Canonical Correlation Analysis in Information Systems for Assessing Economic Growth and Environmental Security Relationships[⋆]

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Abstract

The study presents a comprehensive exploration of canonical correlation analysis applied within advanced information systems for assessing complex interrelations between economic growth indicators and environmental security factors. Leveraging robust computational methodologies and integrated information systems, this research utilizes canonical correlation analysis to quantitatively evaluate relationships between two sets of multidimensional variables: indicators representing economic well-being—including GDP per capita, gross fixed capital formation, value-added industrial production, and household expenditures—and variables reflecting environmental threats such as carbon dioxide and greenhouse gas emissions, and natural resource depletion. Data sourced from the World Bank for 136 countries for the year 2020 served as the empirical foundation of the study. The employed computational information system facilitated advanced preprocessing and normalization procedures, essential for ensuring analytical accuracy given substantial variability across datasets. Statistical computations were executed within a structured digital environment, leveraging computational efficiency to identify canonical variables demonstrating maximal correlation. Results indicated a significant canonical correlation coefficient ($r = 0.9762$), underscoring the robustness of the identified relationships. Further analytical interpretation using Pearson's pairwise correlation confirmed the validity and significance of these variables within constructed canonical sets. The presented findings reaffirm previous scholarly insights into economic-environmental interdependencies and reinforce the pivotal role of computational analysis supported by sophisticated information systems in elucidating complex socio-economic phenomena. This methodological approach proves indispensable for strategic policy formulation aimed at balancing economic advancement and environmental sustainability, contributing to the broader discourse on achieving sustainable development goals through innovative computational and analytical techniques.

Keywords

canonical correlation analysis, information systems, computational analytics, economic growth indicators, environmental security, data normalization, sustainable development.

1. Introduction

In the context of rapid globalization processes, the internationalization of economies, and the innovative development of production, humanity faces an increasing number of challenges associated with the extensive use of natural resource potential. This leads to its uncontrolled depletion, resulting in significant social stratification within society due to uneven access to resources, a decline in biodiversity, a reduction in the productivity of geoecosystems, and environmental deterioration. These factors disrupt the balance of ecosystems, leading to the emergence of threats to ecological security, which in turn contribute to declines in national health, a decrease in life expectancy, and the exacerbation of social conflicts.

Such disturbances necessitate a shift in the trajectory of modern society's development and the formulation of strategic prospects for global development, thereby creating more favorable conditions for living and reproduction. The solution to this problem is the transition to balanced, sustainable development, which combines the even development of economic, ecological, and

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social aspects of societal development and determines the global priorities for social growth [1]. The implementation of the concept of sustainable development involves the use of a model of economic growth, in which urgent issues of the livelihood of society will be effectively resolved based on the perception of nature and its resources as one of the highest values and the priority of preserving the natural environment will prevail over the criterion of economic efficiency. Such a strategy is based on dynamic balance, which avoids irreversible environmental changes and does not threaten humanity's long-term existence.

The interaction between the economic and ecological components occurs within the environmental and economic system. The economic system formed by humans develops exceptionally quickly and is often a destabilizing factor in the environmental system, disrupting its overall balance. In this regard, there is a pressing need to study the relationship between indicators of economic development and factors that pose threats to environmental safety to identify their causes and consequences and to determine the nature of the interaction between these indicators. The application of a scientific approach and modern analytical tools, including economic and mathematical modeling, to data analysis will contribute to the development of strategic decisions necessary for reducing ecological and economic tension, preventing the catastrophic consequences of the global ecological crisis, and mutually beneficial integration of economic growth and environmental protection.

2. Literature review

Sustainable development should be considered in the context of the interaction between two alternative problems: the preservation of ecosystems and the provision of favorable conditions for the stable economic development of society. The deepening of the climate crisis continues to cause significant economic damage, illustrating the essential relationship between the economy and ecology [2]. However, economic well-being does not always lead to achieving ecological balance. Instead, the reverse effect occurs when an increase in economic development can also lead to a deepening of environmental threats and risks. This indirectly demonstrates the ranking of countries by the value of the Environmental Performance Index, which reflects the effectiveness of struggling ecological pollution and the development of national ecosystems. As of 2022, among the G7 countries, only the United Kingdom ranked among the top ten [3].

Problems related to the interaction between the economy and ecology in the context of achieving sustainable development goals have been explored in the research of a wide range of scientists. One of the dominant research areas in this field is assessing the relationship between agricultural development, GDP growth, and waste generation. Agriculture is a branch of the economy that exerts a significant anthropogenic impact on the environment and utilizes available natural resources to a considerable extent. The use of econometric models is quite common in studying these issues. Using Ukraine's data as an example, Zomchak et al. [4] assessed the relationship between environmental pollution and economic growth. Based on the econometric analysis and the Kuznets ecological curve theory, it was concluded that diversified economic development with a reorientation towards clean production is necessary to prevent environmental and economic disasters. Stadnyk et al. [5] determined the motivational factors of structural changes in Ukraine's agro-industrial sector in the context of sustainable economic development. Koval et al. [6] considered the impact of waste on the ecosystem using the example of garbage being transported to a landfill by minimizing residual production while maximizing profit from the companies' activities. The authors concluded that the practical implementation of the results will contribute to increased production productivity and reduced environmental damage.

Using the example of Pakistan, Sajjad et al. [7] considered applying correlation analysis to assess the relationship between agricultural production, economic growth, and carbon dioxide emissions in both the short-term and long-term perspectives. The results highlight the need to transition to the ecologically clean production of agricultural products to mitigate harmful emissions. Hardy et al. [8] examined the relationships between economic growth, agricultural productivity, gross fixed capital formation, and greenhouse gas emissions, using Indonesia as an example. The results obtained enabled the conclusion that the selected factors have a significant long-term influence on one another. Rahman et al. [9] investigated the relationships between economic growth determinants and the state of the environment. The study was conducted using Bangladesh as an example. CO2 emissions and export concentration were found to be the main impediments to economic growth, while remittances and consumption expenditure were positively correlated. Othman et al. [10] substantiated the use of environmental taxes as an effective mechanism of environmental policy, which contributes to introducing innovations in the economic activity of business units. The authors prove that introducing such a tax has a positive effect only in the short term.

Studies [11–15] have used the Kuznets curve. It made it possible to conclude that the relationships between economic development indicators and environmental indicators are non-linear. The factors harming the environment have been identified. The transition to renewable energy sources has also been shown to have a long-term impact on ecological security, and healthcare spending has been found to contribute to economic growth. The issues of defining strategies for the economic development of business structures in the context of ensuring environmental safety are discussed in articles [16–20]. The authors substantiated the mechanisms of strategy formation, which will also contribute to strengthening environmental safety. Considerable research attention is paid to assessing the relationship between the development of the socio-economic system and the ecological environment system at both the national and regional levels. Such issues are considered in studies [21–30]. The authors employed various economic and mathematical modeling techniques, including multivariate analysis methods, artificial intelligence tools, and complex integral evaluation technologies.

The study results reflect the heterogeneity of environmental security degree for different territories, which is determined by the economic development level, economic specialization, natural and climatic conditions of economic activity, and geographical location of territories. The analysis of the presented studies reveals that various analytical tools are currently employed to investigate the mutual influence of economic and ecological systems. At the same time, reasonably thorough results were obtained, illustrating the presence of close relationships between indicators of economic development and environmental threats. At the same time, it is worth noting that environmental threats are often assessed based on single indicators, particularly the volume of carbon dioxide emissions. Our research aims to determine the degree of correlation between a set of indicators of economic development and a set of indicators that reflect environmental threats.

For this, we used the method of canonical correlations. Studies [31, 32] contain a concise description of the evolution of this method and its variations and a graphical interpretation of the results. This method is successfully applied in socio-economic research when analyzing the relationship between two indicator systems. Article [33] provides an example of the method's application in assessing structural changes in GDP for the most prominent Asian countries, as well as the impact of GDP components on these changes. The study [34] examines the relationship between the components of the Global Competitiveness Index and those of the Environmental Efficiency Index using canonical correlation analysis. The results confirm the conclusion of international institutions, particularly the World Economic Forum, regarding the positive correlation between competitiveness and the environmental component of sustainable development. The article [35] demonstrates the application of the method for evaluating the relationship between employment indicators and economic growth indicators. Despite the research conducted and the results obtained, the potential of canonical analysis for researching relationships between indicators of economic development and environmental safety is not fully utilized. This determined the direction of our research.

3. Research methodology

Canonical correlation analysis is a method of multivariate data analysis. This is the most general form of correlation analysis, which allows you to examine the relationship between two sets of variables. In contrast, factor analysis is used to establish relationships within a single set of variables. The primary purpose of the method is to identify combinations of initial and resulting indicators for which the correlation between them is the strongest. The problem of reducing the number of indicators included in the model can also be solved by eliminating those that are insignificant. To some extent, canonical analysis combines methods from correlation, regression, and factor analysis.

Let the resulting indicators Y_1, Y_2, ..., Y_k be influenced by factors X_1, X_2, ..., X_n. The measurement is carried out on m objects. It is logical to assume that there are fewer resulting indicators than factors, $k \leq m$. The output matrix of observations is usually written in the form:

$$\begin{bmatrix} x_{11} & x_{11} & \cdots & x_{1n} & y_{11} & y_{12} & \cdots & y_{1k} \\ x_{21} & x_{212} & \cdots & x_{2n} & y_{21} & y_{22} & \cdots & y_{2k} \\ \cdots & & & & & & & \\ x_{m1} & x_{m2} & \cdots & x_{mn} & y_{m1} & y_{m2} & \cdots & y_{mk} \end{bmatrix} \quad (1)$$

Let's write the linear combinations of the initial indicators in the form of canonical variables U and V:

$$\begin{cases} U = a_1 X_1 + a_2 X_2 + \ldots + a_n X_n; \\ V = b_1 Y_1 + b_2 Y_2 + \ldots + b_k Y_k; \end{cases} . \quad (2)$$

The density of the connection between the canonical variables U and V is determined by the canonical correlation coefficient:

$$r = \frac{\operatorname{cov}(U,V)}{\sqrt{\operatorname{var}(U)\operatorname{var}(V)}} \quad (3)$$

The r values depend on which linear combinations form the initial indicators, that is, on the values of the parameters a_i and b_j. The canonical correlations method is aimed to find such a combination of indicators for which the value of the canonical correlation coefficient will be the largest by the modulus.

The calculation of the canonical correlation coefficient, as follows from formula (3), is based on the extended correlation matrix of indicators:

$$S = \begin{bmatrix} S_{XX} & S_{XY} \\ S_{YX} & S_{YY} \end{bmatrix}, \quad (4)$$

where *RXX* is the correlation matrix between indicators X_i and X_j, $i, j = 1..n$.

RYY is the correlation matrix between indicators Y_i and Y_j, $i, j = 1..k$.

RXY is the correlation matrix between indicators X_i and Y_j, $i = 1..n$, $j = 1..k$.

RYX = *RTXY*.

Let's write the canonical variables in matrix form:

$$\begin{cases} U = X \cdot A; \\ V = Y \cdot B; \end{cases} \quad (5)$$

Then, we get the following expression for the canonical correlation coefficient:

$$r = \frac{\operatorname{cov}(U,V)}{\sqrt{\operatorname{var}(U)\operatorname{var}(V)}} = \frac{A^T S_{XY} B}{\sqrt{A^T S_{XX} A B^T S_{YY} B}} \quad (6)$$

Assume that the canonical variables are standardized; that is, their mean values are equal to zero, and their root mean square deviations are equal to one. The expression (6) is simplified and takes the form:

$$r = A^T S_{XY} B \tag{7}$$

Finding the maximum of function (7) is a problem of finding a conditional extremum and can be solved using the method of Lagrange multipliers. As a result, we get the equation:

$$L = \left(\left[S_{YY}^{-1}\right]\cdot\left[S_{XY}^{T}\right]\cdot\left[S_{XX}^{-1}\right]\cdot\left[S_{XY}\right] - \lambda^2 E\right)B = 0. \tag{8}$$

It follows from this equation that the problem of finding the coefficients of the vector B is reduced to the task of finding the eigenvectors of the matrix:

$$S = \left[S_{YY}^{-1}\right]\cdot\left[S_{XY}^{T}\right]\cdot\left[S_{XX}^{-1}\right]\cdot\left[S_{XY}\right] \tag{9}$$

Note that all eigenvalues of in this case will be positive: $\beta = \lambda^2$. Analogous transformations can give an expression for finding the coefficients of the matrix A as eigenvectors of some matrix similar to (9). However, this is not necessary: we can find the matrix A from the expression:

$$A = \frac{\left[S_{XX}^{-1}\right]\cdot S_{XY}\cdot B}{\lambda} \tag{10}$$

We began the search for the parameters of the linear combination of indicators by considering the coefficients of the vector B, as initially, the assumption was made that the number of resulting indicators would be less than the number of factors. Otherwise, the search for parameters must begin with vector A.

Since $A^T S_{XX} A = B^T S_{YY} B = 1$, then $\lambda = A^T S_{XY} B = r$. Since the goal of the method is to find combinations with the largest value of the canonical correlation coefficient, among all eigenvalues, the largest should be selected for calculations. However, for each eigenvalue, it is possible to construct its pair of canonical variables U and V.

4. Results and discussions

Let us consider the application of the method of canonical correlations in the context of the research tasks at hand. A critical stage is the choice of indicators. The authors' considerations regarding macroeconomic indicators of economic growth and indicators of environmental threats and the results of the analysis of the results of other researchers [4, 8–11, 19, 23] showed that the most widely used indicators characterizing well-being and economic growth, there are the following indicators:

X1—Agriculture, forestry, and fishing, value added (constant 2015 US$).

X2—Industry (including construction), value added (constant 2015 US$).

X3—GDP per capita (constant 2015 US$).

X4—Households and NPISHs Final consumption expenditure (constant 2015 US$).

X5—Gross fixed capital formation (constant 2015 US$).

X6—Exports of goods and services (constant 2015 US$).

As indicators characterizing environmental threats, we will single out the following:

Y1—CO2 emissions (kt).

Y2—Total greenhouse gas emissions (kt of CO2 equivalent).

Y3—Adjusted savings: natural resources depletion (% of GNI).

The study was conducted for countries worldwide, based on data from the World Bank [36]. Considering the limited availability of necessary data due to the lack of indicator values for individual countries, we used indicator values for 136 countries worldwide in our study. We also considered that, starting from 2021, statistical data are missing for a significant number of indicators selected for the study (and not only for these). Therefore, we limit our analysis to data from 2020. The conditions that determined the technique of collecting the necessary data are that, firstly, the canonical analysis gives reasonable results under the condition of a large sample that contains at least 100 elements. Secondly, it is recommended that the sample size be 15–20 times larger than the number of indicators selected for the study. These conditions determined both the number of indicators selected for the research and the size of the sample.

The values of the extended correlation matrix calculated for the selected set of indicators are shown in Table 1.

Table 1
Extended correlation matrix

Indicators	X_1	X_2	X_3	X_4	X_5	X_6	Y_1	Y_2	Y_3
X_1	1.0000	0.5771	0.0194	0.5351	0.5714	0.4450	0.7689	0.8105	-0.0858
X_2	0.5771	1.0000	0.3176	0.9723	0.9907	0.8618	0.9189	0.8870	-0.1152
X_3	0.0194	0.3176	1.0000	0.2694	0.3087	0.5284	0.1927	0.1626	-0.2235
X_4	0.5351	0.9723	0.2694	1.0000	0.9911	0.7865	0.8936	0.8634	-0.0990
X_5	0.5714	0.9907	0.3087	0.9911	1.0000	0.8289	0.9115	0.8792	-0.1104
X_6	0.4450	0.8618	0.5284	0.7865	0.8289	1.0000	0.7462	0.7124	-0.1912
Y_1	0.7689	0.9189	0.1927	0.8936	0.9115	0.7462	1.0000	0.9929	-0.0858
Y_2	0.8105	0.8870	0.1626	0.8634	0.8792	0.7124	0.9929	1.0000	-0.0771
Y_3	-0.0858	-0.1152	-0.2235	-0.0990	-0.1104	-0.1912	-0.0858	-0.0771	1.0000

The matrix S, calculated according to formula (9), has the following form:

$$S = \begin{pmatrix} 0.8395 & 0.2766 & -0.1631 \\ 0.0950 & 0.6562 & 0.0667 \\ -0.0224 & -0.0253 & 0.0574 \end{pmatrix}. \quad (11)$$

For this matrix, we calculate the eigenvalues and eigenvectors using Givens rotations and Householder reflections [37]. The result is shown in Table 2.

Table 2
Eigenvalues of the correlation matrix and values of appropriate eigenvectors

Eigenvalues		
β_1	β_2	β_3
0.9530	0.5437	0.0564
Eigenvectors		
0.8107	−0.5630	0.1603
0.5854	0.7798	−0.2220
0.0000	0.2738	0.9618

We check the significance of the canonical correlation coefficients using the Wilks λ-criterion. The corresponding function is approximated by the distribution χ^2 with n·k degrees of freedom:

$$\chi^2 = -[m - 1 - 0.5(n + k + 1)]\ln \prod_{i=1}^{k} (1 - \lambda_i) \tag{12}$$

The first eigenvalue is $\beta_1 = 0.9530$. Accordingly, the first canonical correlation coefficient is $r_1 = 0.9762$. The corresponding coefficients of the canonical variable V are the components of the first eigenvector. The values of the parameters of the canonical variable U, calculated according to formula 10, are recorded in Table 3.

Table 3
The value of vector *A*

a_1	a_2	a_3	a_4	a_5	a_6
−0.5950	−1.5889	0.0025	−0.9810	1.5217	0.0960

In this case, χ2emp=511.03, χ2kr(0.05; 18)=28.87. Therefore, the hypothesis that a relationship exists between the selected sets of indicators is accepted. Expressions for the canonical variables U and V have a form:

$$\begin{cases} U = -0.5950X_1 - 1.5889X_2 + 0.0025X_3 - 0.9810X_4 + 1.5217X_5 + 0.0969X_6; \\ V = 0.8207Y_1 + 0.6854Y_2; \end{cases} \tag{13}$$

The analysis of the obtained dependencies reveals that the canonical variable U is most influenced by indicators X_2 is Industry (including construction), value added, and X_5 is Gross fixed capital formation, and for variable V, the indicator Y_1 is CO2 emissions. Let's pay attention to the fact that the indicator X_3 is GDP per capita has a relatively insignificant effect on the canonical variable U, and the indicator Y_3 is Adjusted savings: natural resources depletion, in this case, does not affect the corresponding canonical variable V.

Let's analyze the value of Pearson's pairwise correlation coefficients between the initial indicators of each group and the corresponding canonical variables. They are interpreted as canonical factor loadings, reflecting the weight of each output indicator in the corresponding canonical variable. The corresponding values are given in Table 4. Its analysis confirms the earlier conclusion about the importance of the influence of each of the initial indicators on the related canonical variables.

Table 4
The Pearson's pairwise correlation coefficients between the initial indicators and canonical variables

$r_{X1,U}$	$r_{X2,U}$	$r_{X3,U}$	$r_{X4,U}$	$r_{X5,U}$	$r_{X6,U}$	$r_{Y1,V}$	$r_{Y2,V}$	$r_{Y3,V}$
−0.8143	−0.9377	−0.1865	−0.9123	−0.9299	−0.7580	0.9988	0.9976	−0.0823

Canonical correlations do not contain information about what part of the variance each canonical root explains in the studied indicators. However, it is possible to calculate the proportion of the original indicators' variance explained by the corresponding canonical variable as the average value of the squares of the corresponding pairwise correlation coefficients. In this case, for each of the canonical variables, this share is 66%.

Please note that the obtained results were significantly affected by sample heterogeneity, for which the calculations were performed. So, for the X2 indicator, the largest value exceeds the smallest by 50,000 times, for the X5 indicator—by 40,000 times, and for the Y1 indicator—by 36,000 times. The same heterogeneity occurs for normalized values. At the same time, the calculations allow us to conclude that there is a connection between the development of the world's economic system and global environmental threats. This negatively affects progress in achieving the goals of sustainable development. This conclusion is consistent with the results obtained by other scientists, including for different sets of indicators. The research results can be utilized as analytical information for policy review about long-term, sustainable economic development.

Conclusions

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Currently, various analytical tools are used to solve the task. We employed the method of canonical correlations, which enables us to assess the relationship between two sets of indicators: one representing economic growth and well-being, and the other representing environmental threats. The study was conducted for 136 countries using World Bank data from 2020. For analysis, six indicators were selected for the first group and three for the second. Several indicators were identified due to certain limitations inherent in the chosen method. The calculations revealed a reasonably high correlation between the constructed canonical variables, with a value of the canonical correlation coefficient of $r = 0.9762$. Criterion verification confirmed the significance of the calculated indicator. At the same time, it was established that the following indicators influence the canonical variable of economic development: Industry (including construction) and Gross fixed capital formation, and the canonical variable of environmental threats—CO_2 emissions. Calculating Pearson's pairwise correlation coefficients between the original indicators and canonical variables confirmed the importance of the selected indicators. The research results can be utilized as analytical information for reviewing policies related to achieving sustainable development goals, which involves an effective combination of economic development and environmental protection, resulting in mutually beneficial outcomes for both environmental and economic benefits. The direction of further research is to assess the relationship between indicators of economic development and environmental threats for certain groups of countries, grouped, in particular, by the level of GDP per capita or by clustering according to a selected set of indicators.

Declaration on Generative AI

While preparing this work, the authors used the AI programs Grammarly Pro to correct text grammar and Strike Plagiarism to search for possible plagiarism. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

References

[1] Unated Nations. Department of Economic and Social Affairs. Sustainable Development. URL: https://sdgs.un.org/goals

[2] I. Kumekawa, Lessons from Environmental and Economic Crises, Enterprise Society, 25(2) (2024) 628–636. doi:10.1017/eso.2023.54
[3] Environmental Performance Index. URL: https://epi.yale.edu/epi-results/2022/component/epi
[4] L. Zomchak, et al., Economic Growth and Environmental Degradation: Data Intelligence for Sustainable Environment, J. Inf. Technol. Manag. 15(1) (2023) 163–177.
[5] V. Stadnyk, et al., Motivational Aspects of Development of Strategic Network Partnership in the Agro-Industrial Complex, Agricultural and Resource Economics, 7(2) (2021) 77–101. doi:10.51599/are.2021.07.02.05
[6] V. Koval, et al., Modeling the Interaction between Environment and the Economy Considering the Impact on Ecosystem, in: E3S Web of Conferences, vol. 166, 2020, 13002.
[7] A. Sajjad, et al., Analysis of the Nexus of CO_2 Emissions, Economic Growth, Land under Cereal Crops and Agriculture Value-Added in Pakistan Using an ARDL Approach, Energies, 12(23) (2019) 4590. doi:10.3390/en12234590
[8] I. Hardi, et al., Economic Growth, Agriculture, Capital Formation and Greenhouse Gas Emissions in Indonesia: FMOLS, DOLS and CCR Application, J. Econom. 1(2) (2023) 82–91.
[9] M. M. Rahman, E. Velayutham, M. Abul Kashem, Are Environmental Damage and Export Concentration the Major Threats for the Long-Run Economic Growth in Bangladesh?, PLoS ONE, 18(4) (2023) e0284620. doi:10.1371/journal.pone.0284620
[10] N. Othman, et al., Environmental Tax–Economic Growth Nexus in ASEAN-4 Countries, in: BIO Web of Conferences, vol. 73, 2023, 02005. doi:10.1051/bioconf/20237302005
[11] U. N. Kayani, et al., Unbridling the Economic Growth and Environmental Nexus in Pakistan, Int. J. Energy Econom. Policy, 14(1) (2024) 488–495. doi:10.32479/ijeep.15528
[12] M. Udeagha, E. Muchapondwa, Environmental Sustainability in South Africa: Understanding the Criticality of Economic Policy Uncertainty, Fiscal Decentralization, and Green Innovation, Sustainable Development (2022) 1–14. doi:10.1002/sd.2473
[13] M. Abe, Y. Zumba, I. Ladele, Is Economic Growth a Remedy for Environmental Degradation in Oil-Producing Countries?, New evidence from Africa. Energy Economics Letters, 10 (2023) 159–176. doi:10.55493/5049.v10i2.4951
[14] M. Abid, et al., Air Ollution and Economic Development in KSA: Environmental Kuznets Curve and Implications for Sustainable development, Int. J. Energy Econom. Policy, 14(1) (2024) 628–639. doi:10.32479/ijeep.15061
[15] R. Lestari, et al., The Impact of Environmental Performance on Economic Growth: A Study of ASEAN Countries, Int. J. Energy Econom. Policy, 13(5) (2023) 132–138. doi:10.32479/ijeep.14508
[16] L. Ma, X. Liu, Strategies for Environmental Protection and Optimization of Ecological Business Economic Growth from the Perspective of Sustainable Development, Sustainability, 15(3) (2023) doi:10.3390/su15032758
[17] J. Zhang, A Coexisting Strategy of Economic Development and Environmental Protection. Highlights in Business, Econom. Manag. 6 (2023) 1–5. doi:10.54097/hbem.v6i.6299
[18] J. Cai, Q. Chen, Z. Zhang, Balancing Environmental Sustainability and Economic Development: Perspectives from New Structural Economics, preprints, 2024. doi:10.20944/preprints202401.0116.v1
[19] D. Kirikkaleli, et al., Economic Complexity and Environmental Sustainability in Eastern European Economy: Evidence from Novel Fourier Approach, Regional Sustainability, 4(4) (2023) 349–358. doi:10.1016/j.regsus.2023.08.003
[20] M. Petrovic-Ranđelovic, T. Stevanovic, Z. Kostic, The Relationship Analysis between Environmental Performance and Economic Value of the Company, Facta Universitatis, Series: Economics and Organization, 20(2) (2023) 135–149. doi:10.22190/FUEO221123009P
[21] P, Hryhoruk, N. Khrushch, S. Grygoruk, Environmental Safety Assessment: A Regional Dimension, in: IOP Conference Series: Earth and Environmental Science, vol. 628, 2021, 012026. doi:10.1088/1755-1315/628/1/012026

[22] K. Shi, Analysis of the Coupling Correlation between Environmental Protection Efforts and Economic development Level based on Artificial Intelligence Technology, Appl. Math. Nonlinear Sci. 9(1) (2023). doi:10.2478/amns.2023.1.00338
[23] Y. Fan, C. Fang, Q. Zhang, Coupling Coordinated Development between Social Economy and Ecological Environment in Chinese Provincial Capital Cities-Assessment and Policy Implications, J. Cleaner Production, 229 (2019) 289–298. doi:10.1016/j.jclepro.2019.05.027
[24] L. Fu, et al., Analysis of the Coupling Coordinated Development and Evolutionary Trend of Digital Economy and Ecological Environment, Frontiers in Environmental Sci. 10 (2022).
[25] J. Ji, et al., Spatiotemporal Change and Coordinated Development Analysis of "Population-Society-Economy-Resource-Ecology-Environment" in the Jing-Jin-Ji URBAN Agglomeration from 2000 to 2015, Sustainability, 13(7) (2021) 4075. doi:10.3390/su13074075
[26] W. Li, P. Yi, Assessment of City Sustainability-Coupling Coordinated Development Among Economy, Society and Environment, J. Cleaner Production, 256 (2020) 120453. doi:10.1016/j.jclepro.2020.120453
[27] P. Hryhoruk, et al., Assessing the Impact of COVID-19 Pandemic on the Regions' Socio-Economic Development: The Case of Ukraine, European J. Sustainable Development, 10(1) (2021) 63–80.
[28] O. Kovalchuk, et al., The Canonical Discriminant Model of the Environmental Security Threats, Complexity (2023) 5584750. doi:10.1155/2023/5584750
[29] L. Malyarets, et al., Assessment of the Level of Environmental and Economic Sustainability of Subjects of the Public Sector of the Country's Economy, in: Green Sustainability: Towards Innovative Digital Transformation. ITAF 2023, LNNS, vol. 753. doi:10.1007/978-981-99-4764-5_1
[30] P. Y. N. Wulan, R. F. Putri, Relationship between Settlement Environmental Quality and Socio-Economic Conditions in Kwadungan Permai Housing, Kediri Regency, in: E3S Web of Conference, vol. 468, 2023, 06013. doi:10.1051/e3sconf/202346806013
[31] T. Raykov, Canonical Correlation Analysis, International Encyclopedia of Statistical Science, Berlin, Heidelberg, 2011, 199–201. doi:10.1007/978-3-642-04898-2_159
[32] V. Uurtio, et al., A Tutorial on Canonical Correlation Methods, ACM Computing Surveys, 50(6) (2017) 14–38. doi:10.1145/3136624
[33] C. Jayadevan, A Canonical, Correlation Analysis of Sectoral Composition of GDP and Development in Asia, Modern Economy, 9 (2018) 379–392. doi:10.4236/me.2018.92024
[34] S. F. dos Santos, H. S. Brandi, A Canonical Correlation Analysis of the Relationship between Sustainability and Competitiveness, Clean Technologies and Environmental Policy, 16 (2014) 1735–1746. doi:10.1007/s10098-014-0755-2
[35] J. Wang, H.-M. Li, Research on the Canonical Correlation between Employment and Economic Development in China, Advances in Social Science, Education and Humanities Research, 234 (2018) 262–267. doi:10.2991/iced-18.2018.38
[36] DataBank, World Development Indicators. URL: https://cutt.ly/F9alvCj
[37] W. Ford, Implementing the QR Decomposition, Numerical Linear Algebra with Applications, New York: Academic Press (2015) 351–378. doi:10.1016/B978-0-12-394435-1.00017-X