptance, occupational safety, rural development and distributional effects. Governance evidence includes land-use regulation, institutional coordination, policy incentives, stakeholder participation, contractual relationships, monitoring and accountability.

The international literature is complemented by Uzbekistan-specific official evidence, particularly World Bank publications on climate, water and irrigation [18]; [19], as well as government information concerning renewable-energy objectives [7] and the emerging Agri-PV project in Tashkent Region [6]. Because field measurements from mature agrivoltaic operations in Uzbekistan remain limited, the paper does not attempt to estimate local agronomic impacts directly. Instead, international evidence is used to identify potential benefits, risks and indicators that should be tested empirically under Uzbek climatic, agricultural and institutional conditions.

The methodology is therefore exploratory and framework-building rather than experimental. Its purpose is to identify how ESG considerations can be incorporated systematically into future agrivoltaic research, management and policy assessment.

ANALYSIS AND RESULTS

Agrivoltaics: Concept and System Configurations

Agrivoltaics refers to the simultaneous or coordinated use of agricultural land for both agricultural production and photovoltaic electricity generation. Dupraz et al. [5] provided one of the foundational scientific formulations of this concept, arguing that combined food and electricity production could improve overall land-use efficiency. Subsequent research has developed numerous agrivoltaic configurations adapted to different crops, farming operations, climatic conditions and economic objectives [4]; [17].

Elevated agrivoltaic systems position photovoltaic modules several metres above the agricultural surface, allowing crops, farm workers and in some cases conventional machinery to operate underneath. Their main advantage is the preservation of agricultural access and the possibility of controlling the spatial pattern of shade.

However, elevated structures generally require more structural material and higher investment than conventional ground-mounted systems. Structural stability under wind loading, machinery clearance and safe access become central management issues.

Inter-row systems locate photovoltaic modules in separated rows, while cultivation continues in the lanes between them. These systems can reduce structural cost and maintain conventional crop operations, but row spacing creates a clear trade-off between photovoltaic density and agricultural access. Increasing distance between PV rows can increase crop area and improve machinery movement, whereas narrower spacing may increase installed photovoltaic capacity while concentrating shade and reducing working space. Therefore, the economically optimal design may differ from the configuration that maximizes electricity generation.

Vertical bifacial systems place two-sided modules vertically, frequently in an east-west-oriented configuration. Rather than producing a continuous overhead shade, vertical arrays create narrower moving shade bands. Their electricity-generation profile may also differ from south-oriented tilted PV arrays, potentially shifting generation toward morning and afternoon periods. They may be suitable where retaining open agricultural space is important, although wind exposure, machinery interactions and row spacing remain significant design considerations.

PV-integrated greenhouses combine crop protection and energy generation within the greenhouse envelope. In such systems, the central issue is not simply installed PV capacity but the interaction between electricity generation, light transmission, thermal balance and crop-specific spectral requirements. Excessive photovoltaic coverage may reduce usable radiation for plants, while appropriate semitransparent technologies can potentially balance crop and energy objectives.

Orchard and vineyard agrivoltaics are particularly relevant because perennial crops have long production cycles and may benefit from protective overhead structures. Agrivoltaic structures can potentially provide partial protection from excessive radiation or weather events while producing electricity. However, system design must accommodate pruning, spraying, harvesting and machinery operations. Malu et al. [8], for example, examined agrivoltaic potential in Indian grape production, demonstrating the relevance of crop-specific economic and spatial analysis.

Livestock-PV systems represent another form of dual land use, in which grazing or animal management occurs within solar installations. These systems can provide animal shade and reduce vegetation-management costs, although stocking density, animal welfare, electrical safety and access to infrastructure require appropriate management.

The diversity of configurations demonstrates that there is no universally optimal agrivoltaic design. The appropriate configuration depends on crop physiology, climatic conditions, irrigation requirements, machinery, farm size, land tenure, electricity demand, grid access and project economics. This design dependence is central to ESG assessment because different configurations produce different environmental, social and governance outcomes.

Agrivoltaics through an ESG Lens

An agrivoltaic project can appear sustainable when assessed from one perspective and problematic when assessed from another. A system may reduce fossil-based electricity use but cause excessive crop shading. It may generate additional income but allocate most revenue to an external developer rather than farmers. It may maintain crop production technically but operate through unclear land contracts or weak monitoring. ESG analysis is therefore useful because it requires simultaneous consideration of environmental outcomes, social value and governance quality.

The relationship can be conceptualized as:

$$S_{AV} = f(E, S, G) \quad (1)$$

where S_{AV} represents the sustainability performance of an agrivoltaic system and E, S, and G represent environmental, social and governance performance respectively. The relationship should not be interpreted as simple addition: weak governance can undermine environmental monitoring, while poor benefit sharing can reduce social acceptance even where environmental outcomes are positive.

This integrated interpretation is consistent with recent agrivoltaic scholarship. Chen and Shaw [3] argue that future agrivoltaic decision frameworks should incorporate economic, environmental, social and governance considerations rather than focusing primarily on engineering efficiency. Their review identifies multi-criteria decision analysis as a promising mechanism for making trade-offs explicit and incorporating stakeholder priorities.

Environmental Dimension

The environmental case for agrivoltaics begins with renewable-energy production. Electricity generated from photovoltaic modules can reduce reliance on fossil-based electricity, support farm self-consumption and contribute to wider energy-transition objectives. When electricity is used directly by agricultural enterprises, agrivoltaics may also connect renewable generation with irrigation pumping, cooling, processing or storage.

Land-use efficiency is another central environmental argument. Rather than allocating separate areas to solar energy and agriculture, agrivoltaics allows both outputs to be generated from the same land. Dupraz et al. [5] applied land-equivalent concepts to demonstrate the potential productivity advantage of combined systems. However, land-use efficiency should consider both electricity and genuine agricultural production; the presence of minimal or unproductive vegetation underneath solar panels should not automatically qualify a project as agrivoltaic.

Water represents one of the most important environmental dimensions in arid regions. Partial shading can influence soil temperature, evaporation and plant water demand. Barron-Gafford et al. [1], studying dryland conditions, showed that agrivoltaic systems can modify microclimatic conditions in ways that may benefit water relations and plant performance. More recent experimental evidence confirms that outcomes depend on local climate, crop and system design. Senturk et al. [11], examining an open-field agrivoltaic system in Türkiye with approximately 35% PV coverage, reported higher soil moisture beneath the agrivoltaic system but a reduction of

approximately 38.6% in photosynthetically active radiation. This demonstrates a fundamental trade-off: shade may support water conservation while simultaneously reducing light available for photosynthesis.

Crop responses are therefore highly context-specific. Ukwu et al. [15], studying mung bean genotypes under agrivoltaic shading in tropical Nigeria, documented significant modifications in microclimate and crop responses and showed that shade effects can differ across genotypes and panel orientations. Such findings caution against general statements that agrivoltaics necessarily increases crop yields. The relevant question is whether a specific crop, variety, system design and climatic environment produce a positive combined outcome.

Agrivoltaics may also contribute to microclimate regulation by reducing peak radiation and crop canopy temperature. This can be particularly important where heat stress constrains productivity. However, excessively shaded conditions can reduce crop yield, delay maturation or alter quality. The environmental assessment must therefore compare agrivoltaic plots with appropriate agricultural controls rather than report only electricity production.

Soil and biodiversity effects also require attention. Retaining agricultural vegetation can potentially reduce the ecological disturbance associated with conventional solar developments. Vegetation management, pollinator habitat and diversified land cover may provide co-benefits in suitable systems. Conversely, construction can cause soil compaction, drainage changes and disturbance from vehicle movement. Long-term sustainability also requires consideration of module replacement, material recycling and decommissioning.

Consequently, environmental ESG claims should be supported by baseline measurements. Indicators should include electricity output, irrigation volume, crop yield relative to a reference plot, soil moisture, soil temperature, land-equivalent ratio, greenhouse-gas implications and where relevant biodiversity indicators. Without baseline measurement, claims such as “water-saving” or “climate-resilient” risk becoming promotional rather than scientific.

Social Dimension

The social sustainability of agrivoltaics depends substantially on whether farmers and rural communities obtain meaningful benefits. Additional or more stable income is among the most frequently cited potential advantages. Revenue may arise from electricity sales, reduced electricity purchases, leasing arrangements or participation in ownership structures. Agrivoltaics may therefore diversify agricultural income and reduce dependence on a single crop market.

Evidence from farmers confirms the importance of this economic dimension. Wagner et al. [16], in a quantitative study of German farmers, found that perceived usefulness strongly influenced willingness to adopt agrivoltaics and that additional income and future farm development were particularly important motivations. Bureaucratic requirements and uncertain regulatory conditions, rather than lack of trust in the technology itself, were notable barriers.

The distribution of these benefits, however, is crucial. Trommsdorff et al. [14], examining an agrivoltaic case in Maharashtra, India, showed that social outcomes could vary substantially depending on institutional arrangements between farming communities and project investors. A project that is economically viable at system level does not necessarily improve the economic position of all affected farmers.

This issue becomes particularly important for smallholders, tenant farmers and groups with weak bargaining power. Tomasi et al. [12], using environmental- and energy-justice perspectives across Italy, Spain, Belgium and the Netherlands, found that benefits may favor larger landowners and investors when small farmers and communities are excluded from decision-making. The study emphasizes early stakeholder participation, fair distribution of benefits and justice-oriented policy design.

Social acceptance is therefore not automatic. Pascaris et al. [9] found that agrivoltaics can receive stronger support when agricultural activity is visibly retained and local stakeholders perceive tangible community benefits. Torma and Aschemann-Witzel [13], examining stakeholder perceptions across Germany, Belgium and Denmark, similarly identify perceived advantages, compatibility, complexity and social acceptance as important factors influencing agrivoltaic diffusion.

Agrivoltaics may also create employment and training opportunities in rural areas through installation, system monitoring, maintenance, agricultural management and technical services. Universities and extension institutions can contribute by developing practical training on solar-agricultural integration. In emerging agrivoltaic markets, human-capital development is especially important because farm managers may be unfamiliar with the interaction between PV infrastructure and crop production.

Food security represents another social concern. Agrivoltaics should preserve meaningful agricultural activity rather than provide a regulatory justification for transforming farmland into energy sites. Agricultural-production requirements, crop monitoring and clearly defined agrivoltaic eligibility criteria can therefore have social as well as governance relevance.

Occupational safety must also be incorporated into social assessment. Electrical equipment, elevated structures, machinery, maintenance personnel and irrigation infrastructure share the same working space. Agrivoltaic management therefore requires defined safety procedures, access rules, maintenance scheduling and assignment of responsibility.

Governance Dimension

Governance determines whether environmental and social commitments become enforceable responsibilities. Agrivoltaics operates across sectors that are frequently governed separately: agriculture, renewable energy, land administration, water management, environment and rural development. Institutional fragmentation can therefore create regulatory uncertainty and high transaction costs.

Land rights are a foundational issue. Agrivoltaic governance must determine who owns the agricultural land, who owns the photovoltaic infrastructure, who holds electricity-sale rights, and what happens when land is leased rather than owner-

operated. Contracts should specify agricultural access, responsibilities for crop damage, maintenance, revenue allocation, insurance and decommissioning.

Cross-sector institutional coordination is equally important. Carrausse and Arnould de Sartre [2], studying agrivoltaics in France, show that deployment involves interactions among energy companies, agricultural institutions, public authorities and farmers. Weak coordination between energy and agricultural governance can generate local conflict and uncertainty even where national policy supports agrivoltaics.

Recent policy evidence reinforces this conclusion. Pascaris et al. [10], analyzing the Massachusetts agrivoltaic policy through interviews with policymakers, extension professionals, NGOs, farmers and solar developers, show that policy can simultaneously enable and constrain deployment. Formal policy can improve collaboration and farmer participation, but overly prescriptive rules, liability concerns and uncertain evidence requirements can impose burdens. The authors therefore emphasize coordination among policy, research and commercial actors throughout the project lifecycle.

Governance also concerns participation. Consultation conducted only after a project is substantially designed may have limited value. Meaningful participation requires involvement early enough for farmers and communities to influence system design, access arrangements and benefit-sharing mechanisms. Participatory processes can improve trust while revealing locally specific concerns that technical studies may overlook.

Monitoring and reporting are another central governance function. Environmental and social promises should be translated into indicators, baseline measurements, monitoring schedules and assigned responsibilities. A claim of improved water efficiency, for example, should be supported by irrigation metering and comparable baseline data. A claim of farmer benefit should identify how income changes and who receives the benefit.

Governance must also extend to end-of-life responsibility. Agreements should define who is responsible for removal, recycling or replacement of photovoltaic infrastructure and restoration of agricultural land. Without clear decommissioning provisions, current benefits may create future environmental or financial liabilities.

Finally, governance must address greenwashing. Because agrivoltaics carries a strong sustainability narrative, there is a risk that conventional solar projects may adopt the label without maintaining meaningful agricultural production or delivering measurable agricultural benefits. Clear definitions, minimum agricultural-performance requirements and transparent reporting can help protect the credibility of the sector.

ESG Trade-Offs and Strategic Management

The sustainability of agrivoltaics is fundamentally a management problem because technical design choices create simultaneous effects across different objectives. Module height, spacing, tilt and density affect electricity generation, shading, water dynamics, crop productivity, construction costs and machinery access. Crop choice and irrigation management further modify these relationships.

Increasing PV density may raise electricity-generating capacity but reduce crop light availability and machinery space. Increasing module height may improve farm access and shade distribution but raise structural cost. Wider spacing may improve crop productivity but reduce PV capacity per hectare.

Strategic management therefore requires optimization rather than maximization. The objective should not necessarily be maximum electricity output or maximum crop yield in isolation, but an acceptable balance among agricultural, energy, environmental, economic and social objectives.

Multi-criteria decision analysis is particularly relevant. Chen and Shaw [3] note growing use of tools such as the Analytic Hierarchy Process, GIS-supported assessment and other MCDA approaches for agrivoltaic planning. These approaches allow criteria such as electricity production, crop yield, water productivity, investment cost and land-use efficiency to be assessed jointly. Future frameworks should go further by incorporating social acceptance, benefit distribution, governance quality and stakeholder priorities.

An ESG-oriented strategic-management framework can therefore provide a decision-support tool rather than merely a reporting system. By assigning criteria, indicators and weights, managers and policymakers can compare alternative agrivoltaic designs transparently and identify where trade-offs occur.

Agrivoltaics within the Water-Energy-Food-Climate Nexus

Agrivoltaics is particularly relevant to nexus thinking because it connects systems that are often planned separately.

Water is required for crop production, while irrigation frequently requires energy. Energy infrastructure requires land, while food production depends on that same land resource. Climate change influences water availability, crop heat stress and electricity demand simultaneously. A policy that optimizes one sector without recognizing these relationships can shift rather than solve resource pressures.

In an agrivoltaic system, shading can alter crop water demand and soil moisture; PV electricity can potentially supply agricultural loads; agricultural production retains the food function of land; and renewable energy contributes to climate-change mitigation. In principle, this creates an integrated food-energy-water-climate system.

Nevertheless, nexus benefits depend on design. If PV shading substantially reduces agricultural production, the food objective is weakened. If irrigation efficiency is claimed but never measured, the water benefit remains uncertain. If electricity revenue goes primarily to external investors while farmers carry operational constraints, the social benefit is limited. Nexus thinking must therefore be combined with ESG accountability.

Why Uzbekistan Is a Relevant Case

Uzbekistan presents a particularly strong case for agrivoltaic research because its development challenges align closely with the potential functions of agrivoltaics. The country has an arid climate, extensive irrigated agriculture, increasing climate risks and strong solar resources [18].

Agriculture remains economically and socially important. According to the World Bank [19], agriculture contributes approximately one quarter of national GDP and total employment. More importantly from a resource-management perspective, agriculture accounts for about 90% of water consumption.

Water and energy are closely linked. Approximately 2.4 million hectares, representing about 56% of irrigated agricultural land, rely on pumped water. Around 1,700 irrigation pumping stations consume approximately 7.2 billion kWh of electricity per year, equivalent to around 16% of national electricity use [19]. These figures demonstrate that improving agricultural water management can have energy as well as water implications.

Climate change is expected to increase pressure. The World Bank projects that reduced glacier-fed flows, higher evapotranspiration, irregular rainfall and more frequent drought could reduce available water resources by approximately 30-40%, while demand for irrigation services could increase by about 25% [19]. The Uzbekistan Country Climate and Development Report also identifies water scarcity, drought, extreme heat and land degradation as major risks to long-term economic development [18].

At the same time, national energy policy is rapidly increasing the role of renewables. Official plans indicate that Uzbekistan intends to commission more than 17 GW of additional renewable-energy capacity by 2030 and raise green electricity to around 54% of total generation [7].

The emergence of an agrivoltaic pilot in Tashkent Region is therefore important. Official information from 2025 described a planned Agri-PV station at the Scientific Research Institute of Vegetable Crops, Melons and Potatoes with a project area of 1.5 hectares. Approximately one hectare was designated for 819 solar modules, with a stated project capacity of approximately 507.78 kW [6]. This project represents an opportunity to generate domestic evidence on crop performance, water use, energy generation, farmer and stakeholder perceptions, and governance mechanisms.

For Uzbekistan, universities and research institutes could play an important intermediary role. Before large-scale replication, local pilot projects can test crop responses, quantify water use, compare system configurations, train students and farmers, and develop credible monitoring protocols. This approach would reduce the risk of transferring international findings uncritically into very different climatic and institutional conditions.

Proposed ESG Assessment Framework for Agrivoltaics

The principal conceptual contribution of this paper is an ESG assessment framework tailored to agrivoltaic systems. The framework links measurable performance indicators with strategic-management and governance questions (Table 1).

Table 1 shows that the framework comprises 18 indicators distributed equally across the three ESG dimensions: six environmental, six social and six governance indicators. Environmental indicators are expressed mainly in physical units such as kWh/year, m³/ha/year and t/ha relative to a control plot, which allows direct

comparison with conventional agriculture. Social indicators combine income measures with survey-based and participation measures, while governance indicators are largely documentary and record whether contracts, benefit-sharing agreements, risk registers, grievance procedures and decommissioning plans exist and are applied. The table therefore translates the ESG concept into a monitoring checklist that can be used at the pilot stage in Uzbekistan.

Table 1
Proposed ESG Assessment Framework¹

ESG dimension	Proposed indicator	Possible measurement
Environmental	Renewable electricity generation	kWh/year
	Irrigation-water use	m ³ /ha/year
	Crop productivity	t/ha relative to control
	Land-use efficiency	Land Equivalent Ratio
	Soil microclimate	soil temperature/moisture
	Carbon impact	tCO _{2e} avoided
Social	Farmer income	net income/ha
	Income diversification	share of non-crop farm income
	Employment	jobs or FTE supported
	Acceptance	farmer/community survey score
	Occupational safety	incidents and training records
	Participation	proportion of affected stakeholders consulted
Governance	Land and ownership clarity	documented contractual status
	Benefit-sharing	transparent revenue-sharing agreement
	Monitoring	frequency and completeness of ESG reporting
	Risk management	operational risk register
	Grievance process	response and resolution time
	End-of-life responsibility	documented decommissioning plan

For comparative assessment, a composite index could eventually be developed:

$$ESG_{AV} = w_E E + w_S S + w_G G \quad (2)$$

where E, S and G represent normalized environmental, social and governance scores and w_E , w_S and w_G represent context-specific weights.

The purpose of such an index should not be to create an arbitrary sustainability score. Rather, it can make assumptions explicit, permit comparison between project alternatives and expose trade-offs. In water-stressed Uzbekistan, for example, water-use efficiency might legitimately receive greater weight than in a water-abundant agricultural region. Stakeholder participation can be used to determine weighting rather than relying entirely on expert judgement.

Risk Management

Every claimed ESG benefit has a corresponding risk. Effective agrivoltaic management therefore requires a structured risk register.

¹ Source: compiled by the author based on [3; 12; 17].

Crop-yield decline is an environmental and social risk and can be mitigated through crop-suitability assessment, pilot trials and reference plots. Low farmer acceptance is a social and governance risk requiring early consultation, transparent explanation of benefits and clear channels for feedback. Unverified water-saving claims are environmental and governance risks that should be addressed through irrigation baselines, meters and soil-moisture monitoring. Maintenance that disrupts agricultural operations is a social and governance concern and requires defined access plans and servicing schedules. Unclear land rights or contractual relationships are governance risks requiring legal clarification before investment. PV end-of-life waste creates environmental and governance responsibility and should therefore be covered by decommissioning and recycling provisions.

Risk management also requires assigning responsibility. For every major risk, project managers should identify its probability, potential impact, mitigation measure, responsible actor and monitoring indicator. This transforms ESG from a broad sustainability concept into operational management practice.

The evidence reviewed in this paper suggests that agrivoltaics has considerable potential, particularly in regions experiencing simultaneous land, water, energy and climate pressures. However, the literature does not support the proposition that agrivoltaics is inherently sustainable.

Environmental performance depends on system design and crop compatibility. Evidence of increased soil moisture or reduced temperature does not imply that all crops will respond positively to shading. Senturk et al. [11] illustrate this clearly: improved soil-moisture conditions occurred together with substantial reductions in available photosynthetically active radiation. Environmental assessment must therefore examine multiple indicators simultaneously.

Similarly, social benefits are conditional. Additional farmer income is one of the strongest drivers of farmer interest, but income distribution depends on ownership models and contracts. An economically profitable project can coexist with socially unequal outcomes. Tomasi et al. [12] therefore provide an important warning against assuming that the “win-win” language commonly used around agrivoltaics guarantees justice.

Governance may ultimately determine whether environmental and social benefits endure. Agrivoltaics lies at an institutional boundary between energy and agriculture. Where responsibilities are fragmented, permitting becomes uncertain and farmers can face administrative burdens. Policy must protect the agricultural function without creating requirements so rigid that viable projects become impossible.

This is where an ESG approach adds value. Instead of asking only whether an agrivoltaic system generates electricity or whether a crop can survive under modules, ESG assessment asks a broader set of questions: What environmental changes are measurable? Who obtains the economic and social benefits? Who participates in decisions? Who is responsible for risks? How are claims verified?

For Uzbekistan, these questions are particularly important because agrivoltaics is still at an early stage. This provides an opportunity to develop rules and measurement

systems before large-scale deployment. Rather than retrofitting governance after conflicts arise, pilot projects could embed ESG monitoring from the outset.

Policy and Management Implications for Uzbekistan

Uzbekistan should treat agrivoltaics as an integrated agricultural and energy activity rather than as a conventional solar project installed on farmland. This requires a clear national definition distinguishing genuine agrivoltaics from ground-mounted PV with incidental vegetation.

Agricultural productivity should remain a core approval criterion. Pilot projects should monitor crop output against reference plots over multiple seasons. Water-saving claims should be quantified through irrigation data rather than inferred from shade alone.

Project development should incorporate farmers early in decision-making. Benefit-sharing arrangements should be documented transparently and should account for farmers who operate land but do not necessarily hold ownership rights. Particular attention is needed to ensure that small and medium farms can participate rather than allowing agrivoltaics to become accessible primarily to large investors or landholders.

Regulation should also clarify institutional responsibilities. Agriculture, energy, water, environment and land-administration authorities need coordinated procedures for project approval and monitoring.

Universities and research institutes can provide independent technical evaluation, farmer training and ESG monitoring. This is particularly valuable during the pilot phase because objective measurement can help distinguish realistic benefits from promotional claims.

Finally, incentives should be linked to demonstrated dual-use performance. Public support should reward projects that retain meaningful agricultural production, provide measurable environmental benefits and meet governance requirements rather than simply maximizing installed photovoltaic capacity.

Research Gaps and Future Research

Several areas require further research before agrivoltaics can be scaled confidently in Uzbekistan and comparable arid regions. Long-term local field trials are required to understand crop-specific responses under different configurations and irrigation regimes. Water use should be measured directly over multiple seasons. Economic analysis should compare investment costs, electricity revenue, agricultural productivity and risk across farm sizes.

The social dimension requires empirical farmer and community studies. Research should examine willingness to adopt, financing constraints, perceptions of land-use change, preferred ownership structures and expectations regarding benefit sharing. Particular attention should be given to small farmers, women, young farmers and other groups that may have limited influence over investment decisions.

Governance research should examine how Uzbekistan's existing agricultural land, renewable-energy and water regulations would apply to dual-use systems. Comparative analysis with mature agrivoltaic markets could help identify which regulatory instruments are transferable and which require adaptation.

Finally, the ESG assessment framework proposed in this paper requires empirical validation. Future research could use multi-criteria decision analysis to develop weighted indicators with farmers, policymakers, investors and researchers. Such work would move agrivoltaic assessment beyond technical feasibility toward transparent and participatory strategic management.

CONCLUSION AND SUGGESTIONS

Agrivoltaics offers a promising approach to integrating agricultural production and renewable electricity generation on the same land. International evidence shows potential benefits in land-use efficiency, income diversification, microclimate regulation, water management and climate resilience. At the same time, environmental trade-offs, unequal distribution of economic benefits, social acceptance challenges and fragmented governance demonstrate that these outcomes are not automatic.

An ESG perspective provides a useful framework for addressing this complexity. Environmental assessment establishes whether ecological and agricultural benefits are measurable. Social assessment examines livelihoods, participation, safety, acceptance and equity. Governance defines rights, responsibilities, monitoring, benefit sharing and accountability.

These issues are highly relevant to Uzbekistan, where water-intensive agriculture, energy-demanding irrigation systems, climate pressures and rapid renewable-energy development intersect. The country's emerging agrivoltaic experience creates an opportunity to develop evidence-based standards before large-scale deployment.

The central conclusion is therefore that agrivoltaics should be viewed not merely as a solar technology but as an integrated agricultural-management system. Its sustainability depends on designing agricultural, energy, environmental, economic and social objectives together and governing them transparently. For Uzbekistan and other water-stressed regions, agrivoltaics can become an important component of climate-resilient agricultural development, but its success will depend on local experimentation, measurable ESG performance, farmer participation and accountable governance.

Based on the results of the study, the following recommendations are proposed for Uzbekistan:

1. Adopt a national definition of agrivoltaics that distinguishes genuine dual-use systems from ground-mounted PV with incidental vegetation and sets minimum agricultural-performance requirements.
2. Make agricultural productivity a core approval criterion: monitor crop output against reference plots over several seasons and quantify water savings through irrigation metering.
3. Involve farmers early in project design and document benefit-sharing arrangements, including for farmers who operate but do not own land, so that small and medium farms can participate.
4. Establish coordinated approval and monitoring procedures among agriculture, energy, water, environment and land-administration authorities.

5. Use universities and research institutes, starting with the Agri-PV pilot in Tashkent Region, for independent evaluation, farmer training and ESG monitoring.

6. Link public incentives to demonstrated dual-use performance and require decommissioning and recycling plans for photovoltaic infrastructure.

REFERENCES

1. Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., Thompson, M., Dimond, K., Gerlak, A. K., Nabhan, G. P., & Macknick, J. E. (2019). Agrivoltaics provide mutual benefits across the food-energy-water nexus in drylands. *Nature Sustainability*, 2, 848-855. <https://doi.org/10.1038/s41893-019-0364-5>

2. Carrausse, R., & Arnould de Sartre, X. (2023). Does agrivoltaism reconcile energy and agriculture? Lessons from a French case study. *Energy, Sustainability and Society*, 13, 8. <https://doi.org/10.1186/s13705-023-00387-3>

3. Chen, X., & Shaw, R. (2026). Integration of sustainability dimensions with decision-making science: A systematic literature review of agrivoltaics. *Sustainable Energy Research*, 13, 30. <https://doi.org/10.1186/s40807-026-00257-4>

4. Dinesh, H., & Pearce, J. M. (2016). The potential of agrivoltaic systems. *Renewable and Sustainable Energy Reviews*, 54, 299-308. <https://doi.org/10.1016/j.rser.2015.10.024>

5. Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., & Ferard, Y. (2011). Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. *Renewable Energy*, 36(10), 2725-2732. <https://doi.org/10.1016/j.renene.2011.03.005>

6. Government of Uzbekistan. (2025a). Public hearings were held in Tashkent District on major solar panel installation project. Ministry of Ecology, Environmental Protection and Climate Change.

7. Government of Uzbekistan. (2025b, December 5). Address by the President of the Republic of Uzbekistan Shavkat Mirziyoyev at the forum "Powering the Future - Sustainable Energy for New Uzbekistan". <https://president.uz/en/lists/view/8751>

8. Malu, P. R., Sharma, U. S., & Pearce, J. M. (2017). Agrivoltaic potential on grape farms in India. *Sustainable Energy Technologies and Assessments*, 23, 104-110. <https://doi.org/10.1016/j.seta.2017.08.004>

9. Pascaris, A. S., Schelly, C., Burnham, L., & Pearce, J. M. (2021). Integrating solar energy with agriculture: Industry perspectives on the market, community, and socio-political dimensions of agrivoltaics. *Energy Research & Social Science*, 75, 102023. <https://doi.org/10.1016/j.erss.2021.102023>

10. Pascaris, A. S., Swanson, T., Seay-Fleming, C., Gerlak, A. K., McCall, J., Barron-Gafford, G. A., & Macknick, J. (2026). Exploring the effects of policy on stakeholder adoption and deployment of agrivoltaics: A case study of Massachusetts. *Energy Policy*, 208, 114921. <https://doi.org/10.1016/j.enpol.2025.114921>

11. Senturk, B., Oylek, Y., Kanar, Z. S., Celik, R., Kurtulus, G., & Ozden, T. (2025). The impact of photovoltaic panels on the environment and yield parameters in

an open field agrivoltaic system: A case study in Ayaş, Ankara. *Renewable Energy*, 253, 123553. <https://doi.org/10.1016/j.renene.2025.123553>

12. Tomasi, S., Pellegrini, C., Gaspari, F., Vitale, S., Macarulla Martí, M., Gras, A., & Gantioler, S. (2025). Agrivoltaics as a win-win for rural regions? Energy and environmental justice perspectives across Italy, Spain, Belgium, and the Netherlands. *Energy Research & Social Science*, 129, 104369. <https://doi.org/10.1016/j.erss.2025.104369>

13. Torma, G., & Aschemann-Witzel, J. (2023). Social acceptance of dual land use approaches: Stakeholders' perceptions of the drivers and barriers confronting agrivoltaics diffusion. *Journal of Rural Studies*, 97, 610-625. <https://doi.org/10.1016/j.jrurstud.2023.01.014>

14. Trommsdorff, M., Vorast, M., Durga, N., & Padwardhan, S. (2021). Potential of agrivoltaics to contribute to socio-economic sustainability: A case study in Maharashtra/India. *AIP Conference Proceedings*, 2361, 040001 (Agrivoltaics2020 Conference: Launching Agrivoltaics World-wide).

15. Ukwu, U. N., Muller, O., Meier-Grüll, M., et al. (2025). Agrivoltaics shading enhanced the microclimate, photosynthesis, growth and yields of *Vigna radiata* genotypes in tropical Nigeria. *Scientific Reports*, 15, 1190. <https://doi.org/10.1038/s41598-024-84216-3>

16. Wagner, J., Bühner, C., Götz, S., Trommsdorff, M., & Jürkenbeck, K. (2024). Factors influencing the willingness to use agrivoltaics: A quantitative study among German farmers. *Applied Energy*, 361, 122934. <https://doi.org/10.1016/j.apenergy.2024.122934>

17. Weselek, A., Ehmann, A., Zikeli, S., Lewandowski, I., Schindele, S., & Högy, P. (2019). Agrophotovoltaic systems: Applications, challenges, and opportunities. A review. *Agronomy for Sustainable Development*, 39(4), 35. <https://doi.org/10.1007/s13593-019-0581-3>

18. World Bank. (2023). Uzbekistan Country Climate and Development Report. World Bank Group. <https://openknowledge.worldbank.org/handle/10986/40608>

19. World Bank. (2025, May 21). Uzbekistan to modernize its irrigation infrastructure with World Bank support [Press release]. <https://www.worldbank.org/en/news/press-release/2025/05/21/uzbekistan-to-modernize-its-irrigation-infrastructure-with-world-bank-support>

20. Resolution of the President of the Republic of Uzbekistan No. PQ-436 of December 2, 2022 "On measures to increase the effectiveness of reforms aimed at the transition of the Republic of Uzbekistan to a green economy until 2030". <https://lex.uz/docs/6303230>

21. Resolution of the President of the Republic of Uzbekistan No. PQ-4477 of October 4, 2019 "On approval of the Strategy for the transition of the Republic of Uzbekistan to a green economy for the period 2019-2030". <https://lex.uz/docs/4539502>



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