ScientificScholar®
Knowledge is power
Publisher of Scientific Journals

https://jksus.org

Journal of King Saud University – Science

2026 38 (2) 11352025

Research Article

A novel decision-making approach using trigonometric functions: SINCOS method for ranking selected countries on environmental sustainability

Kenan Karagül[a], Yusuf Şahin[b,*], Sezai Tokat[c], Özcan Mutlu[d]

[a]*Department of Logistics, Pamukkale University, Honaz, Denizli, 20330, Turkey*
[b]*Department of Business Administration, Burdur Mehmet Akif Ersoy University, Burdur Mehmet Akif Ersoy University, İstiklal Campus, Burdur, 35100, Turkey*
[c]*Department of Computer Engineering, Pamukkale University, Kinikli Campus, Denizli, 20100, Turkey*
[d]*Department of Industrial Engineering, Pamukkale University, Kinikli Campus, Denizli, 20100, Turkey*

ARTICLE INFO

Keywords:
Decision analysis
Environmental sustainability
SINCOS method
Trigonometric transformation

ABSTRACT

Decision-making can be defined as the process of identifying the optimum solution, especially when multiple and typically conflicting criteria must be considered. Although many Multi-Criteria Decision-Making (MCDM) methods exist, most rely on linear normalization, which may not reflect the nonlinear perception of decision makers regarding changes in criterion values. To address this limitation, this study proposes a novel MCDM method called SINCOS (SINe-COSine). The SINCOS method is based on trigonometric functions: the sine function is used for criteria to be maximized, and the cosine function is used for criteria to be minimized. The performance validation of the method was done through a synthetic case study for which the SINCOS achieved 100% accuracy by successfully reproducing the predefined ranking of eight alternatives. The applicability of the SINCOS method was demonstrated on a real data set to evaluate the environmental sustainability of five countries, i.e., Sweden, Brazil, Germany, India, Canada, Nigeria, China, and the United Arab Emirates. Seven indicators were considered: energy consumption, nuclear and alternative energy, carbon intensity of gross domestic product (GDP), electricity generation from renewable sources, carbon dioxide emissions (CO_2), total natural resource rents, PM2.5 air pollution, and electric power use. The results show that Sweden achieved the highest sustainability score, followed by Brazil, Germany, Canada, India, Nigeria, China, and the United Arab Emirates. The SINCOS method was also compared with some of the highly preferred methods in the literature, namely Multi-Attributive Border Approximation Area Comparison (MABAC), Multi-Attributive Ideal-Real Comparative Analysis (MAIRCA), and Complex Proportional Assessment (COPRAS), using Spearman's rank correlation and Kendall's tau coefficient tests. The test results indicated strong agreement among the methods. However, the SINCOS method provides interpretable results by clearly revealing the criteria that have greater influence on the ranking of alternatives, and it uses simple calculations that make it computationally efficient.

1. Introduction

Decision-making focuses on determining the best option among two or more options (Beach, 1993). Multiple and conflicting criteria are considered when evaluating alternatives. Multi-Criteria Decision-Making (MCDM) methods offer decision-makers a systematic and analytical approach to facilitate the evaluation of alternatives when making more complex decisions (Saaty, 1977; Hwang and Yoon, 1981). The MCDM methods have been applied in a variety of fields, which include economics, engineering, environmental management, and, more recently, health (Triantaphyllou, 2000). Analytic Hierarchy Process (AHP) (Saaty, 1977), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Yoon and Hwang, 1981), Elimination and Choice Expressing Reality (ELECTRE) (Benayoun *et al.*, 1966), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) (Brans, 1982; Brans and Vincke, 1985), and Complex Proportional Assessment (COPRAS) (Zavadskas *et al.*, 1994) are examples of methods widely used to solve MCDM problems.

However, the prevalent methodologies are subject to certain limitations. For example, AHP is highly sensitive to the consistency of pairwise comparison matrices that rely on subjective judgments, and the burden on decision-makers to ensure consistency increases as the number of criteria grows (Forman & Gass, 2001). The TOPSIS method, which is based on the distance from ideal and anti-ideal solutions, can produce significantly different results depending on the normalization and weighting processes (Chen & Hwang, 1992). The VIse Kriterijumska Optimizacija kompromisno Resenje (VIKOR) in Serbian, Multiple Criteria Optimization Compromise Solution method proposes a compromise solution; however, the acceptability of this solution to decision-makers is not always clear (Opricovic & Tzeng, 2004). Multi-objective optimization on the basis of a ratio analysis plus the full multiplicative form (MULTIMOORA) offers robustness by employing three different analytical techniques simultaneously, yet this advantage may result in difficulties in interpretation and practical implementation (Brauers & Zavadskas, 2011). Moreover, in most MCDM methods, linear weightings are used to assess the relative importance of alternatives.

***Corresponding author:**
E-mail address: ysahin@mehmetakif.edu.tr (Y Şahin)

Received: 06 July, 2025 **Accepted:** 11 December, 2025 **Epub Ahead of Print:** 19 February, 2026 **Published:** 24 February, 2026

DOI: 10.25259/JKSUS_1135_2025

In practice, however, the relationship between the criteria and the relative importance of alternatives is often nonlinear. Therefore, there is a growing need for new approaches that address the limitations of existing methods.

In the extant literature on MCDM, novel mathematical tools and algorithms have historically been the focus of considerable attention. In recent developments, calculus, probability theory, fuzzy logic, and artificial intelligence methods have been adopted to enhance the reliability and interpretability of decisions in multi-criteria decision making. (Potomkin *et al.*, 2019). To enhance the understanding and stability of criteria under uncertainties and relationships, Wang and Zhang (2024) formulated an MCDM method through rough fuzzy sets and non-additive attribute measures based on the Choquet integral. The alternative by alternative comparison (ABAC) method also addresses the rank reversal problem common with methods like TOPSIS and VIKOR, providing a more straightforward and scalable approach (Biswas *et al.*, 2022). Similarly, Nguyen (2023) developed an enhanced CURLI (Collaborative Unbiased Rank List Integration) method that does not utilise weights or normalization, thereby providing analogous rank reversal enhancements. Similarly, Sotoudeh-Anvari (2023) proposed the Root Assessment Method (RAM), which employs a square-root-based aggregation structure and does not necessitate pairwise comparisons or normalization. The RAM method has been shown to circumvent the rank reversal problem (2019).

In this paper, a novel procedure, termed SINCOS (SINe-COSine), is introduced to account for the nonlinear relationship of the criteria, as well as the relative importance of the alternatives. The sine function will be employed for criteria that are to be maximised, while the cosine function will be used for criteria that are to be minimised. It facilitates the incremental rise in the relative importance of the alternatives, concomitant with an increase in the criterion score, and the concomitant decrease in the relative importance of the alternatives, in accordance with the actual perceptions of the decision-maker.

The structure of the paper is as follows: In Section 2, the implementation steps of the proposed method are presented, along with the key features of other methods that are utilised for the purpose of comparing with the baseline method, with regard to accuracy. In Section 3, the accuracy and performance of the method are discussed, with this discussion being based on two different examples. Section 4 will provide a comprehensive discussion of the findings and a summary of the comparative advantages of SINCOS to traditional MCDM methodologies. Finally, Section 5 will present the paper's conclusion, including the main contributions and potential directions for future research.

2. Materials and Methods

The motivation and application steps for conducting the SINCOS method are elaborated in further detail in the subsections below.

2.1 Motivation of the SINCOS method

The process of ranking alternatives in MCDM tasks is typically comprised of two primary steps. In the initial phase, the relative importance of alternatives is derived from the performance scores with respect to each criterion. In the subsequent step, the relative performances are synthesised with the corresponding criterion weights to establish a ranking of the alternatives. To determine the relative importance of the alternatives, linear transformations are often applied in most MCDM methods. However, the relationship between the criterion scores and the relative importance of the alternatives is usually nonlinear. The relative importance of the alternatives increases gradually or decreases rapidly as the criterion scores increase. To reflect this phenomenon, trigonometric transformations are proposed in this study. For instance, as the cost of an alternative increases, its relative importance should decrease more rapidly. As illustrated in Fig. 1, both linear and cosine conversions are demonstrated for a cost-type criterion. In the linear conversion, the decline in relative performance is consistent, irrespective of the cost level. In the context of the cosine conversion, the decline in relative performance is negligible at low costs and substantial at high costs.

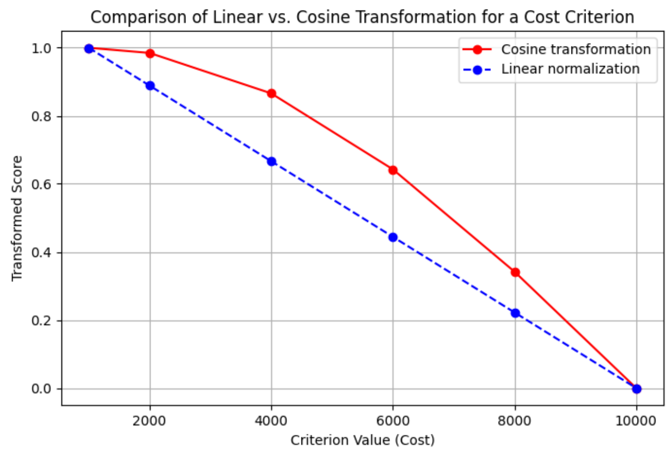

Fig. 1. Comparison of linear and cosine transformation for a cost criterion.

2.2 Steps of the SINCOS method

This research presents a new MCDM technique that relies on the use of trigonometric functions. The method is based on a two-phase normalization. The first phase consists of converting the criterion scores into angular values that vary between 0 and $\pi/2$. In the second phase, trigonometric functions convert the angular value to normalized scores between 0 and 1, where the mapping is done using the angles in the first phase. The process of the proposed method is described as follows:

Let $\left[x_{ij}\right]_{m*n}$ denote the initial decision matrix, where $i = 1,2,\ldots,m$ represents the set of alternatives, and $j = 1,2,\ldots,n$ represents the set of criteria. x_{ij} denotes the performance score of the alternative i with respect to the criterion j.

Step 1: Normalization

The decision matrix is normalized into the interval $\left[0,\pi/2\right]$. To do this, the minimum and maximum values for each criterion j are determined using Equations (1) and (2), respectively:

$$\theta_j = min_{i\in I}\left\{x_{ij}\right\}\forall j \in J \tag{1}$$

$$\omega_j = max_{i\in I}\left\{x_{ij}\right\}\forall j \in J \tag{2}$$

Then, the normalized decision matrix is obtained using Equation (3):

$$b_{ij} = \frac{x_{ij}-\theta_j}{\omega_j-\theta_j}\left(\frac{\pi}{2}\right) \quad \forall i \in I,\ \forall j \in J \tag{3}$$

Step 2: Trigonometric transformation

The normalized values are transformed into the interval [0,1] using trigonometric functions based on the objective direction of each criterion. The sine function is used for maximization criteria, and the cosine function is used for minimization criteria. Let $S = \left[s_1, s_2, \ldots, s_n\right]$ be the vector that represents the objective direction of each criterion, where $s_j \in \left\{max, min\right\}$.

$$A_{ij} = \begin{cases} \sin\left(b_{ij}\right), & if\ s_j = max \\ \cos\left(b_{ij}\right), & if\ s_j = min \end{cases} \forall i \in I, \forall j \in J \tag{4}$$

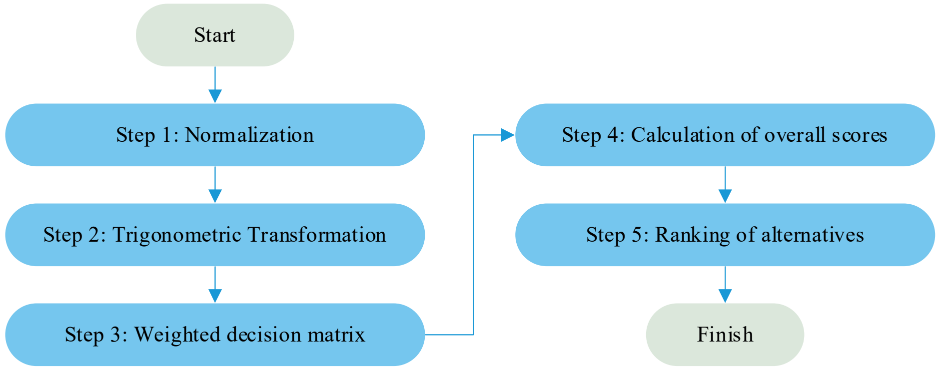

Fig. 2. Steps of the SINCOS method

Step 3: Weighted decision matrix

After the trigonometric transformation, the weighted decision matrix is constructed by multiplying each transformed value by the criterion weight. Let λ_j be the weight of j th criterion, where $0 \le \lambda_j \le 1$ and $\sum_{j=1}^{n} \lambda_j = 1$. The elements of the weighted decision matrix U_{ij} are calculated using Equation (5).

$$U_{ij} = A_{ij} \cdot \lambda_j \qquad \forall i \in I, \forall j \in J \tag{5}$$

Step 4: Calculation of overall scores

The overall score (V_i) for each alternative i is calculated using Equation (6).

$$V_i = \sum_{j=1}^{n} U_{ij} \qquad \forall i \in I \tag{6}$$

Step 5: Ranking of alternatives

The alternatives are ranked in a hierarchical order of overall score (the alternative with the best overall score is the most preferred). Fig. 2 shows that the proposed method includes several stages, such as data normalization, trigonometric transformations, overall performance score calculation, and final rankings.

3. Validation and Application of the SINCOS Method

In order to demonstrate the validation and applicability of the SINCOS method, two numerical examples were used. The first example was synthetically constructed with a known ranking and was used to validate the method's accuracy and reliability. The second example was used to demonstrate the practical application of the proposed method and to compare its effectiveness with other MCDM methods. For this purpose, environmental sustainability rankings of eight countries were determined based on indicators such as energy use, alternative and nuclear energy, carbon intensity of GDP, electricity production from renewable energy sources, carbon dioxide (CO_2) emissions, total natural resource rents, PM2.5 air pollution, and electric power consumption.

3.1 Validation using synthetic data

To validate the proposed method, a synthetic problem was constructed consisting of eight alternatives evaluated with 13 criteria. Table 1 presents the performance scores of the alternatives on each criterion, as well as the weights and objective direction (i.e., maximization or minimization) of each criterion. The performance scores were determined in such a way that the preference order of the alternatives is A1 $\succ$ A2 $\succ$ ... $\succ$ A8.

Step 1: The decision matrix is normalized to the interval [0, $\pi/2$] using Equations (1)-(3). The resulting normalized matrix has been presented in Table 2.

Step 2: To incorporate the objective direction of each criterion, the normalized values are transformed using trigonometric functions using Equation (4). The transformed matrix has been given in Table 3.

Step 3: To incorporate the relative importance of each criterion, the transformed values are multiplied by the corresponding criterion weights. The weighted scores have been presented in Table 4.

Step 4: The overall performance score (V_i) for each alternative is obtained by summing the weighted values of each alternative. The overall performance scores have been presented in Table 4.

Step 5: Finally, the alternatives are ranked in descending order based on their V_i scores. Final rankings have been presented in Table 4.

Fig. 3 presents the performance scores (V_i) and corresponding ranks of eight alternatives obtained from the SINCOS method. Each bar represents the overall performance score of an alternative, and the line

Table 1.
Decision matrix.

Alternative	CR_1	CR_2	CR_3	CR_4	CR_5	CR_6	CR_7	CR_8	CR_9	CR_{10}	CR_{11}	CR_{12}	CR_{13}
A_1	1	200	1500	30000	3500	10000	50	145	10	450	0.12	3.50	1000
A_2	2	180	1300	27000	3100	9000	40	125	20	345	0.21	5.60	2000
A_3	3	120	1200	21000	3000	7000	30	100	30	300	0.35	6.70	3000
A_4	4	80	1000	13000	2800	6000	20	85	40	275	0.45	7.70	4000
A_5	5	70	900	11000	2600	4000	15	65	50	220	0.75	8.80	5000
A_6	6	60	800	9000	2000	3000	10	55	60	185	0.85	9.90	6000
A_7	7	40	600	5000	1700	2000	8	45	70	155	0.95	10.10	7000
A_8	8	20	400	1000	1000	1000	1	15	80	125	1	11.10	8000
Objective	min	max	max	max	max	max	max	max	min	max	min	min	min
Weights	0.12	0.07	0.06	0.08	0.01	0.11	0.11	0.07	0.05	0.07	0.03	0.15	0.07

Table 2.
Normalized decision matrix.

Alternatives	CR_1	CR_2	CR_3	CR_4	CR_5	CR_6	CR_7	CR_8	CR_9	CR_{10}	CR_{11}	CR_{12}	CR_{13}
A1	0.00	1.57	1.57	1.57	1.57	1.57	1.57	1.57	0.00	1.57	0.00	0.00	0.00
A2	0.22	1.40	1.29	1.41	1.32	1.40	1.25	1.33	0.22	1.06	0.16	0.43	0.22
A3	0.45	0.87	1.14	1.08	1.26	1.05	0.93	1.03	0.45	0.85	0.41	0.66	0.45
A4	0.67	0.52	0.86	0.65	1.13	0.87	0.61	0.85	0.67	0.72	0.59	0.87	0.67
A5	0.90	0.44	0.71	0.54	1.01	0.52	0.45	0.60	0.90	0.46	1.12	1.10	0.90
A6	1.12	0.35	0.57	0.43	0.63	0.35	0.29	0.48	1.12	0.29	1.30	1.32	1.12
A7	1.35	0.17	0.29	0.22	0.44	0.17	0.22	0.36	1.35	0.14	1.48	1.36	1.35
A8	1.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.57	0.00	1.57	1.57	1.57

Table 3.
Trigonometric transformation results.

Al.	CR_1	CR_2	CR_3	CR_4	CR_5	CR_6	CR_7	CR_8	CR_9	CR_{10}	CR_{11}	CR_{12}	CR_{13}
A1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
A2	0.97	0.98	0.96	0.99	0.97	0.98	0.95	0.97	0.97	0.87	0.99	0.91	0.97
A3	0.90	0.77	0.91	0.88	0.95	0.87	0.80	0.86	0.90	0.75	0.92	0.79	0.90
A4	0.78	0.50	0.76	0.61	0.90	0.77	0.57	0.75	0.78	0.66	0.83	0.65	0.78
A5	0.62	0.42	0.65	0.52	0.84	0.50	0.43	0.57	0.62	0.44	0.43	0.46	0.62
A6	0.43	0.34	0.54	0.42	0.59	0.34	0.28	0.46	0.43	0.29	0.26	0.25	0.43
A7	0.22	0.17	0.28	0.21	0.43	0.17	0.22	0.35	0.22	0.14	0.09	0.21	0.22
A8	6,E-17	0,E+00	0,E+00	0,E+00	0,E+00	0,E+00	0,E+00	0,E+00	6,E-17	1,E+00	6,E-17	6,E-17	6,E-17

Table 4.
Weighted scores, overall performance, and final rankings.

Alternatives	CR_1	CR_2	CR_3	CR_4	CR_5	CR_6	CR_7	CR_8	CR_9	CR_{10}	CR_{11}	CR_{12}	CR_{13}	V_i	Rank
A1	0.12	0.07	0.06	0.08	0.01	0.11	0.11	0.07	0.05	0.07	0.03	0.15	0.07	1.00	1
A2	0.12	0.07	0.06	0.08	0.01	0.11	0.10	0.07	0.05	0.06	0.03	0.14	0.07	0.96	2
A3	0.11	0.05	0.05	0.07	0.01	0.10	0.09	0.06	0.05	0.05	0.03	0.12	0.06	0.85	3
A4	0.09	0.04	0.05	0.05	0.01	0.08	0.06	0.05	0.04	0.05	0.02	0.10	0.05	0.69	4
A5	0.07	0.03	0.04	0.04	0.01	0.06	0.05	0.04	0.03	0.03	0.01	0.07	0.04	0.52	5
A6	0.05	0.02	0.03	0.03	0.01	0.04	0.03	0.03	0.02	0.02	0.01	0.04	0.03	0.37	6
A7	0.03	0.01	0.02	0.02	0.00	0.02	0.02	0.02	0.01	0.01	0.00	0.03	0.02	0.22	7
A8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8

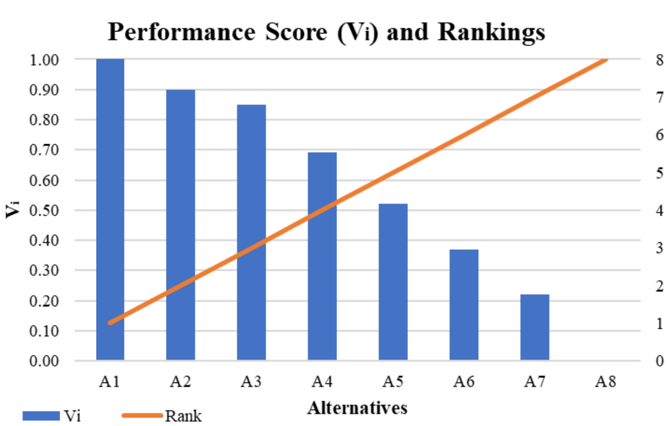

Fig. 3. Results of the SINCOS method.

indicates the ranking order. As shown in the Fig. 3, A1 achieves the highest performance score and ranks first, while A8, with the lowest score, ranks last. This result confirms the validity of the proposed method since it successfully reproduces the predefined rankings for the synthetically constructed decision matrix.

3.2 A real-world application

In today's global context, environmental challenges have become a major element of global development challenges. The issue of sustainability is theoretical; policies must be sound, data-driven, whilst also being systematically assessed for a country's environmental performance. The most severe challenges of our time- climate change, depletion of natural resources, loss of biodiversity, and pollution- are serious risks not only for developing countries but also for highly industrialized countries (IPCC, 2023; ESCAP, 2019). In this day and age, policies need to incorporate environmental sustainability indicators closely monitored and strategically deployed.

The SINCOS method was applied to assess the environmental sustainability performance of eight countries over the period 2005-2020. Table 5 presents the selected countries and their regions. These countries were deliberately chosen to represent diverse geographic regions and varying levels of economic development, resource dependency, and environmental policy implementation.

To evaluate the sustainable environmental performance of these countries, eight indicators were used as assessment criteria. The indicators and their brief descriptions have been presented in Table 6.

The indicator definitions, series names, and the performance scores of the countries on each criterion were obtained from the World Development Indicators (WDI) database of the World Bank for the years 2005, 2010, 2015, and 2020. Table 7 gives the performance scores of

Table 5.
Selected countries.

No	Region	Countries	Abbr.	Feature/Reason
1	Europe	Sweden	SWE	The renewable energy ratio is very high, environmental policies are strong, low-carbon economy.
2	North America	Canada	CAN	Has extensive natural resources, but environmental protection policies are strong; energy exporter.
3	Asia	China	CHN	The world's largest energy consumer, with carbon emissions that are very high, renewable investments are also growing rapidly.
4	South Asia	India	IND	Rapid growth, increasing energy demand, environmental pollution, and deforestation problems are serious.
5	Europe	Germany	DEU	An example of phasing out coal and increasing renewables through “Energiewende” policies.
6	Africa	Nigeria	NGA	High dependence on oil, natural resource revenues puts pressure on the environment.
7	South America	Brazil	BRA	Amazon rainforests, biofuel production, and deforestation pressures all coexist.
8	Middle East	UAE	ARE	Oil-centered economy; a country that has initiated a renewable energy transition.

Table 6.
Environmental sustainability indicators and definitions.

Abbr.	Indicator name (Series code)	Brief definition
CR1	Energy use (kg of oil equivalent per capita) (EG.USE.PCAP.KG.OE)	The consumption of primary energy before its conversion into other end-use fuels.
CR2	Alternative and nuclear energy (% of total energy use) (EG.USE.COMM.CL.ZS)	Non-carbohydrate energy that does not result in the production of carbon dioxide during its generation.
CR3	Carbon intensity of GDP (kg CO2e per 2021 PPP $) (EN.GHG.CO2.RT.GDP.PP. KD)	The annual emissions of carbon dioxide (CO_2),
CR4	Electricity production from renewable sources, excluding hydroelectric (% of total) (EG.ELC.RNWX. ZS)	The proportion of electricity production from renewable sources in relation to the total electricity production.
CR5	Carbon dioxide (CO2) emissions excluding LULUCF per capita (t CO2e/capita) (EN.GHG.CO2.PC.CE.AR5)	Annual CO_2 equivalent emissions per capita from the agriculture, energy, waste, and industry sectors, excluding LULUCF has been standardized.
CR6	Total natural resources rents (% of GDP) (NY.GDP.TOTL.RT.ZS)	The total natural resource rent is the aggregate of oil rents, natural gas rents, coal rents (hard and soft), mineral rents, and forest rents.
CR7	PM2.5 air pollution, mean annual exposure (micrograms per cubic meter) (EN.ATM.PM25.MC.M3)	The average level of exposure of a nation's population to concentrations of suspended particles measuring less than 2.5 microns in aerodynamic diameter.
CR8	Electric power consumption (kWh per capita) (EG.USE.ELEC.KH.PC)	The production of power plants and combined heat and power plants, minus transmission, distribution, and transformation losses, and the heat and power plant's own use.

Source: https://databank.worldbank.org/source/world-development-indicators#

Table 7.
Environmental performance data of selected countries (2005)

Country	CR1	CR2	CR3	CR4*	CR5	CR6	CR7	CR8
SWE	5711.64	49.35	0.11	2.18	6.04	0.44	8.42	15430.96
CAN	8369.96	20.47	0.34	0.92	18.02	5.56	9.57	17852.89
CHN	1369.79	2.94	0.76	0.17	4.81	5.10	51.48	1782.31
IND	425.37	2.94	0.27	0.17	1.05	3.66	62.77	458.88
DEU	4109.88	13.86	0.20	0.64	10.21	0.14	16.55	7144.71
NGA	305.40	1.51	0.16	0.10	0.71	19.39	54.62	132.05
BRA	1173.72	14.65	0.13	0.67	2.00	3.65	15.36	2031.51
ARE	9535.23	0.00	0.29	0.04	26.25	25.33	44.06	12205.05

*Negative values in the 4th criterion data have been normalized using the percentage shift method and converted to positive values.

Table 8. Rankings of countries in 2005.

Weights	0,04	0,17	0,12	0,11	0,28	0,07	0,15	0,08	V_i	Order
Objective	Min	Max	Min	Max	Min	Min	Min	Min		
Countries	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8		
SWE	0.02	0.17	0.12	0.11	0.26	0.07	0.15	0.02	0.91	1
CAN	0.01	0.10	0.10	0.07	0.13	0.07	0.15	0.00	0.62	4
CHN	0.03	0.02	0.00	0.01	0.27	0.07	0.05	0.07	0.52	7
IND	0.03	0.02	0.11	0.01	0.28	0.07	0.00	0.07	0.59	5
DEU	0.03	0.07	0.12	0.05	0.23	0.07	0.14	0.06	0.77	3
NGA	0.04	0.01	0.12	0.01	0.28	0.03	0.03	0.08	0.58	6
BRA	0.03	0.07	0.12	0.05	0.28	0.07	0.14	0.07	0.84	2
ARE	0.00	0.00	0.11	0.00	0.00	0.00	0.08	0.04	0.22	8

the countries in 2005, while the remaining data for the years 2010, 2015, and 2020 have been provided in Appendix 1.

To assess the environmental sustainability performance of the eight countries in 2005, the SINCOS method was applied. The overall performance scores (V_i) and the resulting rankings have been presented in Table 8.

As shown in Table 8, the final rankings of the countries are SWE > BRA > DEU > CAN > IND > NGA > CHN > ARE. Sweden ranked first due to its highest scores in five categories, namely Criterion (CR)2, CR3, CR4, CR6, and CR7. Brazil ranked second, obtaining the highest scores in three categories: CR3, CR5, and CR6. Germany ranked third, achieving the highest scores in CR3 and CR6. Canada ranked fourth due to its moderate performance across all categories. India and Nigeria showed similar performance levels, ranking fifth and sixth, respectively. China ranked seventh due to its poor performance in CR2, CR3, CR4, and CR7. The United Arab Emirates received the lowest overall rating, mainly due to weak performance in all categories except CR3.

These results indicate that the European and South American countries demonstrate a substantial performance advantage as potential leaders in sustainable energy sector implementation. Furthermore, fossil-fuel-based economies, such as China and the United Arab Emirates, showed significant deficits in environmental performance.

3.3 Comparative analysis

In order to evaluate the effectiveness of the SINCOS method, a comparative analysis was conducted with three well-known MCDM methods: MAIRCA (Multi-Attributive Ideal-Real Comparative Analysis), MABAC (Multi-Attributive Border Approximation Area Comparison), and COPRAS (Complex Proportional Assessment). All four methods were applied to evaluate the environmental sustainability performance of eight countries from 2005-2020.

The rankings generated by these methods have been summarized in Table 9. Figs. 4 and 5 also graphically illustrate the rankings of the

Table 9.
Country rankings for the period 2005-2020.

Countries	SINCOS				MABAC				MAIRCA				COPRAS			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
SWE	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1
CAN	4	4	5	6	4	4	4	6	6	6	6	6	6	6	6	6
CHN	7	7	7	5	7	7	7	7	7	7	7	7	7	7	7	7
IND	5	5	4	4	5	5	5	4	4	5	5	5	4	5	4	4
DEU	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
NGA	6	6	6	7	6	6	6	5	5	4	4	4	5	4	5	5
BRA	2	2	2	2	2	2	2	2	2	2	2	2	1	1	2	2
ARE	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8

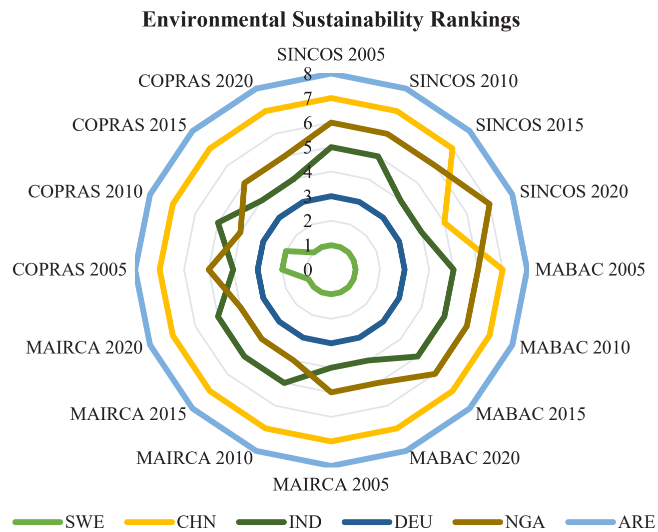

Fig. 4. Rankings of countries based on different MCDM methods.

countries by method and year. Sweden (SWE) has led in environmental sustainability performance for most of the methods and years. This demonstrates that Sweden consistently achieves the highest performance in terms of environmental sustainability across all methods. Brazil (BRA) is generally ranked second in SINCOS and other methods, and first place in COPRAS in the years 2005 and 2010. China (CHN) and the United Arab Emirates (ARE) consistently occupied the lowest ranks across all methods, primarily due to their high energy intensity and carbon emission levels. Canada (CAN) and India (IND) showed mid-level performances, while Nigeria (NGA) fluctuated between lower and mid-level rankings depending on the method. These results show that the SINCOS method produced rankings that are aligned with those obtained from the other methods.

Table 10.
Correlation coefficients between SINCOS and other methods.

Method	Spearman rank				Kendall tau			
	2005	2010	2015	2020	2005	2010	2015	2020
MABAC	1.00	1.00	0.98	0.91	1.00	1.00	0.93	0.79
MAIRCA	0.93	0.91	0.93	0.91	0.86	0.79	0.86	0.79
COPRAS	0.91	0.88	0.98	0.91	0.79	0.71	0.93	0.79

To further evaluate the consistency of the SINCOS with the other MCDM methods, Spearman's rank correlation and Kendall's tau coefficient analyses were conducted. The correlation coefficients have been presented in Table 10 and demonstrated in Fig. 6. There is a high correlation between the SINCOS method and the other approaches. Spearman's rank correlation values range from 0.88 to 1.00, and Kendall's tau values range from 0.71 to 1.00. Specifically, a strong correlation was observed between the MABAC and SINCOS methods.

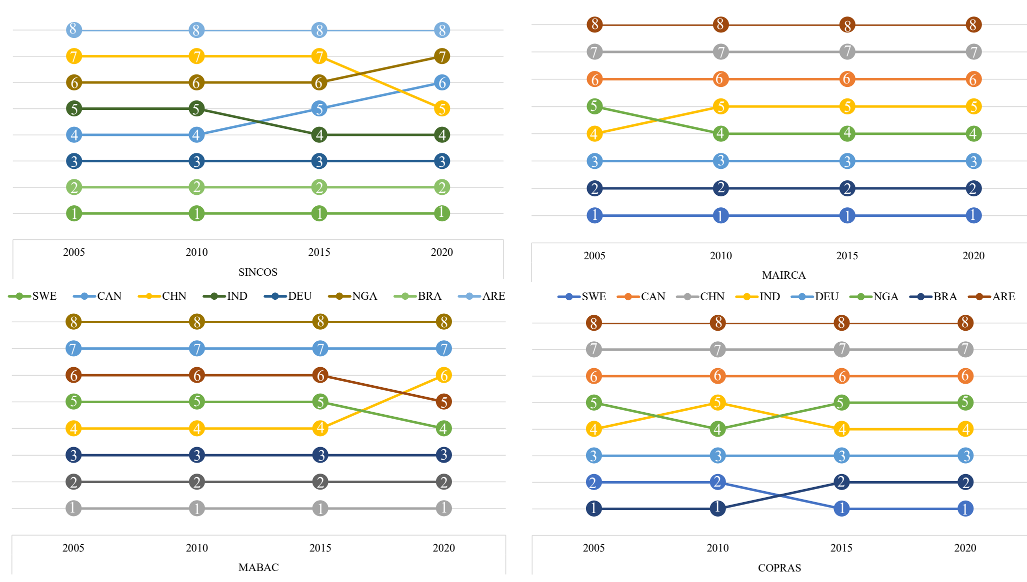

Fig. 5. Rankings of countries based on years.

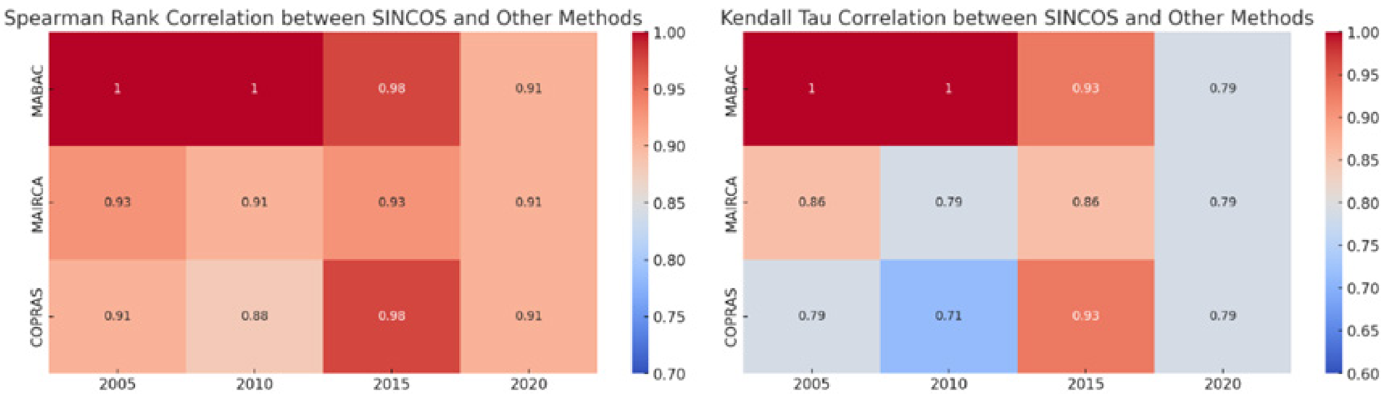

Fig. 6. Correlation heat map.

4. Discussion

The findings derived from both the simulation and empirical cases corroborate the efficacy and validity of the SINCOS method. The application of the SINCOS model to the screening of countries according to their sustainability performance on eight indicators has yielded results that demonstrate reasonable consistency with those obtained by traditional MCDM approaches, including MAIRCA, MABAC, and COPRAS. In contrast to the majority of extant methodologies, including TOPSIS, VIKOR, and MAIRCA, which depend on linear normalization of criteria, SINCOS enhances this approach through a nonlinear trigonometric transformation of the scores between criteria and the relative performance of alternatives. SINCOS implements a simple two-phase normalization process and does not include pairwise comparisons. These processes can create a computational burden for the researcher and compromise the consistency of the results.

5. Conclusions

This study introduced a novel trigonometric MCDM framework, designated SINCOS, which incorporates sine and cosine transformations to account for nonlinear relationships among criteria and the relative effectiveness of alternatives. This constitutes the primary contribution of the present study. In subsequent studies, the SINCOS framework may be integrated with fuzzy logic. At present, the framework is confined to decision-making scenarios that involve numerical criteria. The incorporation of fuzzy logic would endow SINCOS with an augmented degree of flexibility by enabling the implementation of both numeric and linguistic criteria. The SINCOS framework demonstrated highly favourable outcomes in terms of evaluating environmental sustainability. The testing of framework applications in a range of real-world cases has the potential to facilitate a more profound comprehension of the framework's effectiveness and dependability in diverse decision-making scenarios.

CRediT authorship contribution statement

Kenan Karagül Conceptualization, methodology, writing original draft. **Yusuf Şahin:** Investigation, writing original draft, validation, visualization. **Sezai Tokat:** Conceptualization, methodology, validation. **Özcan Mutlu:** Conceptualization, methodology, validation.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work presented in this paper.

Data Availability

Enquiries about data availability should be directed to the authors.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript, and no images were manipulated using AI.

References

Beach, L.R., 1993. Broadening the definition of decision making: The role of prechoice screening of options. Psychol Sci 4, 215-220. https://doi.org/10.1111/j.1467-9280.1993.tb00264.x

Benayoun, R., Roy, B., & Sussman, N., 1966. Manual de référence du programme ELECTRE [Reference manual of the ELECTRE program] (Note de Synthèse et Formation No. 25). Groupe METRA. pp. 1–79.

Biswas, A., Baranwal, G., Kumar Tripathi, A., 2022. ABAC: Alternative by alternative comparison based multi-criteria decision making method. Expert Syst with Applications 208, 118174. https://doi.org/10.1016/j.eswa.2022.118174

Brans, J.P., 1982. The engineering of decision: Elaboration instruments of decision support method PROMETHEE. Laval University, Quebec, Canada. pp. 183-213.

Brans, J. P., & Vincke, P., 1985. A preference ranking organisation method: (The PROMETHEE method for multiple criteria decision-making). Management Science, 31(6), 647–656. https://doi.org/10.1287/mnsc.31.6.647

Brauers, W.K.M., Zavadskas, E.K., 2011. Multimoora optimization used to decide on a bank loan to buy property. Technological and economic development of economy 17, 174-188. https://doi.org/10.3846/13928619.2011.560632

Chen, S. J., & Hwang, C. L., 1992. Fuzzy multiple attribute decision making methods. In S. J. Chen & C. L. Hwang (Eds.), Fuzzy multiple attribute decision making: Methods and applications (pp. 289–486). Springer-Verlag. https://doi.org/10.1007/978-3-642-46768-4_5

Forman, E.H., Gass, S.I., 2001. The analytic hierarchy process—An exposition. Oper Res 49, 469-486. https://doi.org/10.1287/opre.49.4.469.11231

Hwang, C.-L., & Yoon, K., 1981. Multiple attribute decision making: Methods and applications (Vol. 186, Lecture Notes in Economics and Mathematical Systems). Springer-Verlag. https://doi.org/10.1007/978-3-642-48318-9

IPCC, 2023: Summary for policymakers. In: Climate Change 2023: Synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, https://doi.org/10.59327/IPCC/AR6-9789291691647.001

Nguyen, A. T. (2023). The improved CURLI method for multi-criteria decision making. Engineering, Technology & Applied Science Research, 13, 10121–10127. https://doi.org/10.48084/etasr.5518

Opricovic, S., Tzeng, G.-H., 2004. Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. Eur J Oper Res 156, 445-455. https://doi.org/10.1016/s0377-2217(03)00020-1

Potomkin, M.M., Dublian, O.V., Khomchak, R.B., 2019. Approach to the development, improvement, and modification of multi-criteria decision-making methods. Cybern Syst Anal 55, 967-977. https://doi.org/10.1007/s10559-019-00207-7

Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. J Math Psychol 15, 234-281. https://doi.org/10.1016/0022-2496(77)90033-5

Sotoudeh-Anvari, A., 2023. Root assessment method (RAM): A novel multi-criteria decision making method and its applications in sustainability challenges. J Cleaner Prod 423, 138695. https://doi.org/10.1016/j.jclepro.2023.138695

Triantaphyllou, E., 2000. A computational evaluation of the original and the revised AHP. In Multi-criteria decision making methods: A comparative study (Vol. 44, pp. 45–74). Springer. https://doi.org/10.1007/978-1-4757-3157-6_3

United Nations Economic and Social Commission for Asia and the Pacific. (2019). Greening the Blue report 2019: The UN system's environmental footprint and efforts to reduce it. United Nations. https://www.greeningtheblue.org/reports/greening-blue-report-2019

Wang, J., Zhang, X., Shen, Q., 2024. Choquet-like integrals with rough attribute fuzzy measures for data-driven decision-making. IEEE trans. Fuzzy Syst 32, 2825-2836. https://doi.org/10.1109/tfuzz.2024.3363415

World Bank. (n.d.). World Development Indicators. DataBank. https://databank.worldbank.org/source/world-development-indicators#

Yoon, K., Hwang, C.L., 1981. TOPSIS (technique for order preference by similarity to ideal solution)–a multiple attribute decision making, Multiple attribute decision making–methods and applications, a state-of-the-art survey. Berlin: Springer Verlag 128, 140.

Zavadskas, E.K., Kaklauskas, A., Sarka, V., 1994. The new method of multicriteria complex proportional assessment of projects. Technological Econ Dev Economy 1, 131-139.