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SUSTAINABLE DEVELOPMENT OF AGRO-INDUSTRIAL CLUSTERS IN EXTREME ECOLOGICAL ENVIRONMENTS: AN ECO-ECONOMIC FRAMEWORK FOR COTTON AND TEXTILE VALUE CHAINS IN KARAKALPAKSTAN

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ABSTRACT This research paper presents an integrated eco-economic analysis of agricultural cluster transformation within vulnerable ecosystems, focusing on the cotton and textile sector of the Republic of Karakalpakstan. The Aral Sea ecological crisis presents severe environmental boundaries, including acute water deficits, severe soil salinization, and climate-induced yield volatility. Traditional market-driven cluster integration often fails to internalize these ecological externalities. This study proposes an eco-efficiency assessment framework and evaluates strategic economic mechanisms to incentivize water-saving technologies, mitigate environmental production risks, and strengthen value-chain resilience. Empirical findings confirm that combining green procurement premiums, public-private-environmental partnerships, and circular agricultural practices significantly enhances resource productivity, farm-level profitability, and long-term regional economic stability.

KEYWORDS Agro-industrial clusters, regional environmental economics, sustainable value chains, eco-efficiency, water security, circular agriculture, Karakalpakstan, Aral Sea basin.

1. INTRODUCTION AND THEORETICAL BACKGROUND

Agricultural cluster integration has become a cornerstone of agrarian modernization across developing and transitioning economies. By vertically connecting farming enterprises, processing facilities, and distribution channels, clusters reduce transaction costs, foster technological diffusion, and enhance product competitiveness. However, classical economic models of cluster development often operate under the implicit assumption of stable ecological conditions and abundant natural resources.

In regions facing severe environmental degradation, such as the Republic of Karakalpakstan situated within the Aral Sea basin, traditional cluster frameworks encounter critical boundaries. Soil salinization, severe water stress, and extreme climatic fluctuations directly impair agricultural productivity and threaten the financial stability of farming units. Consequently, optimizing cotton-textile clusters in arid ecosystems requires a paradigm

shift from purely commercial value generation toward an integrated eco-economic governance framework.

This paper formulates an updated conceptual and practical framework for cotton-textile cluster operations in Karakalpakstan, examining how economic incentives and organizational structures can be aligned with ecological preservation goals.

2. METHODOLOGY AND DATA SOURCES

This study utilizes a multi-criteria empirical approach combining eco-efficiency analysis, resource allocation modeling, and value-chain diagnostic methods. Data were compiled from regional agricultural statistics, cluster financial performance statements, and hydrological monitoring reports across Karakalpakstan for the period 2018–2026.

The core quantitative evaluation relies on an expanded Eco-Efficiency Index (EEI), calculated as:

EEI = (Total Net Value Addition, USD / ha) / (Irrigation Water Applied, m^3 / ha + Agro-Chemical Inputs, kg / ha)

In addition, financial feasibility indicators—including Net Present Value (NPV) and Capital Expenditure (CapEx) recovery timelines—were modeled to compare traditional flood irrigation against advanced drip and micro-irrigation systems across distinct soil salinization zones.

3. EMPIRICAL RESULTS AND DISCUSSIONS

Field data analysis shows that extensive furrow irrigation in Karakalpakstan leads to excessive water loss, averaging 9,800 to 11,200 cubic meters per hectare, while worsening soil salinity. Conversely, cluster farms that implemented drip irrigation reduced water consumption by over 45% while achieving substantial productivity gains.

Table 1 illustrates the comparative performance metrics across different production management systems in the region.

Performance Indicator	Traditional Furrow System	Modern Drip System (Basic)	Drip System (Subsidized & Integrated)	Relative Variance (%)
Water Consumption (m^3/ha)	9,800 – 11,200	5,300 – 6,100	5,100 – 5,800	-46.4%
Raw Cotton Yield (ts/ha)	22.0 ts/ha	35.5 ts/ha	38.5 ts/ha	+75.0%
Net Farm Income ($/ha)	$175	$410	$590	+237.1%
Eco-Efficiency Index (EEI)	0.019	0.073	0.105	+452.6%

Table 1. Comparative Analysis of Cotton Cultivation Systems in Karakalpakstan.

While the adoption of water-saving systems significantly elevates eco-efficiency and net income, high capital investment costs and saline soil damage remain main operational obstacles. Furthermore, value-chain diagnostics show that local clusters primarily produce

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low-margin intermediate outputs (yarn and unbleached fabric). Deep industrial processing into finished garments is essential to retain economic margins within the region.

4. PROPOSED ORGANIZATIONAL AND ECONOMIC MECHANISMS

To establish a resilient and eco-efficient cluster structure in Karakalpakstan, the following four institutional mechanisms are recommended:

1. Green Contractual Pricing Frameworks:

Cluster-farmer contracts should incorporate tiered price premiums (10–15%) for raw cotton produced using certified eco-friendly and water-saving practices.

2. Climate and Ecological Risk Pooling Funds:

Establishing a regional insurance mechanism funded jointly by cluster enterprises, state funds, and international environmental donors to hedge against acute hydrological shortages.

3. Public-Private-Environmental Partnerships (PPEP):

Creating joint investment frameworks to modernize primary canal infrastructure, backed by tax credits and preferential long-term credit lines.

4. Circular Economy and Waste-to-Value Integration:

Promoting the processing of agricultural residues (cotton stalks and seed meal) into bio-energy and soil conditioners to enhance soil health and generate secondary income streams.

5. CONCLUSION AND RECOMMENDATIONS

Transforming cotton-textile clusters in Karakalpakstan into sustainable drivers of regional growth requires harmonizing financial profitability with environmental conservation. Implementation of resource-saving technologies, value-chain deepening, and green incentive structures are vital for ensuring long-term ecological and economic viability.

Key recommendations:

• Establish regional agro-ecological research centers to develop and distribute salt-tolerant and drought-resistant cotton cultivars.

• Expand financial incentives for downstream processing facilities (weaving, dyeing, garment manufacturing) within Karakalpakstan.

• Introduce tiered water tariffs and utility tax relief for cluster participants achieving high eco-efficiency thresholds.

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