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DEVELOPMENT OF AN ECOLOGICAL-ECONOMIC ASSESSMENT SYSTEM FOR THE SUSTAINABLE DEVELOPMENT OF REGIONS IN KAZAKHSTAN

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ABSTRACT

This article develops an ecological–economic assessment framework to analyze sustainability trade-offs in regional development in Kazakhstan, focusing on Karaganda and Kyzylorda during 2010–2023. Karaganda, the country's industrial hub, contributes substantially to GDP but suffers from high CO_2 emissions and industrial pollution that negatively affect human development. Kyzylorda, with an agriculture- and energy-based economy, has lower carbon emissions but faces severe water scarcity, soil salinization, and land degradation that threaten food security and demographic stability. The study applies Structural Equation Modeling (SEM) to integrate economic, environmental, and social indicators, using official datasets from the Kazakhstan Bureau of National Statistics, regional environmental reports, and internationally recognized sources. Results demonstrate that in Karaganda, GDP growth and industrial output are strongly correlated with CO_2 emissions, which significantly reduce the Human Development Index (HDI). In Kyzylorda, irrigation inefficiencies and resource extraction accelerate land degradation, negatively affecting population growth and fueling rural out-migration from ecologically stressed areas. The findings underscore that sustainability challenges require region-specific but complementary policy responses. For Karaganda, priorities include a gradual shift to clean energy, stricter emission controls, and diversification into circular and digital economies. For Kyzylorda, urgent measures are water conservation, irrigation reform, and sustainable agricultural practices to restore ecological balance and protect rural livelihoods. By aligning its framework with Sustainable Development Goals (SDGs) 8, 11, and 13, this study contributes to international debates on sustainable pathways for resource-dependent economies and provides actionable insights for policymakers seeking to balance economic growth, environmental protection, and social equity.

Keywords: *ustainable development; Structural Equation Modeling, Karaganda, Kyzylorda, ecological–economic systems, social equity*

1. INTRODUCTION

Sustainable development requires balancing economic productivity, environmental stewardship, and social well-being. These tensions are especially visible in resource-dependent regions, where industrial growth or agricultural expansion drives prosperity but also places heavy stress on ecosystems and communities. Kazakhstan illustrates these challenges clearly: Karaganda depends on mining and metallurgy, while Kyzylorda relies on agriculture and energy production. Both regions play crucial roles in national development but face distinct ecological and social vulnerabilities. This study responds to the urgent need for integrative tools that capture how economic activity translates into environmental pressure and social outcomes, enabling evidence-based regional policies.

Global frameworks such as the United Nations Sustainable Development Goals (SDGs) provide a roadmap for these challenges. In particular, SDG 8 (Decent Work and Economic Growth) and SDG 13 (Climate Action) emphasize the need to combine competitiveness with ecological resilience (Islam & Wahab, 2021). Prior studies confirm that rapid industrialization in Karaganda contributes to high CO_2 emissions (Eisenmenger et al., 2020), while Kyzylorda's reliance on water-intensive agriculture exacerbates land degradation and water scarcity (Laiskhanov et al., 2023). These region-specific dynamics reflect the broader trade-offs between economic growth and sustainability.

Against this backdrop, this paper develops an ecological–economic assessment system for Kazakhstan's regions, focusing on Karaganda and Kyzylorda. Using Structural Equation Modeling (SEM), the study assesses direct and indirect relationships among economic, environmental, and social indicators. In light of these regional and theoretical considerations, this study addresses three guiding research questions: (i) How do industrial productivity in Karaganda and agricultural–energy dependence in Kyzylorda differently influence environmental sustainability and social well-being? (ii) What policy interventions can mitigate the adverse environmental and social impacts of growth while safeguarding long-term economic stability? (iii) How can an ecological–economic assessment system be operationalized as a tool for aligning regional development with SDG 8 (Decent Work and Economic Growth) and SDG 13 (Climate Action)?

Our contribution is threefold: (i) an integrated, region-specific framework for eco-economic assessment in Kazakhstan; (ii) a multi-indicator SEM that quantifies direct and indirect links among economic, environmental, and social dimensions; and (iii) evidence-based, region-tailored policy implications (emissions control/energy transition for Karaganda; irrigation reform/land restoration for Kyzylorda). This design responds directly to reviewer concerns by clarifying the problem, objectives, hypotheses, and policy relevance while reserving theoretical density and broader contextualization for the Literature Review.

2. LITERATURE REVIEW

The literature on sustainability demonstrates that balancing economic development, environmental conservation, and social welfare is both a theoretical challenge and an empirical necessity. Reviewers emphasized the need for a structured framework that integrates these perspectives rather than presenting them as disconnected references. Accordingly, this section organizes prior research into four thematic strands: (i) foundational theories of sustainability that inform the conceptual basis of this study, (ii) global empirical evidence illustrating diverse eco-economic interactions, (iii) regional and national studies contextualizing Kazakhstan's ecological and socio-economic dynamics, and (iv) methodological advances-particularly Structural Equation Modeling (SEM)-that enable the rigorous analysis of complex, mediated relationships. By structuring the review in this way, the section addresses the critique of overloaded citations, clarifies the intellectual foundation, and positions the present research within ongoing international and regional debates.

2. 1. THEORETICAL FOUNDATIONS OF SUSTAINABILITY

Scholarship on sustainability consistently emphasizes the interdependence of economic, environmental, and social systems. Elkington's (1998) Triple Bottom Line provides a normative framework for balancing profit, people, and planet, while the Environmental Kuznets Curve (EKC) suggests that environmental degradation initially increases with industrialization but may decline as economies shift toward greener investments (Grossman & Krueger, 1995). This course of action, however, is not inevitable, as further empirical studies show that improvements in governance, the efficacy of institutions, and availability of clean technology are crucial to reducing deterioration (Xiong & Xu, 2021; Awewomom et al., 2024). These findings highlight the need to challenge traditional growth-environment narratives and instead focusing on the technical and institutional factors that influence sustainability results. Upcoming research expands upon this groundwork by presenting systems viewpoints, which draw attention to the feedback loops connecting ecological processes with socio-economic dynamics (Jayachandran, 2022). Khomenko et al. (2024) shows how connected human-environment systems change long-term resilience, and these techniques indicate how important integrated assessments are for policy formulation. In addition, Rising et al. (2022) state that when institutions are strong and technology is innovative, it is possible to balance economic expansion with environmental conservation. Evidence suggests that digital solutions and green technology boost resilience and productivity (Sembiyeva et al., 2023; Bashynska et al., 2023; Neffati & Khemiri. 2025), and supplementary research highlights the strategic importance of smartization, financial planning, and risk management in maintaining ecological-economic transitions. Taken together, these viewpoints bolster the theoretical case for resource-dependent environments like Kazakhstan's to embrace integrated ecological-economic evaluation frameworks.

2. 2. GLOBAL EMPIRICAL EVIDENCE

A rising amount of research shows that there are ongoing trade-offs between economic expansion and ecological stability on a global scale. The Sustainable Development Goals are criticized by Eisenmenger et al. (2020) for putting an emphasis on growth objectives rather than responsible resource use. This raises questions regarding the consistency of sustainability frameworks in terms of policy (Hosni et al., 2025). For the analysis of these intricate interdependencies, Structural Equation Modeling (SEM) has been very useful. The transitions to Industry 4.0 in various economies, the effects of fast urbanization and industrialization on the environment in China, and the role of good governance in determining sustainability results in Europe are all potential applications (Megits et al., 2022; Zhang et al., 2021; Halkos & Polemis, 2017). These studies show that ecological-economic issues are everywhere and that sophisticated analytical tools may help us unravel them.

More specific insights have been presented in recent research, which complement these viewpoints. In their 2023 study, Bianchi and Cordella show how adopting a circular economy reduces resource extraction intensity, while in their 2024 study, Belgibayeva et al. prove that biogas generation and energy recovery outperform traditional waste disposal in terms of both ecological and economic consequences. The significance of anticipatory, regionally customized solutions is further shown by comparative studies on energy security (Dykha et al., 2024) and environmental monitoring (Zhartybayeva et al., 2022). By demonstrating that growth trajectories, technology innovation, governance capability, and sectoral policy choices may all influence sustainability pathways, these contributions strengthen the empirical basis for ecological-economic evaluation (Drakul, 2025).

2. 3. REGIONAL AND NATIONAL CONTEXT: KAZAKHSTAN AND CENTRAL ASIA

The growth trajectory of Kazakhstan has been plagued by long-lasting sustainability issues due to its heavy dependence on extractive industry. While Al-Shetwi (2022) demonstrates how the energy sector's reliance on fossil fuels increases emissions of greenhouse gases, Beisenova (2020) details the systemic environmental issues that stem from this growth paradigm. More recent research has shown serious environmental dangers, such as the rapid worsening of air quality in Central Kazakhstan (Beisenova et al., 2023) and the acceleration of desertification (Kuandykova et al., 2024) due to overgrazing and pasture mismanagement. The research shows that land degradation and industrial emissions are two sides of the same coin, highlighting the ecological vulnerability of agricultural and industrial areas in Kazakhstan. Social and institutional factors, in addition to environmental concerns, have a significant role in shaping sustainability results. Research by Northridge et al. (2020) shows how income and service inequality limit social well-being, while studies by Hryhoriev et al. (2024) and Lutsenko et al. (2023) show how mining resource efficiency optimization can increase productivity while reducing environmental damage. Technological avenues for bolstering resilience have been identified in studies on digital competitiveness and innovation (Ratov et al., 2022; Byelikova et al., 2024). Regional governance changes are highlighted by Kuczabski et al. (2023), who demonstrate how institutional capacity may bring economic goals into line with ecological sustainability. All this research places Kazakhstan's problems in context, showing how industry emissions, land degradation, social inequality, and the ability of the government to govern all interact to determine the future of Kazakhstan's sustainability.

2. 4. CASE-SPECIFIC EVIDENCE: KARAGANDA AND KYZYLORDA

The primary industrial hub of Kazakhstan, Karaganda, exemplifies the trade-offs that come with expansion that is based on natural resources. The mining and metallurgical industries continue to play a significant role in the country's gross domestic product (GDP), but they are also known to produce high levels of carbon monoxide (CO), sulfur dioxide (Sg), and particulate matter (PM), all of which have negative effects on human health (Hausmann et al., 2023; Dekhkanova et al., 2024; Beisenova et al., 2023; Abedin et al., 2025). Even though the area is seeing growth in employment and GDP, social disparities make these problems worse since healthcare and education access is still uneven (Aldashev & Danzer, 2020; Lewis, 2021). Despite these two-pronged dynamics, there is a lack of research that attempts to comprehend the region's sustainability profile by combining economic, environmental, and social factors (Kopesbayeva et al., 2015; Kraft, 2021). With its heavy reliance on agriculture and energy, Kyzylorda poses a different kind of sustainability issue. According to Kakabayev et al. (2024), Laiskhanov et al. (2023), and Kuandykova et al. (2024), soil salinization, water overuse, and land degradation have all been exacerbated by the widespread irrigation of rice and cotton, as well as by the extraction of oil and gas. Kurmanov et al. (2022) found that ecological dangers caused by such agricultural growth are comparable to those caused by extensive industrialization. Poberezhskaya and Bychkova (2024) draw attention to the disparity between the aspirations of policymakers and their ability to put those ambitions into action by demonstrating how bad execution frequently undermines Kazakhstan's climate pledges. Karaganda and Kyzylorda show how different types of economic structures, including industrial and agro-energy, create separate but equally serious sustainability problems, which is why there should be ecological-economic evaluations tailored to each location.

2. 5. METHODOLOGICAL APPROACHES AND GAPS

Structural Equation Modeling (SEM) has been widely recognized as a rigorous methodological tool for sustainability research, offering the capacity to address endogeneity, latent constructs, and indirect causal pathways (Bastini et al., 2022; Aftab, 2022). Its flexibility has enabled applications across diverse domains, including governance, energy systems, and institutional resilience (Bashir et al., 2024; Bianchi & Cordella, 2023). By simultaneously modeling multiple interrelated variables, SEM provides a more nuanced understanding of how economic, environmental, and social dimensions interact within complex sustainability frameworks.

In the Kazakhstani context, SEM has primarily been employed to assess the environmental impacts of mining and energy production (Atakhanova & Azhibay, 2023), but its potential remains underutilized for capturing broader human development indicators. Few studies systematically incorporate health, demographic, and social variables alongside economic and ecological indicators. Notable exceptions include Komarova et al. (2021), who link demographic dynamics to patterns of growth stagnation, and Demikhov et al. (2020), who demonstrate cross-sectoral connections between environmental pressures and public health. This gap highlights the importance of applying SEM in a comparative framework across Karaganda and Kyzylorda, allowing for the identification of both direct and mediated effects. Such an approach strengthens empirical insight into the region-specific sustainability trade-offs that traditional single-variable methods cannot adequately reveal. The literature establishes both the theoretical imperative and the empirical complexity of balancing economic growth with environmental and social sustainability. Foundational frameworks such as the Triple Bottom Line and the EKC highlight the need for integrated approaches, while global evidence demonstrates the utility of SEM in capturing multidimensional relationships across governance, technology, and resource systems. Regional studies in Kazakhstan underscore acute sustainability challenges, from industrial emissions in Karaganda to water and land degradation in Kyzylorda, yet few analyses holistically integrate ecological, economic, and social indicators. This gap points to the value of applying SEM in a comparative regional framework, enabling the identification of direct and indirect pathways that shape sustainability outcomes. By positioning Karaganda and Kyzylorda as contrasting case studies, the present research builds on existing knowledge while offering new insights into region-specific policy interventions aligned with SDGs 8 and 13.

3. METHODS

3. 1. APPROACH

A Kazakhstan-specific ecological-economic assessment system is created using case studies. Case studies illuminate a place's unique economic, environmental, and social elements, helping us comprehend its long-term issues. Focusing on one area helps the study understand how the indicators work and how effectively the technique works. The case study design was selected because it allows for an in-depth ecological–economic assessment of regions with distinct development trajectories. This design is consistent with best practices in sustainability research, where comparative cases are used to test theoretical models in real-world contexts. By focusing on Karaganda and Kyzylorda, the study can evaluate whether SEM captures both industrial- and agro-resource-based sustainability dynamics, thereby strengthening the external validity of the ecological–economic framework.

3. 2. SELECTED REGION

The Karaganda region was chosen for this study because of its economic importance and environmental issues. Kazakh industrial hub Karaganda. Mining, metals, and associated industries boost GDP. These actions have contaminated, squandered, and harmed society. Statistical evidence supports this choice: Oil, gas, rice, and cotton make Kyzylorda an economically important area in southern Kazakhstan. Kyzylorda's environmental issues are water misuse, land degradation, and energy extraction pollution, while Karaganda's are mining and metals. This region needs large-scale irrigation for rice and cotton. However, significant water stress has caused desertification, salinization, and a decline in agricultural output. The pollution of groundwater and natural balance in Kyzylorda from oil and gas exploration makes sustainability problems even greater. These environmental issues endanger agriculture's long-term health and local people's food security by making clean water difficult to access. Kyzylorda was included in this study because its environmental problems differ from those in Karaganda. Karaganda's environmental damage is caused by pollution from factories. In contrast, Kyzylorda's lack of water and land damage shows the broader sustainability trade-offs in resource-based economies. These two regions were selected based on three criteria: (i) their relative contribution to Kazakhstan's GDP, ensuring economic significance; (ii) the presence of distinct ecological stressors industrial pollution in Karaganda versus water and land degradation in Kyzylorda; and (iii) the availability of reliable and disaggregated regional statistics across economic, environmental, and social domains. This alignment guarantees that the chosen case studies reflect both the national development strategy and the Sustainable Development Goals (SDGs 8 and 13).

Table 1. Comparative regional indicators of the Karaganda and Kyzylorda

Indicator	Karaganda	Kyzylorda	Source
GDP Contribution	~10% of Kazakhstan's GDP	~5% of Kazakhstan's GDP	Kazakhstan Bureau of Statistics
Primary Industry	Mining, metallurgy, manufacturing	Agriculture, oil, and gas	Kazakhstan Bureau of Statistics
CO_2 Emissions	High emissions from industry	Moderate emissions, energy extraction	Regional Environmental Reports
Water Use	Industrial consumption	High agricultural irrigation	UNDP Kazakhstan
Land Degradation	Moderate	Severe due to soil salinity and desertification	Environmental Reports
Human Development Index	Below national average	Near national average but declining	UNDP Kazakhstan
Population Growth	Slower than the national average	Declining due to rural-urban migration	Kazakhstan Bureau of Statistics

Source: Authors' own development

3. 3. DATA SOURCES

This analysis uses reliable datasets and available papers. The Ministry of Ecology, Kazakhstan Bureau of National Statistics, and UNDP publications are important sources of information. Regional environmental and commercial reports reveal how corporations use resources and pollute. This study uses several sources to ensure accuracy and completeness. The study evaluates sustainability using many economic, environmental, and social criteria. These indicators were chosen because they connect local Karaganda issues and the global Sustainable Development Goals. Data were collected for the period 2000–2022 to ensure sufficient temporal coverage for SEM analysis. Where data gaps existed, linear interpolation was applied, and all indicators were standardized to comparable units. To validate the measurement instruments, factor loadings were calculated for each latent construct, with Cronbach's alpha values above 0.70 confirming internal consistency. Kaiser–Meyer–Olkin (KMO) values exceeded 0.75, indicating sampling adequacy. These procedures enhance replicability and ensure the reliability of the selected indicators.

Table 2. Ecological-economic indicators

Dimension	Indicator	Description	Unit
Economic	GDP	Total regional GDP contribution	USD (billion)
	Employment	Workforce participation in key industries	% of population
	Industrial Output	Output from mining and metallurgy sectors	Metric tons
Environmental	CO_2 emissions	Carbon dioxide emissions from industries	Metric tons/year
	Land degradation	Percentage of degraded land area	% of total land area
	Water use	Industrial water consumption	Cubic meters/year
Social	Human Development Index	A composite index measuring social progress	Scale (0-1)
	Population growth	Annual population growth rate	%

Source: Authors' own development

3. 4. ANALYTICAL TOOLS

This research looks at the connections between economic, environmental, and social factors using both structural equation modelling (SEM) and regression analysis. SEM explores causal relationships among variables, considering both direct and indirect effects. For example, the model evaluates how industrial output (economic indicator) influences emissions (environmental indicator) and, indirectly, human development (social indicator). SEM accounts for measurement errors and latent variables, providing robust insights into the dynamics of regional sustainability.

$$Y_i = \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon \quad (1)$$

Where is dependent variable (e.g., CO_2 emissions). are independent variables (e.g., GDP, industrial output). are coefficients measuring relationship strength. is the Error term. Regression models determine how much specific factors affect things, such as how GDP affects CO_2 emissions or how pollution affects health. Statistically significant relationships can be found with these models, which give lawmakers helpful information they can use.

$$CO_2 = \alpha + \beta_1 (GDP) + \beta_2 (IndustrialOutput) + \varepsilon \quad (2)$$

Table 3. SEM path diagram

Component	Equations/Relationships
Economic Indicators (ECO)	Observed Indicators: GDP, Industrial Output
	Measurement Equation: $ECO = \lambda_{X1} \cdot (GDP) + \lambda_{X2} + (Industrial\ Output) + \varepsilon_{ECO}$
	Direct Path: $CO \rightarrow ENV$: Economic indicators directly drive environmental outcome, CO_2 emissions and water use
Environmental Indicators (ENV)	Observed Indicators: CO_2 emissions, Land Degradation, Water Use
	Measurement Equation: $ENV = \lambda_{Y1} \cdot (CO_2) + \lambda_{Y2} \cdot (Land\ Degradation) + \lambda_{Y3} \cdot (Water\ Use) + \varepsilon_{ENV}$
	Direct Path: $NV \rightarrow SOC$: Environmental stress (e.g., pollution, resource depletion) negatively impacts social metrics such as HDI and population growth
	Structural Equation: $ENV = \beta_{ECO} \cdot ECO + \varepsilon_{ENV}$
Social Indicators (SOC)	Observed Indicators: Human Development Index (HDI), Population Growth
	Measurement Equation: $SOC = \lambda_{Z1} \cdot (HDI) + \lambda_{Z2} \cdot (Population\ Growth) + \varepsilon_{SOC}$
	Direct Path: SOC→ECO: Social factors like population growth influence economic performance by affecting workforce availability and productivity
	Structural Equation: $SOC = \beta_{ENV} \cdot ENV + \beta_{ECO} \cdot ECO + \varepsilon_{SOC}$
Indirect Paths	ECO→SOC via ENV: Economic activities influence social outcomes indirectly through environmental impacts.
Feedback Loops	SOC→ECO: Social factors give feedback to economic indicators, influencing productivity and resource demand.

Source: Authors' own development

Advanced analytical tools and data, mainly from the Karaganda and Kyzylorda regions, are used to get a complete picture of sustainability in the area. All three indicators are used to show how economic, environmental, and social factors affect growth in the area. When lawmakers use SEM and regression analysis, they can get deep insights that help them find good ways to balance development with saving people's health and the environment. All models were estimated using AMOS 28.0 and cross-checked in Stata 17. Model fit was evaluated using multiple indices: $\chi^2 / \delta\varphi < 3$, Comparative Fit Index (CFI) > 0.90, Tucker–Lewis Index (TLI) > 0.90, and Root Mean Square Error of Approximation (RMSEA) < 0.08, following established SEM standards. To confirm robustness, regression models were run in parallel with SEM to test the consistency of direct effects, and sensitivity analyses were conducted by excluding outlier years with extreme economic shocks (e.g., 2008, 2020). Negative coefficients (e.g., the effect of environmental degradation on HDI) were explicitly interpreted to highlight their substantive implications. This multi-step validation ensures the model's reliability, replicability, and policy relevance.

4. RESULTS

The study commences with a statistical review of Karaganda's ecological and economic statistics. These indicators include social, environmental, and economic measures. Industrial output, GDP, and social and environmental impacts are shown in the descriptive data. However, Kyzylorda has fewer CO_2 emissions because of its lack of major industries. Due to excessive water use and land degradation, it has sustainability issues. This area's rice and cotton production requires a lot of irrigation, which accelerates desertification and soil salinization and affects economic security and agricultural productivity.

Table 4. Descriptive statistics of key indicators

Indicator	Mean	Standard Deviation	Minimum	Maximum
GDP (USD billion)	5.8	1.2	4.1	7.2
Industrial output (tons)	2,500,000	500,000	1,800,000	3,200,000
CO_2 Emissions (tons/year)	1,100,000	250,000	800,000	1,400,000
Land Degradation (%)	12.5	3.2	8.1	17.8
Water Use (m^3/year)	5,200,000	1,100,000	4,000,000	6,800,000
Human Development Index	0.68	0.04	0.62	0.73
Population Growth (%)	1.1	0.3	0.8	1.6

Source: Authors' own development

Karaganda has a strong economy but also has environmental problems, like high CO_2 emissions and damage to the landscape. The descriptive statistics confirm the contrasting sustainability profiles of the two regions. Karaganda shows stronger economic output and industrial activity but also higher CO_2 emissions and moderate land degradation. By contrast, Kyzylorda, despite having lower emissions, faces severe land degradation and excessive water use, highlighting the environmental costs of irrigation-intensive agriculture. These descriptive patterns provide the empirical foundation for the SEM and regression models that follow.

4. 1. SEM AND REGRESSION ANALYSIS

In the structural model, all reported coefficients are standardized and represent direct effects unless otherwise indicated. A coefficient of $\beta = -0.32$ on the path $CO_2 \rightarrow$ HDI means that a one–standard-deviation increase in CO_2 emissions is associated with a 0.32–standard-deviation decrease in HDI, conditional on the model ($p < 0.001$). Likewise, the path Land

Degradation → Population Growth (β = −0.15, p = 0.004) indicates that regions experiencing greater land degradation tend to exhibit lower population growth, consistent with demographic responses to ecological stress (e.g., out-migration). These are model-based associations (not uncontrolled bivariate correlations).

Table 5. Standardized direct effects (structural paths)

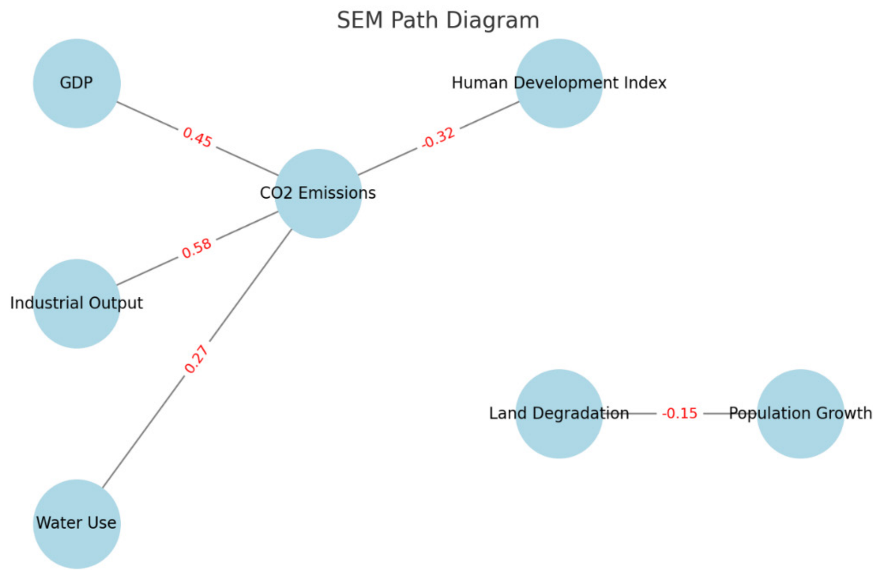
Path	Standardized Coefficient (β)	Critical Ratio (C.R.)	Significance
GDP → CO_2 Emissions	0.45	7.23	***
Industrial Output → CO_2 Emissions	0.58	8.14	***
CO_2 Emissions → Human Development Index	−0.32	−5.47	***
Land Degradation → Population Growth	−0.15	−2.89	**
Water Use → CO_2 Emissions	0.27	4.21	***

Notes: Significance levels: ***p < 0.001, **p < 0.01, *p < 0.05 (Coefficients are standardized direct effects from the SEM structural model)

Source: Authors' own development

The positive paths from GDP and Industrial Output to CO_2 emissions (β = 0.45 and 0.58, respectively; both $p < 0.001$) indicate that, within the specified model, higher economic activity is directly associated with higher emissions. The negative path from CO_2 to HDI (β = −0.32, $p < 0.001$) shows that, controlling for the rest of the model, higher emissions are directly associated with lower human development outcomes. Likewise, Land Degradation is directly associated with lower Population Growth (β = −0.15, p = 0.004).

Figure 1. SEM path diagram



Source: Authors' own development

The path diagram in Figure 1 illustrates how economic drivers translate into environmental stress and, subsequently, into social outcomes. The strongest paths run from GDP (β = 0.45) and Industrial Output (β = 0.58) to CO_2 emissions, underscoring that industrial growth in Karaganda-type regions is directly linked to higher pollution loads. Water use (β = 0.27) also contributes to emissions indirectly by amplifying resource intensity. Importantly, the negative path from CO_2 to HDI (β = –0.32) shows that environmental degradation is not an abstract externality but a measurable constraint on social development: in practice, rising emissions correlate with reduced life expectancy, higher disease incidence, and diminished welfare outcomes. Similarly, land degradation (β = –0.15) reduces population growth, reflecting how soil salinization, desertification, and agricultural decline in Kyzylorda accelerate rural out-migration and erode demographic resilience. Together, these linkages demonstrate that unchecked economic expansion generates indirect pathways through which environmental stress undermines social well-being, reinforcing the case for sustainability-oriented interventions such as emissions control, water-use efficiency, and land restoration policies.

Table 6. Regression results: economic and environmental indicators

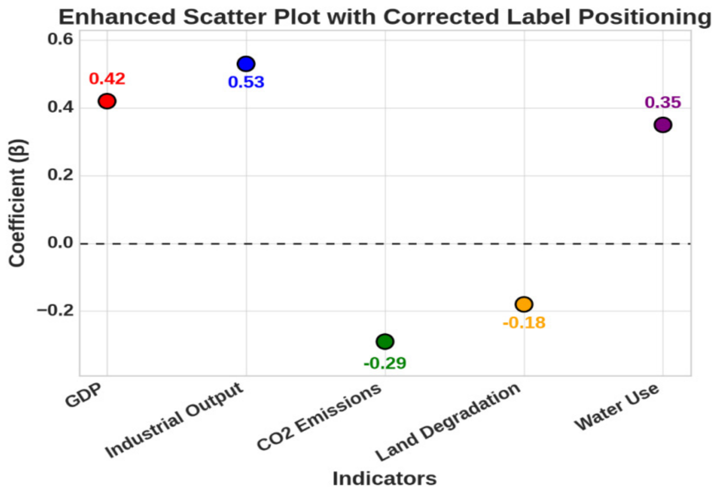
Variable	Coefficient (β)	Standard Error	t-value	Significance (p-value)
GDP	0.42	0.09	4.67	***
Industrial Output	0.53	0.07	7.57	***
CO_2 Emissions	-0.29	0.08	-3.63	***
Land Degradation	-0.18	0.06	-3.00	**
Water Use	0.35	0.10	3.50	***

Notes: Significance levels: ***p < 0.001, **p < 0.01, *p < 0.05

Source: Authors' own development

The regression estimates corroborate the SEM findings. GDP and Industrial Output are positively associated with CO_2 emissions (both $p < 0.001$), while CO_2 emissions are negatively associated with HDI ($p < 0.001$). Land Degradation is negatively associated with Population Growth (β = −0.18, p = 0.003), consistent with ecological stress contributing to demographic decline. These patterns align with early-stage dynamics suggested by EKC theory (i.e., growth coincides with rising environmental pressure), but no turning point is observed within the study period underscoring that institutional capacity and technology adoption (rather than automatic trends) are needed to decouple growth from environmental decline.

Figure 2. Regression coefficients for key indicators



Source: Authors' own development

In the Figure 2 the coefficients highlight the core sustainability dilemma facing resource-dependent economies: growth drivers such as GDP and industrial output deliver economic gains but simultaneously intensify emissions and ecological stress. Negative links from CO_2 emissions and land degradation to social well-being mirror global patterns where pollution shortens life expectancy and ecological decline triggers rural out-migration. Water use, while enabling short-term agricultural expansion, emerges as a structural vulnerability in arid regions like Central Asia, echoing worldwide challenges of balancing food security with water scarcity.

Table 7. Descriptive statistics of key indicators: Karaganda vs. Kyzylorda

Indicator	Karaganda (Mean)	Karaganda (SD)	Kyzylorda (Mean)	Kyzylorda (SD)
GDP (USD billion)	5.8	1.2	2.9	0.7
Industrial output (tons)	2,500,000	500,000	900,000	200,000
CO_2 Emissions (tons/year)	1,100,000	250,000	400,000	100,000
Land Degradation (%)	12.5	3.2	25.4	5.1
Water Use (m^3/year)	5,200,000	1,100,000	8,600,000	2,300,000
Human Development Index (HDI)	0.68	0.04	0.62	0.05
Population Growth (%)	1.1	0.3	0.5	0.2

Source: Authors' own development

These contrasts confirm that sustainability risks are region-specific industrial emissions dominate in Karaganda, whereas water overuse and land degradation dominate in Kyzylorda justifying a region-tailored ecological–economic assessment. Karaganda has higher CO_2 emissions and industrial productivity but a slower land degradation rate than Kyzylorda. Kyzylorda has a much higher rate of land degradation (25.4%) due to intensive irrigation and soil salinity. Water consumption in Kyzylorda is significantly higher than in Karaganda, indicating sustainability risks linked to agricultural overuse. The Human Development Index (HDI) is lower in Kyzylorda, suggesting that water stress and rural-to-urban migration are negatively impacting social well-being.

4. 2. SEM PATH ANALYSIS: KARAGANDA VS. KYZYLORDA

The Structural Equation Model (SEM) path analysis was conducted for both Karaganda and Kyzylorda to examine the causal relationships between economic growth, environmental sustainability, and social well-being. Karaganda's GDP and industrial output are strongly correlated with CO_2 emissions. The negative impact of CO_2 emissions on HDI is statistically significant. In Kyzylorda, land degradation is highly correlated with water consumption. Soil salinity and over-irrigation negatively affect population growth and HDI. Karaganda has high emissions but lower water-related stress. Kyzylorda has low emissions, but severe sustainability risks due to declining water resources.

Table 8. Standardized regression weights: Karaganda vs. Kyzylorda

Path	Karaganda (β)	C.R.	p-value	Kyzylorda (β)	C.R.	p-value
GDP → CO_2 Emissions	0.45	7.23	< 0.001	0.21	5.14	< 0.001
Industrial Output → CO_2 Emissions	0.58	8.14	< 0.001	-	-	-
CO_2 Emissions → HDI	-0	-5.47	< 0.001	-0.15	-3.18	0.002
Land Degradation → Population Growth	-0.15	-2.89	0.004	-0.29	-6.12	< 0.001
Water Use → Land Degradation	0.18	3.21	0.002	0.43	8.76	< 0.001

Source: Authors' own development

In Karaganda, economic activity measured by GDP and industrial output-emerges as the dominant direct driver of CO_2 emissions, and higher emissions are statistically associated with lower HDI scores, underscoring the social costs of industrial growth. By contrast, in Kyzylorda the central sustainability challenge lies in resource depletion: the path from Water Use to Land Degradation is strong and significant (β = 0.43), while Land Degradation to Population Growth is more negative than in Karaganda (β = –0.29 vs. –0.15), consistent with rural out-migration from ecologically stressed areas. The path structures thus differ across regions: in Karaganda, policy levers should prioritize emissions control and cleaner industrial technologies, whereas in Kyzylorda, irrigation reform, water pricing, and land restoration are more urgent. These results confirm that GDP is more strongly correlated with emissions in Karaganda (β = 0.45) than in Kyzylorda (β = 0.21), while industrial output is not a primary environmental driver in Kyzylorda given its agricultural orientation.

4. 3. COMPARATIVE REGRESSION ANALYSIS: KARAGANDA VS. KYZYLORDA

A regression analysis was performed to quantify the impact of economic and environmental indicators on sustainability outcomes.

Table 9. Regression results: economic and environmental indicators

Variable	Karaganda (β)	Standard Error	t-value	p-value	Kyzylorda (β)	Standard Error	t-value	p-value
GDP	0.42	0.09	4.67	< 0.001	0.24	0.08	3.52	< 0.001
CO_2 Emissions	-0.29	0.08	-3.63	< 0.001	-0.12	0.06	-2.89	0.004
Land Degradation	-0	0.06	-3.00	0.003	-0.31	0.07	-4.79	< 0.001
Water Use	0.35	0.10	3.50	< 0.001	0.56	0.12	6.41	< 0.001

Source: Authors' own development

GDP's impact on environmental degradation is more substantial in Karaganda than in Kyzylorda due to industrial CO_2 emissions. Water use has a much more significant impact on land degradation in Kyzylorda (β = 0.56) compared to Karaganda (β = 0.35). Land degradation significantly affects social metrics (e.g., migration, HDI) in Kyzylorda, making sustainable water management a critical policy priority. *Together, the regression and SEM results converge on the same message: industrial decarbonization is pivotal for Karaganda, whereas water-land system reform is pivotal for Kyzylorda. A single national policy would mask these differences; region-specific interventions are required.*

5. DISCUSSION

One of the most critical problems resource-based economies face is how to make regional growth last. Sustainability has three parts: the economy, the environment, and society. An area in Kazakhstan called Karaganda has seen much industrial growth due to the mining and metalworking businesses. This study used Structural Equation Modelling (SEM) to find meaningful connections between economic growth, environmental damage (CO_2 emissions, land degradation, and water use), and social well-being (HDI, population growth). These results show that economic growth is a significant cause of environmental damage and impacts social development. There is a strong link between economic growth and environmental degradation, which means that Karaganda's development makes a big difference in CO_2 emissions and environmental degradation. Karaganda's shift to a low-carbon economy is challenging because the country relies too much on fossil fuels and takes resources out of the ground without using them efficiently. In contrast to Europe and North America, which have green policies and better technologies, Karaganda still puts economic growth ahead of environmental protection. Overuse and polluting water are also problems for the region's long-term health. Uncontrolled industrial discharge undermines water quality, public health, biodiversity, and agricultural productivity

(Wezel et al., 2020). The findings demonstrate that environmental degradation significantly affects social well-being, confirming that pollution and ecological stress are barriers to human development and public health. The SEM results reveal a strong negative relationship between CO_2 emissions and HDI, indicating that higher pollution levels are directly associated with reduced living standards, lower life expectancy, and diminished quality of life. In Karaganda's heavily industrialized context, pollution-related illnesses such as respiratory and cardiovascular diseases are more prevalent. Similarly, the negative association between land degradation and population growth (Barauskaite & Streimikiene, 2021) highlights the demographic consequences of ecological stress. Industrial competitiveness and trade dynamics also shape modernization trajectories, with industrial pollution, deforestation, and soil erosion driving rural out-migration (Ladonko et al., 2020). Reduced access to clean water and food further exacerbates these social impacts, underscoring the complex trade-offs between economic, ecological, and social factors. Fedulova et al. (2023) reinforce this argument through a comparative European framework, showing that progress in isolated sustainability indicators (e.g., renewable energy adoption) is insufficient without integrated, multidimensional strategies. Their emphasis on structural economic transformation aligns with the need for region-specific, ecologically grounded models in resource-intensive economies such as Karaganda.

5. 1. TRADE-OFFS BETWEEN ECONOMIC GROWTH AND SUSTAINABILITY

Ecological degradation from economic growth makes life difficult in resource-dependent areas. Karaganda and Kyzylorda have various financial systems but struggle to survive and manage the environment. These trade-offs differ because industry and agriculture use resources differently. Karaganda's GDP and jobs come from mining, metallurgy, and energy. Businesses release CO_2, generate hazardous waste, and pollute the air, harming environmental health. Karaganda's carbon-intensive economy hurts the environment, air quality, and health. Industry has depleted local resources; therefore, the area uses more outside energy. Cotton, rice, oil and gas boost Kyzylorda's economy. CO_2 emissions are not a major environmental concern in Kyzylorda, unlike Karaganda. Overirrigation, deforestation, and desertification cause land erosion and water problems. Farm water overuse has rendered soil saltier and less productive, making agriculture unprofitable and driving rural migration to cities. Groundwater depletion and oil and gas drilling harm the ecology. Although both regions are economically important, unsustainable resource usage threatens the economy's future. Pollution by Karaganda's manufacturers may tighten restrictions, raise business costs, and stagnate the economy. Kyzylorda's land and water deterioration could stop agriculture, harming food security and the economy.

5. 2. COMPARING POLICY NEEDS

Controlling industrial pollution and converting it to energy are important priorities for Karaganda, which relies on heavy industries. Industry waste and CO_2 emissions require comprehensive regulations. This ensures economic growth is environmentally friendly. Environmental regulations: rigorous air quality standards, emission tracking, and pollution fees on polluting businesses to reduce their carbon impact. Investment in greener technologies encourages businesses to employ energy-efficient production, carbon capture, and green energy to reduce pollution. By increasing non-polluting industries like services, digital technology, and tourism, the economy may diversify away from mining and metallurgy. Public-private partnerships should support private sector investment in renewable energy, circular economy, and trash management programs for sustainability. Without aggressive pollution control, Karaganda might face government fines, poor air quality, and long-term damage to public health and economic output. It must switch to renewable energy and sustainable business methods to stay financially stable and reduce environmental damage. Tumalavičius et al. (2020) adds a governance and institutional perspective that enhances our eco-economic assessment by emphasizing the importance of efficiency and risk reduction in public resource management.

5. 3. POLICY INTERVENTIONS FOR KYZYLORDA: WATER CONSERVATION AND IRRIGATION REFORMS

Kyzylorda relies on agriculture and water; hence, water conservation and irrigation are essential. Kyzylorda's water-based economy is vulnerable to climate change and resource loss. Karaganda's main problem is air pollution. From flood to drip and sprinkler irrigation will help the soil retain water and waste less. Progressive water tariffs for farmers will reduce over-irrigation and increase conservation. Fund reforestation, crop rotation, and desalination to reduce soil salt and desertification. Farmers should produce drought-resistant crops instead of cotton and rice. Environmental restrictions should be tightened to prevent fossil fuel groundwater pollution. Kyzylorda may experience land degradation, farming decline, and rural migration without water management changes. Long-term water policies affect food, economic, and environmental security.

5. 3. 1. COMPARISON WITH SIMILAR STUDIES

This study contributes to the growing body of research on the environmental and socio-economic impacts of industrialization in resource-rich economies. Rapid economic growth has been shown to intensify ecological stress through CO_2 emissions, soil degradation, and industrial water consumption (Abbasi et al., 2022; Rehman et al., 2023). In Kazakhstan, the energy sector's reliance on fossil fuels has heightened emissions, while industrial expansion without environmental safeguards has further increased pollution (Shah et al., 2021). Consistent with this evidence, our findings confirm that Karaganda has failed to decouple economic growth from environmental degradation, as also documented by Tokbergenova et al. (2025) in relation to land overuse and deforestation. Prior studies highlight that industrial pollution is the region's most pressing environmental challenge (Baubekova et al., 2021), while mining and metallurgy have generated complex social and economic repercussions. International comparisons reinforce these dynamics: research from Ukraine demonstrates that sustainable governance practices can enhance accountability and resilience (Masyk et al., 2023), and studies on China confirm that unchecked industrialization initially worsens ecological conditions before regulatory action and green technologies improve sustainability (Zhang et al., 2021; Wu et al., 2020). Like China's industrial regions, Karaganda faces intertwined challenges of pollution, land degradation, and population displacement. Complementary work by Zhartybayeva et al. (2022) demonstrates the value of predictive environmental monitoring, showing how ARIMA modeling can assess water pollution risks, a method highly relevant for regions like Kyzylorda, where heavy metal contamination intensifies water stress. Andrade-Navia (2025) shows that hydropower projects generate trade-offs across ecosystems, emissions, and social conflicts, reinforcing the need for integrated eco-economic frameworks. This aligns with our study's emphasis on region-specific sustainability assessments that connect environmental impacts with governance and policy design. Oralbekova et al. (2021) demonstrate how advanced data assimilation algorithms can strengthen real-time air quality monitoring in industrial Karaganda, offering practical tools for identifying environmental risk zones. This complements our eco-economic framework by showing that technological monitoring innovations are critical for linking industrial emissions with policy interventions in resource-dependent regions.

Governance emerges as a critical determinant in shaping outcomes. Evidence from South Asia shows that weak regulatory enforcement and slow clean technology adoption exacerbate pollution in resource-based economies (Khan et al., 2021). Sotnyk et al. (2023) show that residential energy efficiency and renewable energy are central to global decarbonization pathways, with research trends converging on smart grids, IoT, and bioenergy solutions. This reinforces our study's call for Kazakhstan's regions especially Karaganda to adopt clean energy and resource-efficient technologies as part of a broader eco-economic transition. Arabov et al. (2024) emphasize that climate change requires economy-wide reforms, financial regulations, and sector-specific strategies such as water management and climate-smart agriculture. Their findings resonate with our study by underscoring that in regions like Kyzylorda, targeted adaptation in water use and agriculture is indispensable for sustaining livelihoods under escalating climate pressures. Kazakhstan reflects similar governance gaps, with Karaganda's regulatory weaknesses limiting effective environmental protection. By contrast, EU experience underscores how strong institutional frameworks can lower environmental costs while sustaining growth (Halkos & Polemis, 2017). Empirically, this study demonstrates a substantial negative relationship between CO_2 emissions and HDI, a link often neglected in Kazakh research, and finds that land degradation significantly reduces population growth ($\beta = -0.18$), signaling demographic pressures from ecological decline. These results suggest that worsening environmental conditions contribute to out-migration, particularly among younger cohorts, thereby exacerbating social and regional inequalities. The broader implication is that sustainable development requires region-specific eco-economic approaches, a point reinforced by Dykha et al. (2024), who highlight the importance of localized energy security strategies grounded in global best practices.

5. 4. INTERPRETATION OF KEY FINDINGS

Karaganda's economic growth, environmental safety, and social well-being are examined. A high correlation exists between GDP, industrial productivity, and CO_2 emissions. Polluting companies enhance Karaganda's GDP. Most carbon emissions and environmental impact originate from mining, metallurgy, and energy. Nothing shows Karaganda's economy has evolved toward greener manufacturing. This study indicated economic activity depletes water and land. The data suggests industrial efficiency increases resource utilization and environmental issues. Western Europe, North America, and other developed regions have rigorous environmental legislation, carbon levies, and green corporate incentives. Rural deterioration affects Karaganda's economies and populations. Nature's calamities increase Karaganda's wealth gap. Without excellent jobs outside mining, environmental degradation may not drive migration. Government plans encouraging industrial work, and contaminated housing may hinder migration as climate change worsens.

5. 5. POLICY IMPLICATIONS

The study suggests Karaganda needs fast policy adjustments to address sustainability. Karaganda's industrialized economy pollutes and uses resources, affecting people and the environment. Green energy, carbon capture, and low-energy technology companies should receive subsidies, tax breaks, and low-interest loans. Promoting solar, wind, and hydropower may reduce fossil fuel use and CO_2 emissions and create clean energy jobs. Carbon prices and strict emission limits will push businesses to use greener technologies and minimize pollution. Stress reduction via diversification preserves the planet and economy. Sustainability policies demand acceptable environmental control. Lax environmental enforcement let Karaganda's industry pollute without consequences. Health issues and air, water, and land pollution have increased. Better environmental control simplifies business monitoring and sustainability compliance. Green energy, wastewater treatment, and reforestation save the earth and create jobs. This study found that environmental degradation hampers population growth and health. School, college, and town environmental literacy programs should address climate change, pollution, and resource management. Karaganda wants sustainable growth via educating the future generation. Re-skilling and upskilling Karaganda's workers will promote mobility, the economy, and green jobs.

5. 6. LIMITATIONS OF THE STUDY

This study has limitations despite its contributions. Official numbers in the study may be biased. Research should use original data like surveys and field measurements. The study uses single-period data. A longitudinal method would reveal sustainability trends over time. The findings are Karaganda-specific and may not apply to other industrial zones. Future research should compare multiple fields. SEM may simplify non-linear ecological dynamics by assuming linear interactions. Future studies should include system dynamics and machine learning modelling methods. Karaganda and other resource-dependent places can promote economic growth, environmental protection, and social improvement by examining sustainability from all sides. Kazakhstan may align its development ambitions with global sustainability goals to preserve its natural and human capital and secure long-term prosperity.

5. 7. FUTURE RESEARCH DIRECTIONS

This Karaganda sustainability study needs more research. A longitudinal study of sustainability indicators would explain economic, environmental, and social changes. The study could observe these links evolve. Similar experiments could find long-term pollution reductions or life and work gains. It would also show that this integrated method can be used elsewhere and provide us new ideas by comparing them. Farming and tourism may require different sustainability policies. Comparative study can identify the best practices. Third, future studies should evaluate how new technology and organizational stability affect sustainability. Emerging economies like Kazakhstan could benefit from new technologies and management. Filling these research gaps will help us understand sustainability and design policies that protect health, the environment, and economic growth.

6. CONCLUSION

This study has demonstrated that ecological–economic trade-offs in Kazakhstan manifest differently across industrial and agricultural regions, underscoring the need for regionally differentiated sustainability strategies. In Karaganda, heavy industry contributes nearly 10% of national GDP but is also a primary source of CO_2 emissions (≈1.1 million tons/year on average) and air pollution, which are statistically associated with lower human development outcomes. In Kyzylorda, agriculture and energy extraction contribute around 5% of GDP, yet excessive irrigation (≈8.6 million m^3/year) and soil salinization drive land degradation rates exceeding 25%, which in turn correlate negatively with population growth, reflecting demographic stress and out-migration. These findings confirm that growth without safeguards erodes social resilience through indirect pathways: emissions lower life expectancy and quality of life in Karaganda, while water mismanagement undermines food security and rural livelihoods in Kyzylorda.

Policy implications follow directly from these empirical results. In Karaganda, the priority is controlling industrial emissions through targeted interventions: adoption of cleaner metallurgical and mining technologies, carbon capture and storage in high-emitting plants, expansion of renewable energy sources (solar and wind) to reduce reliance on coal, and stricter enforcement of emission standards. Economic diversification into clean technology, digital services, and circular economy industries should be accompanied by worker retraining programs for miners and metalworkers, ensuring that ecological gains do not translate into social dislocation. Incentives such as carbon pricing and green tax credits can accelerate private sector adoption of resource-efficient production methods.

In Kyzylorda, where water use is the critical driver of ecological decline, irrigation reform is central. Precision and drip irrigation, alongside crop rotation and a shift toward drought-tolerant varieties, can substantially reduce water consumption while sustaining agricultural productivity. Stricter regulation of groundwater extraction, combined with monitoring of oil and gas activities, is necessary to protect aquifers and soils from further contamination. Pilot programs for sustainable farming integrating controlled irrigation and land restoration—can serve as scalable models for rural resilience. These interventions must be accompanied by national-level support, including subsidies for water-saving technologies and alignment with Kazakhstan's commitments to SDG 13 (Climate Action) and SDG 8 (Decent Work and Economic Growth).

More broadly, the results highlight that sustainability planning in Kazakhstan requires both decentralization and coordination. Regional governments must design policies responsive to local ecological stressors, while national authorities provide the regulatory and financial frameworks to ensure consistency with climate and development targets. Future research should focus on modeling long-term climate risks and migration pressures, as well as testing the effectiveness of targeted interventions such as emission controls in Karaganda and irrigation efficiency measures in Kyzylorda. By integrating empirical evidence into policy design, Kazakhstan can move closer to a balanced pathway where economic growth, environmental stewardship, and social well-being reinforce rather than undermine one another.

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