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Economic Growth and Environmental Pressure in Kazakhstan: Social Implications

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ABSTRACT

In the context of increasing environmental pressures and waste volumes, there is a growing need to assess the relationship between economic growth and environmental performance indicators. The purpose of the study is to assess the relationship between Kazakhstan's economic growth and indicators of waste generation and recycling, energy consumption, energy intensity, and energy productivity. The study's information base consisted of official statistical data from the Republic of Kazakhstan for 2015-2024. The research employs normalization, gray relational analysis, and multiple regression analysis. According to the results of the gray relational analysis, the highest coefficients of correlation with GDP dynamics were established for the specific volume of municipal waste per unit of GDP (0.717), the volume of hazardous waste (0.714) and the volume of industrial waste (0.707), which indicates that the changes in these indicators most closely coincided with the direction and nature of the change in GDP in the studied period. The volume of hazardous waste has statistically significant negative relationship with GDP (B = -0.645; p = 0.012), while the association of industrial waste with GDP has not been statistically confirmed (B = -0.033; p = 0.827). The results show that Kazakhstan's economic growth was more closely related to an increase in waste volumes, especially hazardous waste, than to the development of recycling and increased energy efficiency. The findings substantiate the need to develop recycling infrastructure, strengthen control over hazardous waste, and transition to a more resource-efficient model of economic growth.

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Қазақстандағы экономикалық өсу және экологиялық жүктеме: әлеуметтік салдарлар

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ТҮЙІН

Экологиялық жүктеменің күшеюі және қалдықтар көлемінің өсуі жағдайында экономикалық өсу мен экологиялық тиімділік көрсеткіштері арасындағы өзара байланысты бағалау қажеттілігі артады. Зерттеудің мақсаты Қазақстанның экономикалық өсуі мен қалдықтардың түзілуі және қайта өңделуі, энергия тұтыну, энергия сыйымдылығы және энергетикалық өнімділік көрсеткіштері арасындағы өзара байланысты бағалау болып табылады. Зерттеудің ақпараттық базасын Қазақстан Республикасының 2015–2024 жылдардағы ресми статистикалық деректері құрады. Зерттеуде нормализация, реляциялық талдау және көптік регрессиялық талдау әдістері қолданылды. Сұр реляциялық талдау нәтижелері бойынша ЖІӨ динамикасымен байланыстың ең жоғары коэффициенттері ЖІӨ бірлігіне шаққандағы коммуналдық қалдықтардың үлестік көлемі (0.717), қауіпті қалдықтардың көлемі (0.714) және өнеркәсіптік қалдықтардың көлемі (0.707) үшін белгіленген, бұл көрсетілген көрсеткіштердің өзгерістері зерттеудегі ЖІӨ өзгерісінің бағыты мен сипатына барынша сәйкес келетіндігін көрсетеді кезең. Қауіпті қалдықтар көлемінің ЖІӨ-мен статистикалық тұрғыдан маңызды теріс байланысы бар (B = −0.645; p = 0.012), ал өнеркәсіптік қалдықтардың ЖІӨ-мен байланысы статистикалық тұрғыдан расталмады (B = −0.033; p = 0.827). Алынған нәтижелер Қазақстанның экономикалық өсуі қайта өңдеуді дамыту және энергия тиімділігін арттырумен салыстырғанда қалдықтар көлемінің, әсіресе қауіпті қалдықтардың көбеюімен тығыз байланысты болғанын көрсетеді. Қорытындылар қайта өңдеу инфрақұрылымын дамыту, қауіпті қалдықтарды бақылауды күшейту және экономикалық өсудің неғұрлым ресурстық тиімді моделіне көшу қажеттілігін негіздейді.

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Экономический рост и экологическая нагрузка в Казахстане: социальные последствия

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АННОТАЦИЯ

В условиях усиления экологической нагрузки и роста объемов отходов возрастает необходимость оценки взаимосвязи между экономическим ростом и показателями экологической эффективности. Цель исследования заключается в оценке взаимосвязи между экономическим ростом Казахстана и показателями образования и переработки отходов, потребления энергии, энергоёмкости и энергетической продуктивности. Информационную базу исследования составили официальные статистические данные Республики Казахстан за 2015–2024 гг. В исследовании применены методы нормализации, серого реляционного анализа и множественного регрессионного анализа. По результатам серого реляционного анализа наиболее высокие коэффициенты связи с динамикой ВВП установлены для удельного объёма коммунальных отходов на единицу ВВП (0,717), объёма опасных отходов (0,714) и объёма промышленных отходов (0,707), что свидетельствует о том, что изменения указанных показателей в наибольшей степени совпадали с направлением и характером изменения ВВП в исследуемом периоде. Объём опасных отходов имеет статистически значимую отрицательную связь с ВВП (B = −0,645; p = 0,012), тогда как связь промышленных отходов с ВВП статистически не подтверждена (B = −0,033; p = 0,827). Полученные результаты свидетельствуют о том, что экономический рост Казахстана был теснее связан с увеличением объёмов отходов, особенно опасных, чем с развитием переработки и повышением энергоэффективности. Выводы обосновывают необходимость развития инфраструктуры переработки, усиления контроля за опасными отходами и перехода к более ресурсоэффективной модели экономического роста.

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1. Introduction

In recent years, the importance of developing and implementing green economy principles has increased, including expanding low-carbon energy sources and improving resource efficiency (Zhironkin & Cehlár, 2022). Higher resources and energy efficiency generate economic returns, reduce costs, and support the development of recycling, renewable energy, and environmental technologies. In contrast, economic growth depends on how efficiently resources are used rather than on their volume. This requires a shift to development models that combine economic growth with environmental sustainability and rational resource use, as traditional models based on intensive consumption become less effective amid global instability and resource depletion (Trushkina, 2022).

The relevance of this topic for Kazakhstan stems from the combination of the economy's resource dependence and the need to transition to a sustainable development model. Given the high share of fossil fuels in the economy, there is a need to change resource-use approaches, reduce emissions, and improve energy efficiency. The transition to a green economy is seen as a key means of ensuring long-term economic growth and improving the quality of life for the population (Diyar et al., 2014).

Reliance on intensive consumption of natural resources, fossil fuels, and energy-intensive industries affect environmental sustainability and the population's living conditions. Environmental pollution, waste accumulation, and natural resource depletion pose additional risks to public health and the quality of the urban environment, making the transition to a green economy a global challenge in modern development. Kazakhstan continues to face the need for structural transformation of the energy sector and a reduction in dependence on coal, oil, and gas. The development of energy-efficient technologies and renewable energy sources is important for reducing resource pressure and improving environmental conditions in populated and industrial areas. High energy consumption levels contribute to environmental burdens in regions with concentrated economic activity (Imangali & Bekturganova, 2024).

Institutional and infrastructural factors, including the need for stronger government regulation, investment, and personnel training, constrain the development of a green economy in Kazakhstan. Thus, there is a need to assess the relationship between economic growth, resource use, energy efficiency, and environmental burden in the context of Kazakhstan's economic transformation towards sustainable development (Zhandar et al., 2025).

Despite the growing number of studies on green growth, decarbonization, and energy transition in Kazakhstan, empirical evidence on the joint relationship of economic growth with waste generation and recycling, as well as energy efficiency, remains limited. Previous studies have mainly considered individual environmental or energy indicators, while the cumulative dynamics of indicators related to waste and energy use have not been sufficiently studied. The present study aims to fill this gap by combining indicators of waste generation and recycling, energy consumption, energy intensity and energy productivity within a single analytical approach.

Sustainable development combines economic growth, environmental sustainability, and social well-being. Resource use, waste generation, and energy efficiency influence not only environmental outcomes but also the quality of the living environment and the long-term sustainability of territorial development. The purpose of the study is to assess the relationship

between Kazakhstan's economic growth and indicators of waste generation and recycling, energy consumption, energy intensity, and energy productivity.

2. Literature review

The green approach examines the economy in terms of the use of natural resources, the generation of waste, and its subsequent recycling or reduction, allowing for an assessment of its impact on the environment and quality of life. Costanza et al. (2014) demonstrated that economic activity is directly linked to the health of ecosystems, as they form part of the value created, and pollution and waste accumulation are accompanied by a decrease in this value due to the deterioration of natural capital. Moreover, the authors found that countries with intensive land-use change, including developing economies in Asia and Latin America, experience a significant decline in the value of natural resources and environmental functions. Fritz and Koch (2014) link resource use and waste generation to constraints on economic growth and living standards, where the priority shifts to reducing pressure on resources. The authors conducted an assessment across 38 countries and showed that high levels of well-being are achieved with lower resource intensity and lower environmental burdens. Thus, the social effect of the green approach is reflected in improved quality of life, better environmental conditions, and the preservation of long-term well-being.

On the other hand, countries with rapid economic growth experience rising waste and environmental pressures. In this regard, resource use, energy consumption, and waste volumes serve as indicators of the performance of the green economy, and their quantitative assessment is provided through energy intensity, carbon productivity, waste volumes, and the level of their recycling (Loiseau et al., 2016; Zvarych et al., 2022). Thus, EU countries are characterized by higher resource productivity: a larger volume of GDP is generated with less resource use and a smaller increase in waste, with a significant portion of waste returned for recycling and reuse. In Ukraine, GDP growth is accompanied by faster increases in waste volumes and a low recycling rate. At the same time, resource productivity remains low, thereby increasing the resource burden per unit of economic output. Resources, waste, and recycling are considered key areas of development for the transition to a more sustainable economy (Ospanova et al., 2022). Thus, the implementation of a green economy depends on national priorities, with differences in the share of renewable energy, the level of waste recycling, and the degree of resource efficiency, all of which contribute to varying speeds of transition to a sustainable development model. Thus, international experience shows that the impact of economic growth largely depends on resource efficiency and waste recycling. Higher recycling and resource productivity rates are associated with lower environmental impacts. As a result, resource efficiency and recycling development impact not only the environment but also the long-term quality of life (Arion et al., 2023).

Improving resource efficiency, developing recycling, and introducing energy-efficient technologies support GDP growth by reducing material intensity and environmental impact. Resource efficiency, waste recycling, and energy efficiency directly impact GDP growth and its structure. Valero et al. (2015) found that conclusions about economic efficiency vary depending on the set of indicators used. When using the traditional GDP/DMC indicator based on resource volumes, abundant, cheap materials such as limestone exert a strong influence, creating the perception of higher economic efficiency. Indicators that account for energy intensity and resource scarcity change assessment structure: fuel and scarce materials become the key drivers, and the economic burden is estimated to be higher. Using Spain as an example, the same level of GDP yields

different efficiency estimates depending on whether only resource volumes or their energy and economic significance are considered, with recycling and reducing the use of energy-intensive resources proving critical to improving economic efficiency. Birat (2015) showed that recycling materials reduces production costs and increases economic returns. Thus, due to the use of fewer primary resources, GDP growth may be improving. Cerqueira et al. (2021) found that the estimated relationship between environmental factors and GDP varies across indicators. When considering GDP growth alone, the dependence on increased resource consumption remains. Recycling and renewable energy reduce environmental impact and increase GDP. OECD countries ensure lower resource dependence of GDP through a high share of recycling and renewable energy. Low levels of recycling and energy efficiency lead to a greater resource burden. However, the impact of waste recycling and energy efficiency on the economy varies (Guoyan et al., 2022). Waste recycling reduces the need for primary raw materials. Energy efficiency reduces resource consumption in production. Renewable energy helps reduce the economy's dependence on traditional resources. It is not just GDP growth that matters, but also the amount of resources required to achieve it. The higher the waste recycling and resource efficiency, the fewer resources are required to produce the same amount of economic output (Garg et al., 2025).

Analysing the relationships among environmental, energy, and economic parameters requires tools capable of handling heterogeneous indicators and limited time series. Grey Relational Analysis is used to assess the degree of consistency between the dynamics of various indicators and to identify their relative importance in shaping economic outcomes. This approach is particularly characteristic of studies that use gross domestic product as a benchmark, with environmental and resource indicators considered as determinants of its dynamics. Kose et al. (2013) analysed which types of energy consumption shape economic growth. They found that energy consumption dynamics are directly related to GDP dynamics, with certain energy types exhibiting stronger correlations with economic growth. Koçak (2020) examined the factors that determine green growth in OECD countries and ranked environmental and resource indicators to identify those most closely related to economic development dynamics; this analysis led to CO_2 emissions and environmental technologies being identified as key drivers. Alshuwaikhat et al. (2023) assessed environmental sustainability and identified the contribution of energy, technology, and environmental factors to emission-reduction targets. Banjerdpaiboon and Limleamthong (2023) analyzed cross-country differences in levels of circular economy and found that recycling and resource productivity indicators explain differences in economic performance and sustainability. All studies construct their analysis by comparing indicators with GDP dynamics, which serve as the dependent variable, using time series of limited length, typically around 10 years. Such assessments are important for identifying environmental factors that may influence the sustainability of territorial development and environmental conditions in areas with concentrated economic activity.

The approaches discussed demonstrate that assessing the relationship between environmental indicators and economic growth depends on the choice of indicators and analytical methods. Existing studies state differences in results when changing the set of indicators and consistently compare environmental factors with GDP dynamics. Studies on countries with transition economies, including Kazakhstan, also note that the structure of economic growth remains linked to resource use, energy intensity, and the level of processing, with individual indicators demonstrating varying degrees of influence on economic performance.

Under these conditions, a quantitative comparison of environmental and economic indicators is needed to determine their relative importance for economic growth. Using methods based on comparing indicator dynamics allows identifying which indicators correlate most closely with GDP and serve as the basis for economic dynamics.

3. Research methods

Based on the literature review, indicators reflecting environmental pressure, recycling performance, and energy efficiency were selected. The data was obtained from official resources and covered the period from 2015 to 2024.

Table 1 presents the selected variables and their corresponding codes used for further analysis.

Table 1. Selected indicators for grey relational analysis for 2015-2024.

Indicator	Unit of measurement	Code
GDP (PPP, constant 2021 prices)	million international dollars	X0
Industrial waste generation	thousand tons	X1
Hazardous waste generation	thousand tons	X2
Municipal solid waste generation	thousand tons	X3
Municipal waste per GDP	kg per 1000 international dollars (2021 prices)	X4
Recycling rate of industrial waste	percent	X5
Recycling rate of municipal waste	percent	X6
Primary energy consumption	million tons of oil equivalent	X7
Energy intensity of GDP	toe per thousand USD (2015 prices)	X8
Energy productivity	USD per toe (2005 prices)	X9

Note: compiled by authors based on data from the Bureau of National Statistics (2025).

The X4 indicator (municipal waste per GDP) was included in the analysis as an indicator of the waste burden per unit of economic output. This indicator characterises the volume of municipal waste per unit of GDP and is used to assess the intensity of waste generation in economic activity. Because the indicator incorporates GDP into its calculation structure, the interpretation of the results is based on an assessment of the relationship between economic growth and the waste burden. Therefore, the results for X4 are interpreted as reflecting the waste burden relative to economic output rather than as a separate measure independent of GDP.

To identify the relationship between economic growth and selected indicators, the Grey Relational Analysis method was applied. The strength of association between variables was evaluated under conditions of limited and heterogeneous data by measuring the similarity of their dynamic patterns.

At the first stage, all variables were normalized using the min–max method. The normalization for indicators with a positive effect was performed based on formula (1):

$$x' = \frac{x - min}{max - min} \qquad (1)$$

where:

x' – normalized value of the indicator;

x – actual value of the indicator;

min – minimum value of the indicator in the study period;

max – maximum value of the indicator in the study period.

For indicators with a negative effect, normalization was carried out according to formula (2):

$$x' = \frac{max - x}{max - min} \qquad (2)$$

where:

x' – normalized value of the indicator;
x – actual value of the indicator;
min – minimum value of the indicator in the study period;
max – maximum value of the indicator in the study period.

Next, the absolute deviations between the reference sequence and comparative sequences were calculated based on formula (3):

$$\Delta = |X_o - X_i| \qquad (3)$$

where:

Δ – absolute deviation between the reference and comparative sequences;
X_o – reference sequence (GDP);
X_i – comparative sequence for indicator *i*.

Next, grey relational coefficients were calculated using formula (4):

$$\gamma = \frac{\Delta_{min} + 0{,}5 \times \Delta_{max}}{\Delta + 0{,}5 \times \Delta_{max}} \quad (4)$$

where:

γ – Grey relational coefficient;
Δ – absolute deviation between the reference and comparative sequences;
Δ_{min} – minimum deviation observed among all observations;
Δ_{max} – maximum deviation observed among all observations;
0.5 – distinguishing coefficient used in Grey Relational Analysis.

Then, the average Grey relational coefficient for each indicator was calculated based on formula (5):

$$\bar{\gamma} = \frac{1}{n} \sum \gamma \qquad (5)$$

where:

$\bar{\gamma}$ – average Grey relational coefficient;
γ – Grey relational coefficient for each observation;
n – number of observations.

Providing average values enabled the ranking of factors by their degree of association with economic growth. To validate the robustness of the obtained results, a regression analysis was conducted. The regression model is specified as follows (6):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon \qquad (6)$$

where:

Y – GDP;
β_0 – intercept;
$\beta_1 \ldots \beta_n$ – regression coefficients;
$X_1 \ldots X_n$ – explanatory variables selected based on Grey relational ranking;
ε– random error term.

To complement the grey relational analysis, multiple linear regression analysis was conducted to assess the statistical significance and direction of the relationships between GDP and selected indicators. Given that the dataset contains ten annual observations, the regression results were interpreted as exploratory associations rather than evidence of causal effects..

4. Results

The results revealed the general structure of relationships among selected indicators and the dynamics of their interaction over time, from 2015 to 2024.

At the first stage, the normalized values obtained using the min–max method were analyzed, where "0" corresponds to the lowest relative position of an indicator over the observed period, while "1" corresponds to its highest relative level. The normalised indicators were grouped into two categories according to their economic interpretation. The first group includes indicators with a negative effect, where higher initial values correspond to greater environmental pressure. The second group consists of indicators with a positive effect, in which higher values indicate improved efficiency or sustainability.

Table 2 presents the normalised values for indicators with a negative effect.

Table 2. Normalised values of indicators with negative impact (min–max transformation).

Indicator	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
X1	0	0,574	0,742	0,460	0,432	0,674	0,337	0,285	0,195	1
X2	0	0,478	0,595	0,485	0,339	0,543	1	0,979	0,992	1
X3	0	0,053	0,481	0,916	0,583	0,731	1	0,899	0,890	0,493
X4	0	0,056	0,417	0,750	0,667	0,694	0,917	0,917	1,000	0,889
X6	1	0,967	0,701	0,598	0,456	0,282	0,104	0,021	0,091	0
X7	1	0,525	0,472	0,007	0,062	0,418	0,288	0,207	0,004	0

Note: compiled by the authors.

In 2015, the waste generation indicators X1–X4 recorded their lowest normalised values, equal or close to zero, whereas the municipal waste recycling indicator (X6) and primary energy consumption indicator (X7) had normalised values of 1.000. These values reflect the relative positions of the indicators at the beginning of the study period. Since different normalisation directions were applied, the results should be interpreted in terms of relative dynamics rather than absolute maxima or minima.

The waste generation indicators X1–X4 generally increased over the study period, although their dynamics differed. Hazardous waste generation (X2) reached its maximum normalised value of 1.000 in 2021, remained close to this level in 2022 and 2023, with values of 0.979 and 0.992, respectively, and returned to 1.000 in 2024. Industrial waste generation (X1) increased to 0.742 in 2017 and amounted to 0.674 in 2020. It subsequently declined to 0.337 in 2021, 0.285 in 2022, and 0.195 in 2023, before rising sharply to its maximum normalised value of 1.000 in 2024. These dynamics indicate considerable fluctuations in industrial waste generation and persistently high relative levels of hazardous waste toward the end of the study period.

Municipal waste generation (X3) demonstrated less stable dynamics. Its normalised value reached a maximum of 1.000 in 2021 and subsequently decreased to 0.899 in 2022, 0.890 in 2023, and 0.493 in 2024. The municipal waste intensity indicator (X4) reached 0.917 in both 2021 and 2022, increased to its maximum value of 1.000 in 2023, and then declined slightly to 0.889 in 2024.

The normalised values of municipal waste recycling (X6) and primary energy consumption (X7) declined from 1.000 in 2015 to 0.000 in 2024. However, these indicators represent different

dimensions and should therefore be interpreted separately. Overall, the dynamics reveal an increase in several waste generation indicators alongside a weaker relative position of municipal waste recycling. This pattern may indicate a growing imbalance between waste generation and recycling performance.

Table 3 presents the normalised values for indicators with a positive effect.

Table 3. Normalised values of indicators with positive impact (min–max transformation).

Indicator	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
X5	1	0,79	0,55	0,48	0,51	0,26	0,14	0	0,59	0,80
X8	0	0,67	0,56	1	0,70	0,36	0,33	0,29	0,30	0,10
X9	1	0,29	0,40	0	0,26	0,60	0,63	0,67	0,64	0,88

Note: compiled by the authors.

The normalised value of the industrial waste recycling rate (X5) decreased from 1.000 in 2015 to its minimum value of 0.000 in 2022. It subsequently increased to 0.590 in 2023 and 0.800 in 2024. These dynamics indicate a deterioration in the relative position of industrial waste recycling until 2022, followed by a noticeable recovery during 2023–2024.

The normalised value of GDP energy intensity (X8) increased from 0.000 in 2015 to its maximum value of 1.000 in 2018. After 2018, it generally declined and reached 0.100 in 2024. This decline indicates that less energy was required to generate a unit of GDP toward the end of the study period, reflecting an improvement in energy-use efficiency. The normalised value of energy productivity (X9) reached 1.000 in 2015 and declined to its minimum value of 0.000 in 2018. It subsequently increased from 0.260 in 2019 to 0.670 in 2022, decreased slightly to 0.640 in 2023, and rose to 0.880 in 2024. Thus, despite some fluctuations, energy productivity demonstrated an overall recovery after 2018. In 2024, the economy generated more economic output per unit of energy consumed than in 2018.

The observed increase in several waste-generation indicators, combined with the relatively weak performance of waste recycling during part of the study period, may place additional pressure on the waste management system. In the long term, such dynamics may create risks for urban development, efficient land use, environmental safety, and favourable living conditions for the population.

Table 4 presents the absolute deviations between the normalised reference sequence representing GDP and the comparative sequences representing the selected environmental and energy indicators.

Table 4. Absolute deviations between GDP and selected indicators.

Indicator	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
X1	0,000	0,540	0,580	0,165	0,016	0,314	0,171	0,338	0,618	0,000
X2	0,000	0,444	0,433	0,189	0,109	0,183	0,492	0,356	0,179	0,015
X3	0,000	0,019	0,319	0,621	0,135	0,371	0,492	0,276	0,077	0,507
X4	0,000	0,022	0,254	0,454	0,219	0,335	0,409	0,294	0,187	0,111
X6	1,000	0,933	0,539	0,302	0,008	0,077	0,404	0,602	0,721	1,000
X7	1,000	0,491	0,310	0,289	0,386	0,058	0,220	0,416	0,808	1,000
X5	1,000	0,756	0,393	0,188	0,061	0,097	0,372	0,623	0,225	0,205
X8	0,000	0,637	0,395	0,704	0,252	0,002	0,179	0,337	0,513	0,900
X9	1,000	0,257	0,240	0,296	0,191	0,244	0,118	0,046	0,170	0,120

Note: compiled by the authors.

For industrial waste generation (X1), the deviations are 0 in 2015 and 2024, and amount to 0.016 in 2019, while in 2016–2017 they range from 0.540 to 0.580, indicating an alternation between periods of convergence and divergence. For hazardous waste generation (X2), deviations mostly do not exceed 0.500, decreasing to 0.015 in 2024. For MSW generation (X3), values change unevenly: a sharp increase in the deviation to 0.621 in 2018 and 0.492 in 2021 is followed by a decrease to 0.077 in 2023. For municipal solid waste per unit of GDP (X4), values are mainly concentrated in the 0.187–0.409 range, with a minimum of 0.022 in 2016. Compared with X3, the deviations for X4 vary within a narrower range and exceed 0.400 only in 2021. In terms of the share of solid waste recycling (X6), the values over several years range from 0.933 to 1.000, while in 2019 a practically zero deviation of 0.008 was recorded, indicating alternating between very low and very high deviation values. For energy consumption (X7), the deviations are also equal to 1.000 in 2015 and 2024, with a minimum of 0.058 in 2020 and a range of 0.220–0.491 in 2016–2023. For the share of industrial waste recycling (X5), the values range from 1.000 in 2015 to 0.061 in 2019, then increase to 0.623 in 2022, and decrease to 0.205 in 2024, with the lowest values of 0.188-0.097 in 2018–2020. For the energy intensity of GDP (X8), values range from 0 in 2015 to 0.704 in 2018, with a minimum deviation of 0.002 in 2020, and are 0.179–0.513 in 2021–2023. For energy productivity (X9), deviations range from 0.118 to 0.296, with a 2015 value of 1.000 and a 2022 minimum of 0.046. Lower deviation values for X9 are observed in most years after 2018..

Next, the grey coefficients showed the degree of proximity between indicator dynamics and GDP (see Table 5).

Table 5. Grey relational coefficients between GDP and selected indicators.

Indicator	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
X1	1	0,481	0,463	0,752	0,969	0,614	0,745	0,597	0,447	1
X2	1	0,530	0,536	0,725	0,821	0,732	0,504	0,584	0,736	0,972
X3	1	0,963	0,611	0,446	0,787	0,574	0,504	0,644	0,866	0,497
X4	1	0,959	0,663	0,524	0,696	0,599	0,550	0,630	0,727	0,818
X6	0,333	0,349	0,481	0,623	0,983	0,866	0,553	0,454	0,409	0,333
X7	0,333	0,504	0,617	0,634	0,565	0,896	0,694	0,546	0,382	0,333
X5	0,333	0,398	0,560	0,727	0,892	0,838	0,574	0,445	0,689	0,709
X8	1	0,440	0,559	0,415	0,665	0,995	0,736	0,597	0,494	0,357
X9	0,333	0,660	0,675	0,628	0,724	0,672	0,808	0,917	0,746	0,806

Note: compiled by the authors.

Positive indicators (X5, X8, X9) reflect processes generally considered favourable within the framework of sustainable development. Industrial waste recycling reduces waste accumulation and enables more efficient use of resources. Reduced energy intensity and increased energy productivity are associated with more efficient energy use, enabling greater economic returns with lower resource expenditure. For indicators with a positive effect, higher Grey coefficient values indicate a closer relationship between economic growth and processes that promote resource efficiency, waste recycling, and increased energy productivity. From a social perspective, such dynamics are associated with more efficient use of resources and the creation of conditions for sustainable territorial development.

Negative indicators (X1, X2, X3, X4, X6, X7) characterise processes related to waste generation, environmental impact, and resource consumption. Growing volumes of industrial, hazardous, and municipal waste increase the need for their collection, transportation, processing, and disposal.

Insufficient infrastructure increases the burden on urban areas and waste management systems. For indicators with a negative impact, higher grey coefficient values indicate a closer relationship between economic growth and increased waste volumes, environmental burden, and resource consumption. From a social perspective, these dynamics increase demands on waste management systems, urban infrastructure, and measures to ensure environmental safety for the population.

For indicators with positive effects (X5, X8, X9), a stronger correlation with GDP is observed compared to the beginning of the period. The most pronounced increase in coefficients was observed for industrial waste processing (X5) and energy productivity (X9). The X5 coefficient increased from 0.333 in 2015 to 0.892 in 2019 and remained at 0.689–0.709 in 2023–2024. For X9, the value increased from 0.333 in 2015 to 0.917 in 2022 and remained at 0.746–0.806 in 2023–2024. For the energy intensity of GDP (X8), the coefficient reached 0.995 in 2020 and decreased to 0.357 in 2024.

For indicators with negative effects (X1, X2, X3, X4, X6, X7), the coefficients exhibit more pronounced fluctuations. The highest values at the end of the period were observed for industrial (X1) and hazardous (X2) waste generation. The X1 coefficient increased from 0.463–0.481 in 2016–2017 to 0.969 in 2019 and reached 1.000 in 2024. For X2, the value was 0.972 in 2024. The coefficients for municipal waste (X3) and waste per unit of GDP (X4) remained above 0.500 during most of the study period. The indicators of municipal solid waste recycling (X6) and energy consumption (X7) varied from 0.333 to 0.983 and from 0.333 to 0.896, respectively.

Figure 1 presents the ranking of the indicators based on the average grey coefficient values, where higher values indicate a greater consistency between the indicator dynamics and GDP.

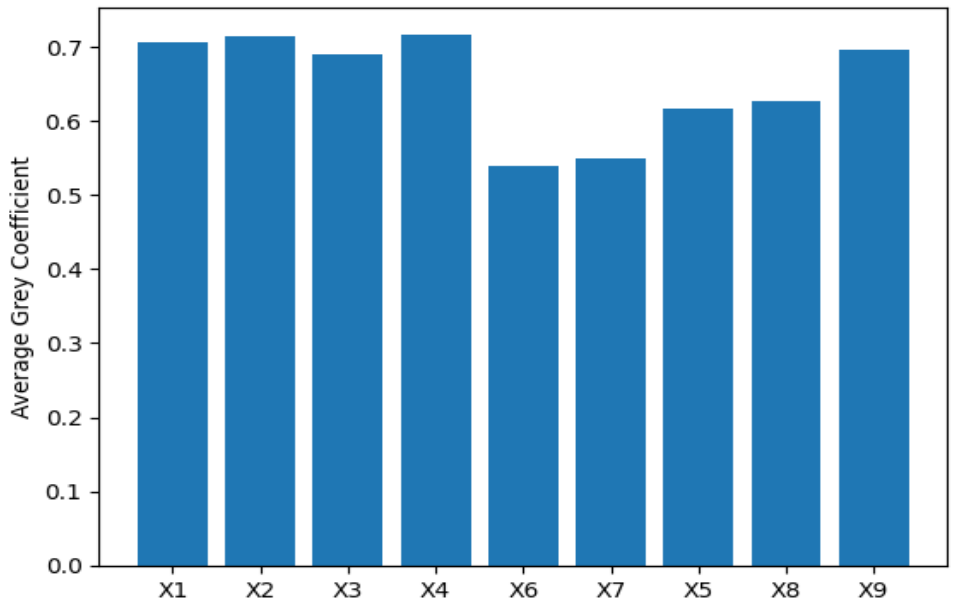


Figure 1. Ranking of indicators based on average grey relational coefficients.

Waste-related indicators occupied four of the five highest positions in the ranking. The highest Grey relational grades were obtained for municipal waste intensity (X4 = 0.717), hazardous waste generation (X2 = 0.714), and industrial waste generation (X1 = 0.707), followed by energy

productivity (X9 = 0.697) and municipal solid waste generation (X3 = 0.689). Lower grades were recorded for GDP energy intensity (X8 = 0.626), industrial waste recycling (X5 = 0.617), primary energy consumption (X7 = 0.550), and municipal waste recycling (X6 = 0.539). These results indicate that GDP dynamics were more closely aligned with the dynamics of waste-related indicators than with recycling and energy-efficiency indicators.

The regression analysis focused on waste-related indicators because the empirical hypotheses concerned different sources of waste pressure. Although X4 had the highest Grey relational grade, it was excluded from the regression analysis because GDP is incorporated into its calculation, which could create a mechanical relationship with the dependent variable. Therefore, municipal solid waste generation (X3), industrial waste generation (X1), and hazardous waste generation (X2) were selected for the regression analysis.

H1: Municipal solid waste generation (X3) is statistically significantly associated with GDP dynamics.

H2: Industrial waste generation (X1) and hazardous waste generation (X2) are statistically significantly associated with GDP dynamics.

Table 6 shows the results of the model estimation and analysis of variance for hypothesis 1.

Table 6. Model summary and ANOVA results for H1 (X4, X3).

Model	R	R^2	Adjusted R^2	RMSE	Sum of Squares	df	Mean Square	F	p
M_0	0.000	0.000	0.000	58741.863					
M_1	0.995	0.990	0.987	6788.346	3.073×10^{10}	2	1.537×10^{10}	333.461	< .001
Residual					3.226×10^{8}	7	4.608×10^{7}		
Total					3.106×10^{10}	9			

Note: compiled by the authors.

The ANOVA results confirmed the model's statistical significance and supported hypothesis 1. The R^2 is 0.990, which means that the selected indicators explain 99.0% of the variation in GDP. The p-value does not exceed the threshold of 0,005.

Table 7 presents the regression coefficients for hypothesis 1.

Table 7. Regression coefficients for H1 (X4, X3).

Variable	Unstandardized	Std. Error	Standardized	t	p	Tolerance	VIF
Intercept	555390.947	31644.166		17.551	< .001		
X4	-88739.549	4197.434	-1.953	-21.141	< .001	0.174	5.751
X3	158.862	12.191	1.204	13.031	< .001	0.174	5.751

Note: compiled by the authors.

The analysis of multicollinearity showed that the VIF is 5.751, within the acceptable limit of 10. The p-values for both indicators are = 0.001 and do not exceed the established significance threshold of 0.05. Therefore, both indicators demonstrate a statistically significant relationship with GDP. Indicator X4 (MSW generation per unit of GDP) has a negative coefficient, indicating the waste burden relative to economic output. Thus, higher waste intensity is associated with lower GDP. Indicator X3 (municipal solid waste generation) has a positive coefficient, indicating that higher waste volumes are associated with GDP growth.

Table 8 shows the ANOVA results for the second model.

Table 8. Model summary and ANOVA results for H2 (X1, X2).

Model	R	R^2	Adjusted R^2	RMSE	Sum of Squares	df	Mean Square	F	p
M_0	0.000	0.000	0.000	58741.863					
M_1	0.801	0.641	0.539	39882.482	1.992×10^{10}	2	9.961×10^{9}	6.262	0.028
Residual					1.113×10^{10}	7	1.591×10^{9}		
Total					3.106×10^{10}	9			

Note: compiled by the authors.

The ANOVA result for the second model confirmed hypothesis 2. The R^2 is 0.641, which means that the selected variables explain 64.1% of the variation in GDP. The p-value does not exceed the alpha level of 0,05 and is equal to 0.028 (within the significance limit).

Table 9 shows the regression coefficients for hypothesis 2.

Table 9. Regression coefficients for H2 (X1, X2).

Variable	Unstandardized	Std. Error	Standardized	t	p	Tolerance	VIF
Intercept	738216.556	115932.776		6.368	< .001		
X1	-0.033	0.144	-0.053	-0.227	0.827	0.927	1.079
X2	-0.645	0.193	-0.785	-3.339	0.012	0.927	1.079

Note: compiled by the authors.

The results for multicollinearity indicators showed that the VIF values for the H2 are within acceptable limits (1.079). The results for indicator X1 showed no statistically significant impact, with a p-value of 0.827. Thus, an increase in industrial waste volume does not have a statistically significant impact on GDP. Indicator X2 showed a statistically significant impact (p-value = 0.012), which is below the significance level of 0.05. Therefore, hypothesis H2 received partial support, as only hazardous waste generation demonstrated a statistically significant relationship with GDP. Indicator X2 (hazardous waste generation) has a negative coefficient, indicating that higher levels of hazardous waste generation are associated with lower GDP values.

5. Conclusions

The study examined the relationship between economic growth and indicators of environmental pressure, including waste generation and energy intensity, and assessed their implications for sustainable territorial development, waste management systems, and environmental conditions affecting society. The results show that indicators of environmental load have the strongest association with economic growth, whereas recycling and resource-efficiency indicators demonstrate weaker relationships. Higher economic output is associated with increasing environmental pressure, while improvements in recycling and efficiency remain limited. The results indicate the persistence of a development pattern in which economic growth is accompanied by increasing resource use and waste generation.

It was found that increases in GDP are accompanied by higher waste volumes and a persistently high burden per unit of output. Thus, economic growth is based on increasing resource consumption without improving efficiency. Reductions in specific burden are not sustained, and hazardous waste management does not lead to sustained reductions. As a result, the waste structure persists, increasing pressure on the economy. Recycling does not align with the actual structure of waste generation and does not offset its growth. Waste management is not structured, limiting the effectiveness of measures. Energy efficiency and productivity indicators do not form a

stable relationship with GDP growth, confirming the lack of a transition to a more efficient growth model.

The implementation of extended producer responsibility is recommended, with specific recycling obligations at all stages of the product life cycle. An increase in the share of waste recycling and energy recovery is needed, along with the simultaneous modernisation of technologies, which will reduce the burden per unit of output. A transition to a payment system based on the actual volume of waste generated at the household and business levels is necessary. Control over hazardous waste management should be strengthened through mandatory sorting, accounting, and recycling, thereby reducing its impact on economic indicators.

Growing volumes of industrial and hazardous waste are increasing the environmental burden in areas with high economic activity. Waste generation is outpacing recycling capacity and improvements in resource efficiency. Insufficient recycling rates lead to waste accumulation and additional pressure on waste management systems. Higher recycling rates, greater resource efficiency, and stronger environmental regulation can reduce pressure on waste management systems and limit further growth in environmental burden..

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