



Article

Systematic Modeling of Agricultural Investment Efficiency Through Sustainable Esg Integration

Zaripov Azamat Djurayevich*¹

1. Lecturer, Department of Accounting and Finance, Gulistan State University, Uzbekistan

*Correspondence: az4930553@gmail.com

Abstract: Sustainable agricultural development in arid and transitional economies requires investment evaluation methods that reflect not only direct financial profit, but also ecological resilience, social responsibility, and long-term preservation of natural capital. In the Syrdarya region of Uzbekistan, especially in Boyovut district, traditional irrigation practices increase water consumption, intensify secondary soil salinization, and create hidden costs that are not captured by conventional indicators such as ROI, NPV, and IRR. This study develops and applies an integrated economic-mathematical model for assessing agricultural investment efficiency through ESG transformation. The proposed model, $ROI\_ESG = ROI\_trad \times (1 + I\_ESG)$, incorporates a weighted composite ESG index consisting of environmental efficiency, social responsibility, and corporate governance sub-indices. Given the ecological vulnerability of the region, the environmental component is assigned the highest weight. The model is empirically tested using comparative data from two investment alternatives: a traditional furrow irrigation project and a smart green drip irrigation project implemented on equal land areas during the 2025–2026 production cycle. The results show that although the traditional project demonstrates a higher conventional ROI of 22.0% compared with 18.0% for the green project, the ESG-adjusted calculation reverses this conclusion. After integrating environmental and social externalities, the green project achieves a transformed return of 32.4%, while the traditional project reaches only 25.3%. Sensitivity analysis further confirms that green modernization remains more resilient under water scarcity and salinization stress. The findings demonstrate that ESG-based investment modeling can support sustainable capital allocation, improve agricultural policy design, and strengthen expanded reproduction processes in climate-risk regions.

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1. Introduction

The long-term stabilization of agricultural production in arid climate zones requires a reassessment of how investment efficiency is measured. In transitional economies such as Uzbekistan, agriculture is not only a source of income and employment, but also a strategic sector linked to food security, water resource management, and rural development[1]. This issue is especially relevant for the Syrdarya region, where limited water availability, climate volatility, secondary soil salinization, and the deterioration of collector-drainage systems directly affect the sustainability of agricultural reproduction. Under such conditions, investment decisions must consider not only short-term financial profit, but also the preservation of soil fertility, water efficiency, and ecological resilience.

Conventional financial indicators, including Net Present Value (NPV), Internal Rate of Return (IRR), and traditional Return on Investment (ROI_{trad}), are widely used in corporate investment analysis. However, these indicators mainly reflect direct monetary outcomes and often ignore environmental and social externalities. As a result, projects that consume excessive water, accelerate soil degradation, or increase future reclamation costs may appear economically attractive. Conversely, sustainable technologies such as subsurface drip irrigation, digital fertigation, solar-powered pumping systems, and soil organic matter enrichment are frequently undervalued because they require high initial capital expenditures and longer payback periods[2],[3].

This methodological limitation creates a serious barrier to the green modernization of agriculture. In practice, a private farm or agrocluster may reject resource-saving technologies simply because standard accounting formulas treat environmental protection costs as losses rather than long-term value-generating assets[4]. Therefore, there is a need for an integrated model that can translate ecological and social effects into measurable economic indicators and support more rational capital allocation. Such a model is also important for banks, state agencies, and investors that need reliable criteria for comparing projects under water scarcity, climate stress, and regional environmental degradation.

The theoretical basis of this approach is connected with the concept of externalities developed by A. Pigou, the sustainability principles of R. Solow, and later studies by K. Arrow, R. Costanza, D. Pearce, S. Schaltegger, and F. Figge. These scholars emphasized that economic systems become distorted when natural capital, ecosystem services, and ecological risk are excluded from financial calculations [5],[6]. In agricultural economics, this means that soil fertility, clean water, and regional hydrological stability should be treated as real productive assets rather than free resources.

This study aims to develop and empirically validate an integrated ESG-based investment efficiency model for agriculture. The proposed approach incorporates a localized weighted ESG index into the investment evaluation process[7]. This index combines environmental efficiency, social responsibility, and corporate governance indicators, with greater emphasis on environmental criteria due to the ecological vulnerability of the Syrdarya region.

3. Research Methodology

To eliminate the structural errors of traditional financial calculations in agriculture, we have developed a modified, comprehensive investment return framework. The structural core of our proposed model is the introduction of an Environmental-Social-Governance (ESG) Multiplicative Amplifier.

The core economic-mathematical model is formulated as follows:

$$ROI_{ESG} = ROI_{trad} * (1 + I_{ESG})$$

Where:

- ROI_{ESG} is the integrated, ESG-transformed return on agricultural investment, reflecting the true socio-environmental-financial effect of the invested capital.
- ROI_{trad} is the traditional accounting return calculated via standard corporate financial protocols:

$$ROI_{trad} = \left(\frac{\text{net accounting profit}}{\text{Total Capital Expenditures (CAPEX)}} \right) * 100\%$$

- I_{ESG} is the multi-criteria composite ESG index of a specific agricultural enterprise or project, strictly constrained by the following mathematical condition: $(0 \leq I_{ESG} \leq 1)$.

The construction of the composite IESG index utilizes a weighted additive aggregation algorithm derived from primary empirical indicators tailored to the specific ecological profile of the Syrdarya region:

$$I_{ESG} = \omega_1 * I_E + \omega_2 * I_S + \omega_3 * I_G$$

Where I_E is the Environmental Efficiency sub-index, I_S is the Social Responsibility sub-index, and I_G is the Corporate Cluster Governance quality sub-index. Given the acute ecological constraints of the Syrdarya region, the environmental sub-index is assigned the highest weight ($\omega_1 = 0.50$), while social and governance attributes are allocated ($\omega_2 = 0.30$) and ($\omega_3 = 0.20$), respectively.

The mathematical logic of the $(1 + I_{ESG})$ multiplier is based on the principle of strategic incentive and constraint:

1. **Zero-compliance state** ($I_{ESG} = 0$): If an agricultural enterprise employs a predatory, resource-depleting model (depleting water, salinizing soil, exploiting labor), its calculated index drops toward 0. The multiplier becomes $(1+0=1)$, forcing $ROI_{ESG} = ROI_{trad}$. The enterprise gains no institutional advantage or premium.
2. **High-sustainability state** ($I_{ESG} \rightarrow 1$): If an agrocluster maximally implements "green" technologies, eliminates harmful drainage runoff, and improves labor conditions, its I_{ESG} index approaches 1. The multiplier expands toward $(1+1=2)$, mathematically doubling the baseline financial return profile. This premium is the tangible representation of mitigating future ecological risks and structural costs.

By applying our proposed transformation system, the initial financial index is passed through a specific institutional evaluation gate-the Composite ESG Multiplicative Amplifier $(1 + I_{ESG})$. This amplifier acts as an analytical filter verifying whether the agricultural enterprise is conserving local resources or depleting them. If the asset scores highly on environmental protection (I_E), social equity (I_S), and transparent corporate governance (I_G), the multiplier opens. This enables the identification of projects that shield expanded reproduction from ecological risks (such as secondary soil salinization and water scarcity).

The implementation of this optimization model requires a strict sequence of systematic capital phases, which is outlined in Table 1:

Table 1. The step-by-step strategic capital pipeline for internalizing eco-social assets in agricultural budgets¹.

Phase	Systematic Name	Operational Content and Actions	Project Examples & Metrics (Options A & B)	Economic-Methodological Function
Phase 01	CAPEX Input	Direct accounting of the initial capital expenditures of the project from invoices into the financial ledger.	Project A: \$150,000 Project B: \$240,000	Defining the baseline investment foundation and the scale of committed expenditure.
Phase 02	Resource Filtration	Gathering non-financial technical and operational data directly from the fields.	Water consumption per hectare (m3/ga), crop yield rates, and soil salinization state.	Determining the physical environmental load of the system in quantifiable metrics.
Phase 03	Sub-index Formulation	Standardizing collected field parameters through multi-criteria mathematical scoring.	Project A (I_{ESG}): 0.10 points Project B (I_{ESG}): 0.85 points (Weight: 0.50)	Transforming qualitative characteristics into comparative economic-mathematical values.

¹ Author's development.

Phase 04	Multiplier Activation	Determining the total ESG coefficient and calculating the transformative value filter formula.	Project A: $1+0.15=1.15\times$ Project B: $1+0.80=1.80\times$	Converting the environmental premium into a driver of financial growth.
Phase 05	Capital Direction	Comparing the integrated returns (ROI_{ESG}) of the projects and executing the final capital allocation decision.	Project A: 22.0% to 25.3% Project B: 18.0% to 32.4%	Reorienting capital allocation priorities toward preserving long-term systemic value.

Source: Compiled by the author based on the research model components.

The sequence reflected in Table 1 illustrates the systematic steps from primary data collection to the optimal allocation of corporate capital budgets. This pipeline converts the abstract concept of sustainable development into a repeatable corporate process. In Phase 1, capital expenditures (CAPEX) are recorded directly from project invoices. In Phase 2, non-financial operational data (physical parameters such as real water volume consumed per hectare and collector-drainage runoff) are extracted directly from the fields.

In Phase 3, these field parameters are mathematically standardized to form sub-indices (I_E, I_S, I_G). This establishes a clean comparative baseline regardless of the farm's size or crop type. Phase 4 triggers the Multiplicative Amplifier Coefficient by applying multi-criteria weights. Finally, Phase 5 reconfigures capital priorities so that short-term, resource-depleting models lose their artificial accounting superiority. This directs strategic capital toward green investments that safeguard long-term ecological sustainability.

4. Empirical Results

To test and validate the functionality of the developed model, empirical field data were collected from the 2025–2026 agricultural production cycles of agroclusters located in the Boyovut district of the Syrdarya region. The analytical matrix cross-examined two distinct investment paths:

Project A (Traditional Model): Continuing standard intensive cotton and grain cultivation using conventional furrow irrigation methods.

Project B (Green Modernization Model): Introducing an integrated smart farming system encompassing subsurface drip irrigation networks, targeted fertigation, solar-powered automated pumping stations, and deep soil organic matter enrichment[8].

The quantitative accounting indicators and multi-criteria score distributions are presented in Table 2.

Table 2. Comparative financial and eco-social input parameters for agricultural investment projects in the Boyovut district² (Data for 2025–2026).

Technical and Financial Indicators	Project A (Traditional Furrow Irrigation)	Project B (Smart Green Drip Irrigation)	Unit of Measurement
Total Area Covered by the Project	100	100	hectar (ga)
Initial Capital Expenditures (CAPEX)	150,000	240,000	US Dollar (\$)
Gross Revenue (Annual Average)	110,000	142,000	US Dollar (\$)
Operational Expenditures (OPEX)	77,000	98,800	US Dollar (\$)

² Author's development.

Net Accounting Profit (Annual Average)	33,000	43,200	US Dollar (\$)
Traditional Return on Investment (ROI_{trad})	22.0%	18.0%	percentage (%)
Water Consumption Metrics	8,500	4,250	m3/ga (annual)
Environmental Efficiency Sub-index (I_E)	0.10	0.85	score (0 - 1)
Social Responsibility Sub-index (I_S)	0.20	0.75	score (0 - 1)
Corporate Cluster Governance Sub-index (I_G)	0.20	0.75	score (0 - 1)
Composite ESG Index (I_{ESG})	0.15	0.80	score (0 - 1)

Source: Developed by the author based on primary accounting data of agro-structures in the Boyovut district (Syrdarya region, 2025–2026).

The quantitative empirical data aggregated in Table 2 reveal the core socio-economic paradox hindering sustainable agricultural transformation in transition economies[9]. Under standard corporate finance protocols, a financial analyst evaluating these two independent options would look exclusively at the row indicating the ROI_{trad} metric. Here, Project A displays a superior return rate of 22.0%, outperforming Project B by a substantial 4.0%. This mathematical advantage stems from Project A's much lower Capital Expenditures (CAPEX) threshold (\$150,000 vs. \$240,000). By utilizing simple open furrows to distribute water, Project A avoids the large upfront investments required for high-density polyethylene (HDPE) pipes, sand-gravel filtration units, digital fertigation dosing systems, and precision automated flow meters[10],[11].

However, a horizontal analysis of the technical and non-financial operational rows reveals that this high financial return is achieved by imposing massive environmental liabilities (damages) onto the regional ecosystem. Project A demands an intensive annual water withdrawal of 8,500 m3/ga, yielding a minimal Environmental Sub-index (I_{ESG}) score of 0.10. This excessive water load triggers an immediate, artificial elevation of the shallow, saline groundwater table characteristic of the Syrdarya region.

Conversely, Project B represents a highly efficient ecological framework. By implementing smart subsurface drip irrigation networks, it successfully reduces real water withdrawals to 4,250 m3/ga—a precise 50% technical saving—while simultaneously expanding annual gross revenue to \$142,000 due to enhanced crop quality. This yields a robust environmental sub-index score of 0.85. Despite generating \$10,200 more in annual net accounting profit (\$43,200 compared to \$33,000), Project B's expanded asset base (\$240,000 CAPEX) penalizes it within traditional linear formulas, forcing an artificially depressed return profile of 18.0%. This confirms that standard accounting systems view sustainable resource preservation as a financial penalty (loss) rather than a value-generating asset.

When our proposed transformation formula is applied, the integrated returns are recalculated, revealing a stark microeconomic reversal (inversion) of economic efficiency, as illustrated in Table 3.

Table 3. Recalculation matrix and final efficiency outcomes via the transformed ROI_{ESG} system³

Analysis Phase and Parameter	Project A (Traditional)	Project B (Green Drip Irrigation)	Mathematical Transformation Mechanism
Baseline Economic Efficiency	22.0%	18.0%	Core accounting data extracted from corporate ledgers

³ Author's development.

(ROI_{trad})			
Calculated Asset ESG Index (I_{ESG})	0.15	0.80	Weighted score: $0.50(I_E) + 0.30(I_S) + 0.20(I_G)$
Integrated Multiplier Component ($1 + I_{ESG}$)	1.15	1.80	Multiplicative scale coefficient for the environmental premium
Final Transformed Return (ROI_{ESG})	25.3%	32.4%	$ROI_{ESG} = ROI_{trad} * (1 + I_{ESG})$
Net Efficiency Shift (Δ_{ESG})	Baseline	+7.1%	Comparative delta indicating real integrated return

Source: Calculated by the author based on the research model formulas.

Table 3 displays the mathematical execution of the developed transformation framework, illustrating the complete microeconomic inversion of project priorities once non-market externalities are fully integrated. The operational foundation of this mechanism is the composite index value acting through the structural multiplier ($1 + I_{ESG}$). For Project A, the injection of its low eco-social compliance score ($I_{ESG} = 0.15$) generates a minimal, highly restricted expansion coefficient of 1.15. Applied to its initial accounting baseline, Project A's final integrated return is adjusted slightly from 22.0% to a transformed return of 25.3%. This minor upward shift reflects basic social compliance in terms of local employment but provides no environmental premium due to intensive resource depletion[12].

The transformative power of this model is fully manifested in the evaluation of Project B. Because Project B incorporates extensive resource-saving, low-carbon mechanisms, it captures a composite index score of 0.80, triggering a powerful 1.80x multiplicative amplifier. This amplifier monetarily represents the avoidance of future land reclamation (leaching) expenses, reduced pressure on collector-drainage networks, and the mitigation of regional ecological hazards[13].

As a direct mathematical consequence, Project B's final integrated return surges to 32.4%, entirely dismantling the 4.0% artificial advantage previously held by the traditional model under conventional accounting rules. This produces a net efficiency shift (Δ) of +7.1% in absolute terms. By elevating Project B to the highest priority in capital budgeting allocation, this model successfully proves that when long-term ecological degradation parameters and expanded reproduction constraints are fully factored in, "green" modernization pathways possess a significantly higher real economic efficiency, aligning private corporate incentives with macro-ecological sustainability.

To verify the structural robustness of the model under volatile operational conditions, a detailed sensitivity analysis was conducted, as set forth in Table 4:

Table 4. Strategic sensitivity analysis and return variation matrix under changing regional climate scenarios⁴

Simulated Ecological Scenario Model	Water Resource Availability Alteration Factor	Secondary Soil Salinization Growth Vector	Project A Final Return (ROIESGA)	Project B Final Return (ROIESGB)	Absolute Efficiency Difference (Spread Margin) (Δ)
Baseline Optimistic Matrix	Stable Supply (+0%)	Controlled (+0%)	25.3%	32.4%	+7.1%
Moderate Climatic Stress Vector	Water Reduction (-15%)	Elevated (+20%)	18.2%	31.8%	+13.6%

⁴ Author's development.

Severe Ecological Crisis State	Chronic Drought (-30%)	Intensive (+45%)	11.4%	30.5%	+19.1%
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Source: Developed by the author based on localized hydrological forecasting matrices for the Syrdarya region.

The data compiled in Table 4 evaluate the long-term reliability of our transformed model by simulating real-world climatic shocks, testing its analytical power across varying degrees of water scarcity and soil salinization. In standard corporate evaluation models, climate volatility is treated as an unforecastable random variable. In our system, environmental variations directly impact internal sub-indices, automatically recalculating final investment returns.

When a Moderate Climatic Stress Vector is applied (a 15% reduction in freshwater supply and a 20% spike in soil salinization), Project A collapses, with its integrated return dropping sharply from 25.3% to 18.2%. This rapid decline occurs because its open furrow system possesses no protective buffer against water scarcity; evaporation losses force the farm to pump highly mineralized groundwater, quickly damaging crop root zones and suppressing yields.

In sharp contrast, Project B demonstrates high structural resilience under identical climatic shocks. Its transformed return experiences only a minimal contraction, moving from 32.4% to 31.8%. Because its subsurface drip lines deliver water directly to the crop root zone with negligible evaporation, Project B maintains a stable local soil profile.

When the model simulates a Severe Ecological Crisis State (a 30% reduction in water and a 45% increase in soil salinization), Project A's return plunges below the cost of capital to 11.4%, while Project B stands firm at 30.5%. This expands the absolute efficiency difference (spread margin) to a striking +19.1%. This stress test confirms that our transformed model accurately tracks long-term risk mitigation, proving that "green" investments preserve capital value and guarantee sustainable agricultural reproduction even under severe regional ecological degradation.

5. Discussion

The quantitative shifts demonstrated in the empirical tables offer profound insights into the mechanisms of agricultural economic survival in arid zones like the Syrdarya region. The apparent superiority of Project A (22.0% traditional ROI) is an analytical mirage born of incomplete accounting. In open furrow irrigation models, over 45% of conveyed water is lost to deep filtration and evaporation. In the Boyovut district, where the water table is naturally shallow and highly mineralized, this massive hydrological influx causes rapid groundwater upwelling, pulling toxic salts directly into the crop root zone through capillary action.

Consequently, within a short horizon of 3 to 5 years, an enterprise relying on Project A inevitably faces severe soil degradation. To maintain baseline yields, the cluster is forced to commit unplanned capital to intensive soil leaching, deep ripping, and increased chemical fertilizer deployment, or face a permanent, systemic decline in crop yields of 15–20%. Traditional ROI is entirely blind to this impending financial crisis; it treats natural resource depletion as a free input, thereby externalizing the true costs of land degradation onto the state and future generations.

Applying the modified ROI_{ESG} model corrects this systemic blindness. Project B's higher integrated efficiency rate (32.4%) signifies its capacity for risk mitigation and capital preservation. By halving water intake (from 8,500 m³/ga to 4,250 m³/ga), the drip system eliminates the hydrological pressure driving secondary salinization. The soil matrix remains stable, ensuring predictable, high-quality yields across multi-year operational cycles.

From the standpoint of economic reproduction theory, the $(1 + I_{ESG})$ serves as a functional accounting transmission mechanism. It takes qualitative indicators of environmental health and translates them into a quantitative form that is understandable to commercial banks, state ministries, and foreign institutional investors.

For Uzbekistan's agriculture, this model provides an empirical framework for redesigning agricultural policy instruments. "A fundamental improvement of financial incentive mechanisms and increasing investment attractiveness for the widespread introduction of resource-saving 'green' technologies in agriculture is a strategic task" [14]. Instead of distributing the same type of subsidies to agriculture, the Ministry of Agriculture and commercial banks could implement a dynamic assessment system that directly links the availability of preferential interest rates, long-term land leases, and direct green tax credits to the applicant enterprise's approved ROI_{ESG} rating [15].

6. Conclusion

The findings of this study demonstrate that the traditional accounting approaches currently used to evaluate investment efficiency in Uzbekistan's agricultural sector are not fully adequate for assessing projects implemented under ecological stress, water scarcity, and climate-related risks. Conventional investment indicators mainly focus on short-term financial profitability and do not sufficiently reflect the long-term value of natural capital, water-saving capacity, soil fertility, social responsibility, and institutional sustainability. As a result, environmentally sustainable agricultural projects are often underestimated because they require higher initial Capital Expenditures (CAPEX), while conventional resource-depleting practices appear more attractive in short-term financial calculations.

The transformed economic-mathematical approach developed in this research eliminates this methodological limitation by integrating environmental, social, and governance-related effects into the overall assessment of agricultural investment efficiency. The empirical analysis conducted on agricultural enterprises in the Boyovut district of the Syrdarya region confirms that green modernization projects, despite their higher initial investment costs, provide a considerably stronger integrated socio-economic return than traditional irrigation and production systems. In particular, the smart green drip irrigation project achieved an integrated return of 32.4%, whereas the conventional furrow irrigation model reached only 25.3%.

These results show that sustainable agricultural investment should not be viewed merely as an environmental obligation or an additional financial burden. On the contrary, green modernization represents a rational economic strategy that contributes to the preservation of capital value, the reduction of future ecological risks, and the stabilization of expanded agricultural reproduction. Water-saving technologies, improved soil management, reduced salinization risks, and stronger governance mechanisms create long-term advantages that are not visible in traditional accounting calculations.

Therefore, it is recommended that this assessment approach be gradually introduced into Uzbekistan's agricultural investment policy, especially in the evaluation of large-scale agrocluster projects, public-private partnerships, preferential credit programs, and state-supported green modernization initiatives. Its practical application can improve the transparency of investment decisions, redirect capital toward resource-efficient projects, and support the transition of Uzbekistan's agriculture toward sustainable, climate-resilient, and economically stable development.

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