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Evaluating ecological sustainability performance of OECD countries via entropy-based TOPSIS

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Abstract

The aim of this study is to comparatively examine the ecological footprint performances of 25 OECD member countries for the year 2022 using the Entropy-based TOPSIS method. The analysis includes six criteria: pasture lands, agricultural lands, forest areas, fishing grounds, built-up areas, and carbon footprint. The analysis revealed that the most significant criterion determining ecological footprint performance is the Carbon Footprint (CF). Based on the data obtained in this study, the highest total ecological footprint was observed in the United States, whereas Norway demonstrated the closest performance to the ideal solution. This indicates that countries with high ecological footprints have room for improvement in terms of environmental sustainability, while those closer to the ideal solution exhibit a more balanced environmental performance under current practices

Keywords Ecological Footprint, OECD Countries, Entropi based TOPSIS, Sustainability

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1. Introduction

The concept of sustainable development was first defined by the United Nations (UN) Brundtland Commission in 1987 and later endorsed by world leaders at the 1992 Rio Earth Summit. At its core, sustainable development is about meeting the needs of the present generation without compromising the ability of future generations to meet their own needs. It emphasizes a balanced approach that considers environmental protection, economic growth, and social well-being simultaneously. In other words, true sustainability requires that we advance economically and socially while preserving the planet for those who come after us (Akgül, 2010; Özmehmet, 2008; Tosunoğlu, 2015).

Significant progress in measuring sustainable development has been made through the Rio and Johannesburg conferences. These gatherings emphasized the importance of developing sustainability indicators, assessing environmental, social, and economic dimensions together, and strengthening mechanisms for international cooperation (UN, 2014). Among the 12 sustainability indicators identified by Parris & Kates (2003), the Ecological Footprint holds a particularly prominent place, as it provides a clear measure of humanity's impact on the planet.

The Ecological Footprint is a key indicator that measures the impact of human activities on nature and assesses the level of sustainable living. Developed by the Global Footprint Network, the Ecological Footprint is updated annually at the national level, allowing for comparisons over time and analyses of historical trends (Borucke et al., 2013). It consists of six main components: grazing lands, croplands, forests, fishing grounds, built-up areas, and the carbon footprint, each reflecting a different aspect of human pressure on the environment. The concept of the Ecological Footprint was first introduced by Wackernagel & Rees (1998) and later further developed by Arrow et al. (2004) and Ewing et al. (2008). It serves as an indicator of how much of the biosphere's regenerative capacity is being used by human activities. The Ecological Footprint evaluates the extent to which biologically productive areas on Earth are being consumed and the risk of exceeding their future regenerative capacity. Calculations also consider long-term environmental impacts and factors such as soil erosion.

The Ecological Footprint can be expressed in terms of global hectares (gha) per person or as the "Number of Earths", indicating how many planets would be needed to sustain humanity if everyone lived with the same footprint. It measures how much of the biologically productive land and water areas are required to produce all the resources consumed by an individual, a population, or an activity, and to absorb the resulting waste with current technology. Due to the global nature of trade, a country's Ecological Footprint also includes land and sea areas in different parts of the world. This concept is commonly referred to simply as the "Footprint" (Global Footprint Network, 2024).

In Ecological Footprint analysis, the concept of biocapacity refers to a region's ability to generate natural resources and ecosystem services. Biocapacity areas are classified to cover different ecosystem types and human activities. These include forests, croplands, grazing lands, lakes and oceans, built-up areas, and carbon sequestration zones (Borucke et al., 2013). Such areas are critical for assessing societies' natural resource use and overall sustainability levels. Research in this field has demonstrated that Ecological Footprint calculations serve as a valuable tool for evaluating environmental sustainability performance. For example, Borucke et al. (2013) analyzed the components of the Ecological Footprint at a global scale, while Shafiei & Salim (2014) focused on sustainability strategies aimed at reducing carbon emissions. Additionally, Ifeakor (2023) conducted regional analyses on organic farming and its environmental impacts. However, these studies often concentrate on specific regions or individual components and do not provide up-to-date, comparative performance analyses for OECD countries.

This study provides a comparative analysis of the Ecological Footprint and its subcomponents for 25 OECD member countries in 2022 using an entropy-based TOPSIS method, offering a holistic and objective assessment of their sustainability performance. Furthermore, the study identifies the relative importance of the Ecological Footprint components, highlighting the critical role of the carbon footprint. In this way, the research makes a timely, comprehensive, and methodologically original contribution to the existing literature.

2. Theoretical Framework

The concept of the Ecological Footprint was first introduced by Wackernagel & Rees (1998) and later further developed by Arrow et al. (2004) and Ewing et al. (2008). It serves as a key indicator of how much of the biosphere's regenerative capacity is being utilized by human activities. The Ecological Footprint assesses the use of biologically productive areas on Earth and the risk of exceeding their future regenerative capacity. Additionally, its calculations take into account long-term environmental impacts and factors such as soil erosion.

The Ecological Footprint is typically measured in global hectares (gha) per person, indicating the amount of biologically productive land and water required to produce the resources consumed and absorb the resulting waste of an individual, population, or activity using current technology and resource management practices. Another way to express it is the "Number of Earths", which represents how many planets would be needed to sustain humanity if everyone lived at the same level of consumption.

Due to the widespread nature of global trade, the Ecological Footprint of an individual or a country can encompass land and sea areas in different parts of the world. In this context, the Ecological Footprint is mostly considered from a consumption-based perspective, which is why the term "consumption Ecological Footprint" is also used. Commonly referred to simply as the "Footprint" (Global Footprint Network, 2024), it classifies biocapacity areas into forests, croplands, grazing lands, lakes and oceans, built-up areas, and carbon sequestration zones (Borucke et al., 2013). In this way, the Ecological Footprint serves as a critical tool for assessing the sustainability of natural resource use, making the extent of environmental pressures visible and guiding policy development processes.

Figure 1 presents a comparative overview of per capita Ecological Footprint values across OECD countries. This visual illustrates the differences in resource consumption among countries and highlights which nations exert greater pressure on the environment in terms of sustainability. From Figure 1, it is evident that some developed countries contribute to increased environmental pressure due to their high Ecological Footprint values, while others maintain lower levels of consumption.

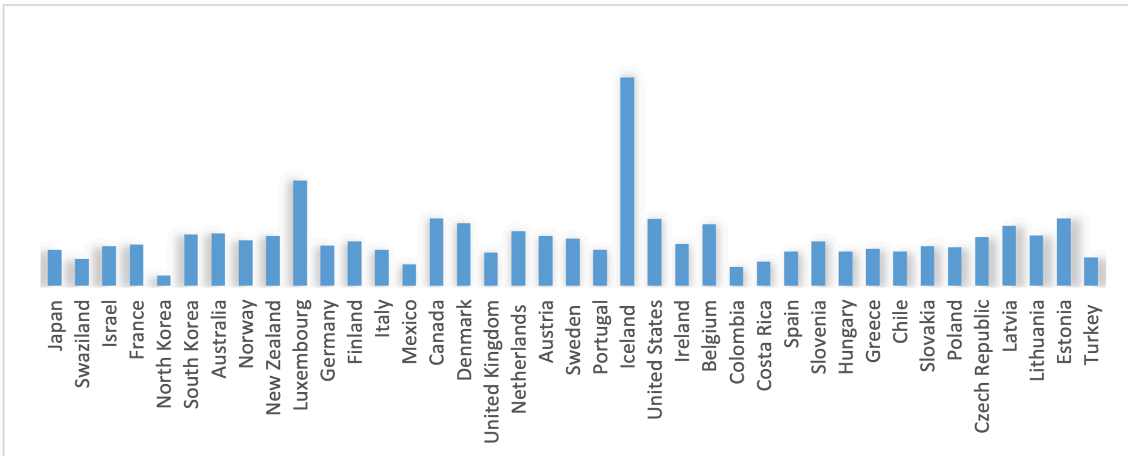

Figure 1. Countries Ranked by Per Capita Ecological Footprint in OECD Nations (2024)

Source: Global Footprint Network (2024). Available at: https://www.footprintnetwork.org

The components of the Ecological Footprint are categorized as follows:

- Carbon Footprint: The biologically productive area required to sequester CO_2 emissions resulting from fossil fuel consumption, land-use changes, and chemical processes, using oceans and forests.
- Grazing Land Footprint: The area needed to support livestock activities for the production of animal-based products such as meat, milk, leather, and wool.
- Fishing Grounds Footprint: The water area required for the production of fish and seafood harvested from marine and freshwater species.
- Cropland Footprint: The agricultural land used for producing food, fiber, animal feed, oil crops, and rubber for human consumption.
- Built-up Land Footprint: The area occupied by human activities such as transportation, housing, industry, and energy production (https://www.obi.bilkent.edu.tr/ekookul/pdf/ekolojikayakizi.pdf, accessed November 22, 2024).

These components are used to calculate the Ecological Footprint of an individual or a society, providing important indicators of the sustainability of nature. Ecological Footprint analyses reveal the sustainability of natural resource use and highlight the areas where environmental pressures are most intense, thereby offering guidance for policymakers and society at large.

3. Literature Review

In the Turkish literature, studies on the Ecological Footprint can generally be grouped under four main categories:

- Theoretical and Conceptual Studies: This category includes studies that examine the Ecological Footprint from an environmental sustainability perspective, define the concept, and explain its calculation methods. These studies evaluate the advantages and disadvantages of the Ecological Footprint and emphasize its importance in measuring environmental impacts (Özsoy & Dinç, 2016; Tosunoğlu, 2015).

- Review and Literature Survey Studies: Studies in this group systematically examine the academic knowledge on the Ecological Footprint and provide a framework by integrating different research findings. For instance, Kaypak (2013) highlights that the Ecological Footprint is steadily increasing and poses a threat to environmental peace. The study emphasizes that developed countries tend to overconsume resources, disrupting the global ecological balance, and argues that the sustainable use of Earth's resources and the reduction of the Ecological Footprint are essential for maintaining environmental peace. Similarly, Mızık & Yiğit Avdan (2020) define the Ecological Footprint as a quantitative tool for measuring the sustainability of natural resource use. Their study underscores its value as a tool for sustainable resource management when linked with economic indicators. They also note that the Ecological Footprint concept has been extended to a "Footprint Family", allowing for the monitoring of the sustainable use of different ecological resources.

- Econometric Studies: Studies in this category examine the relationships between the Ecological Footprint and economic or environmental variables, often employing advanced econometric methods such as regression analysis. For example, Yurtkuran (2019) supported findings using the Fourier stationarity test. In Ablay (2025) study, the Ecological Footprint of OECD countries was analyzed using Entropy and TOPSIS methods. The weights of the Ecological Footprint components were determined through the Entropy method, while the countries' performance rankings were obtained using TOPSIS. According to the findings, the carbon footprint criterion held the highest importance, whereas the built-up land criterion was of lowest importance; in the performance ranking, the United States exhibited the highest performance, and Germany the lowest (Ablay, 2025). Similarly, the present study evaluates the Ecological Footprint performance of OECD countries using the same Entropy-TOPSIS framework, revealing their environmental sustainability status. When compared with Ablay (2025), both studies are methodologically parallel; however, differences in country rankings and criterion weights arise due to study-specific datasets and selected indicators. This highlights both the applicability of the methods and the fact that results may vary depending on the scope of analysis and the time period considered.

- Field Data-Based Studies: This category includes studies conducted using survey data collected directly from the field. As summarized by Rüstemoğlu (2023), such Ecological Footprint calculations based on field data are exemplified in research by Akıllı et al. (2008), Keleş et al. (2008), Coşkun and Sarıkaya (2014), Eren et al. (2016, 2017), and Özgen and Aksoy (2017).

In the international literature, focusing on studies outside of Türkiye, econometric analyses have increasingly taken center stage in recent years for examining the Ecological Footprint and environmental sustainability (Afshan & Yaqoob, 2022; Pata, 2021; Tiwari et al., 2022; Tuna, 2022). In this context, the quantile ARDL method has emerged as a frequently employed approach in such analyses (Afshan & Yaqoob, 2022; Tiwari et al., 2022). Tuna (2022) adopted FMOLS and DOLS methods, providing a different perspective. Additionally, the literature highlights the use of mathematical modeling and other quantitative approaches in Ecological Footprint studies (Balezentis et al., 2022; Lai et al., 2022). Some studies have gone beyond analyzing the Ecological Footprint alone by also examining the determinants of CO_2 emissions, offering a more comprehensive view of environmental pressures (Pata, 2021; Tuna, 2022).

In the literature, studies that, similar to the present research, combine Ecological Footprint indicators with multi-criteria decision-making (MCDM) methods are summarized in Table 1. This similarity is particularly evident in the evaluation of environmental performance through multi-criteria analyses and the application of MCDM methods in sustainability assessments.

Table 1. Literature Review

Author(s)	Covered Period / Scope	Variables / Criteria	Method	Summary of Findings
Meral (2024)	Türkiye and Turkic Republics, estimated 2020–2023	Sustainable development indicators	CRITIC-LOPCOW, CoCoSo	Uzbekistan, Kyrgyzstan, and Kazakhstan achieved the highest performance; Türkiye and Tajikistan ranked lower.
Alpdoğan (2023)	OECD countries, 2015–2022	Sustainable development policies	ARAS method	New Zealand, South Korea, and Iceland were the most effective; the USA, Canada, and Türkiye performed the lowest.
Torkayesh et al. (2024)	G7 countries, 2018–2023	Contribution of entrepreneurial activities to social sustainability	Shannon Entropy – MARCOS	Italy and the USA led in entrepreneurship contributing to social sustainability.
Arı & Dursun (2024)	Current aircraft models, 2023	Environmental friendliness of aircraft models	Bayesian BWM, IF EDAS	“Alternative 7” model selected as the most environmentally friendly aircraft.
Fatemi et al. (2021)	Iran, Fars Province, 2018–2020	Rural biocapacity, Ecological Footprint	Analytic Hierarchy Process (AHP)	Emphasized the importance of ecological indicators in agricultural planning and proposed a paradigm shift.
Zhao et al. (2022)	Island regions, 2010–2015	Economic and ecological development indicators	Combination of TOPSIS and Entropy	Developed balanced economic and ecological strategies to

	ensure long-term sustainability.

4. Materials and Methods

In this study, although 33 OECD member countries were initially considered, the analyses were conducted using data from only 25 countries. The main reason for this limitation is the lack of up-to-date and comparable datasets for the six Ecological Footprint components used in this study for certain countries. The countries excluded due to missing data are Colombia, Costa Rica, the Czech Republic, Estonia, Finland, Slovakia, Slovenia, and Hungary. To maintain the methodological integrity and comparability of the study, only countries with complete datasets were included in the analysis. Accordingly, the analyses were performed for 25 countries, taking into account data quality and consistency.

In this study, the Entropy and TOPSIS methods were jointly employed to evaluate the Ecological Footprint performance of OECD countries. These methods were chosen because they allow for the objective and systematic analysis of multiple criteria. The Entropy method is an objective technique that determines the weights of criteria based on the variability of the data, ensuring that criteria which highlight differences between countries receive higher weights, thereby minimizing subjective influence. On the other hand, the TOPSIS method ranks countries based on their distance from the ideal (best) and negative ideal (worst) values, providing a relative assessment of each country's Ecological Footprint performance.

The combined use of these methods enables objective evaluation of the data and allows for a comparative analysis of countries' environmental performance. Additionally, it helps identify the most influential criteria, offering guidance for shaping sustainability policies. This section also details the dataset used, the criteria included in the analysis, and the applied methods.

The main aim of the study is to investigate the Ecological Footprint and its components in 25 OECD countries for the year 2022 and to determine whether these impacts exhibit persistent effects. The countries included in the analysis are: Australia, Austria, Belgium, Canada, Chile, Denmark, France, Germany, Greece, Israel, Italy, Japan, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Türkiye, the United Kingdom, and the United States. These countries were selected based on data completeness and comparability criteria.

The data used in this study, measured in per capita global hectares (gha), were obtained from the Global Footprint Network database. The analysis focused on the six components of the Ecological Footprint: cropland, grazing land, forest land, built-up land, fishing grounds, and the carbon footprint. Using these data, the differences in Ecological Footprint among countries were thoroughly analyzed, and the implications of these differences for environmental sustainability were evaluated. During the analysis process, care was taken to ensure that the dataset was complete and comparable, and countries with missing data were excluded from the study.

4.1. Entropy Method

The steps for applying the Entropy method to calculate criterion weights are outlined below, based on the approaches of Alp, Öztel, and Köse (2015), Wang et al. (2017), Es and Kocadağ (2020), and Ersoy (2021).

Step 1: Construction of the Decision Matrix

A decision matrix is created for m alternatives under n criteria.

$$D = \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix} \quad (1)$$

Here, x_{ij}, represents the performance value of the i th alternative with respect to the j th criterion ($i = 1, 2, ..., m$ and $j = 1, 2, ..., n$).

Step 2: Normalization of the Decision Matrix

In this step, i represents the alternatives and j represents the criteria. r_{ij} denotes the normalized values, and x_{ij} represents the original benefit values of the decision matrix.

$$r_{ij} = \frac{x_{ij}}{\sum_{p=1}^{m} x_{pj}}, \qquad i = 1, 2, ..., m \text{ and } j = 1, 2, ..., n \quad (2)$$

The normalized decision matrix $R = [r_{ij}]_{mxn}$ is obtained using the normalization formula.

Step 3: Determination of Entropy Values for Criteria

Using the formula, the entropy value for each criterion is calculated.

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} r_{ij} \ln r_{ij}, \qquad i = 1, 2, ..., m \text{ and } j = 1, 2, ..., n \quad (3)$$

Here, k represents the entropy coefficient, and e_j denotes the entropy value for the j-th criterion

Step 4: Determination of the Degree of Divergence

The degree of divergence, denoted as d_j, is calculated for each criterion using the entropy values obtained in the previous step as follows:

$$d_j = 1 - e_j, \qquad j = 1, 2, ..., n \quad (4)$$

Step 5: Calculation of Entropy-Based Criterion Weights

The weight of each criterion is determined as the ratio of its degree of divergence to the total degree of divergence. As a result, the weight values (w_j) are calculated as follows, ensuring that $\sum_{j=1}^{n} = 1$

$$w_j = \frac{d_{ij}}{\sum_{j=1}^{n} d_{ij}} \quad (5)$$

4.2. TOPSIS Method

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method was developed by Hwang & Yoon (1981) and is widely used in multi-criteria decision-making (MCDM) problems (Hwang & Yoon, 1981; Joshi & Kumar, 2016). The core principle of TOPSIS is that the best alternatives are those closest to the ideal solution. Compared to the ELECTRE (Elimination and Choice Expressing Reality) method, the TOPSIS approach is generally less complex and faster (Yaralıoğlu, 2010).

In TOPSIS, alternatives are ranked based on their geometric distances to the positive and negative ideal solutions, allowing for an objective comparison of performance. Criterion evaluations are conducted using quantitative values (Afsordegan et al., 2016). The key elements of the TOPSIS method can be defined as follows (Biswas et al., 2015).

- $A = \{A_1, A_2, ..., A_m\}$ set of alternatives,
- $C = \{C_1, C_2, ..., C_n\}$ set of criteria,
- $D = (d_{ij}), \quad i = 1, 2, ..., mj = 1, 2, ..., n$ performance ratings
- $W = \{w_1, w_2, ..., w_n\}$ criterion weight vector,

The steps of the TOPSI;S method are explained as follows (Lourenzutti & Krohling, 2016; Yaralıoğlu, 2010).

Step 1: Construction of the Decision Matrix

In the decision matrix, the rows represent the alternatives and the columns represent the criteria. The matrix A shown below is the initial matrix created by the decision-maker.

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} \tag{6}$$

In the A matrix, m represents the number of alternatives, and n represents the number of evaluation criteria.

Step 2: Construction of the Standardized Decision Matrix

The standardized decision matrix is calculated using Eq. 7

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}} \tag{7}$$

Here, r_{ij} represents a definite value for all $i \in \{1, 2, ..., m\}$ and $j \in \{1, 2, ..., n\}$. The normalized decision matrix R is obtained as follows:

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} \tag{8}$$

Step 3: Construction of the Weighted Standardized Decision Matrix

The weight values for the prioritized evaluation criteria are determined, and the normalized values are multiplied by these weights to obtain Eq. 5. Using this equation, the weighted decision matrix V is constructed.

$$V = \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \dots & w_n r_{1n} \\ w_1 r_{21} & w_2 r_{22} & \dots & w_n r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_1 r_{m1} & w_2 r_{m2} & \dots & w_n r_{mn} \end{bmatrix} \tag{9}$$

Step 4: Determination of the Positive Ideal and Negative Ideal Solutions for Each Criterion

Generally, for benefit criteria:

$$v_j^+ = \max\left(w_1 r_{1j}, \dots w_j r_{mj}\right) \text{ and } v_j^- = \min\left(w_1 r_{1j}, \dots w_j r_{mj}\right) \tag{10}$$

For cost criteria:

$$v_j^+ = \min\left(w_1 r_{1j}, \dots w_j r_{mj}\right) \text{ and } v_j^- = \max\left(w_1 r_{1j}, \dots w_j r_{mj}\right) \tag{11}$$

Step 5: Calculation of Separation Measures for Each Alternative

In the TOPSIS method, it is necessary to determine the deviations of each alternative's evaluation criterion values from the positive and negative ideal solution sets. The separation from the positive ideal (S_i^+) is calculated using Eq. 12, while the separation from the negative ideal (S_i^-) is calculated using Eq. 13.

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2}, \quad i = 1, 2, \dots, n \tag{12}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2}, \quad i = 1, 2, \dots, n \tag{13}$$

Step 6: Calculation of the Relative Closeness to the Ideal Solution for Each Alternative

The relative closeness of each alternative to the ideal solution is calculated using the separation measures from the positive and negative ideal solutions. The relative closeness to the ideal solution (C_i^+) is computed using Eq. 14.

$$C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-} \tag{14}$$

Here, C_i^+ takes a value in the range [0, 1], where $C_i^+ = 1$ represents the absolute distance of the alternative from the positive ideal solution, and $C_i^+ = 0$ represents the absolute distance from the negative ideal solution. The alternatives $(A_1, A_2, \dots A_m)$ are ranked according to their C_i^+ values, with higher values indicating higher priority or preference among the alternatives.

5. Research Findings

An analysis of the total ecological footprint of 25 OECD member countries for the year 2022 reveals significant differences among the countries. The results indicate that some countries are in a more advantageous position in terms of sustainability, while others exert higher pressure on natural resources. Table 2 presents the countries' total ecological footprints in global hectares (gha) along with their rankings. This table enables a comparative assessment of the environmental impacts of the countries.

Table 2. Ranking of OECD Countries by Total Ecological Footprint (in Global Hectares, 2022)

Rank	Country	Total Ecological Footprint (Global Hectares)
1	United States (USA)	2.66 billion gha
2	Japan	586 million gha
3	Germany	388 million gha
4	Canada	355 million gha
5	France	285 million gha
6	United Kingdom (UK)	280 million gha
7	Italy	210 million gha
8	Australia	185 million gha
9	Spain	170 million gha
10	Sweden	165 million gha
11	Poland	150 million gha
12	Netherlands	145 million gha
13	Switzerland	130 million gha
14	Portugal	125 million gha
15	Norway	110 million gha
16	Denmark	100 million gha
17	Austria	95 million gha
18	Greece	85 million gha
19	South Korea	80 million gha
20	Belgium	75 million gha
21	Luxembourg	70 million gha
22	Chile	65 million gha
23	Mexico	60 million gha
24	Türkiye	55 million gha
25	Indonesia	50 million gha

Table 2 presents the total ecological footprints of 25 OECD countries for the year 2022. The data are ranked based on the countries' populations and per capita ecological footprints. According to the table, countries with large and developed economies generally exhibit higher total ecological footprints. For example, the United States (USA) ranks first with 2.66 billion global hectares, while other major economies such as Japan and Germany also occupy high positions in the ranking.

The six criteria presented in the table represent different aspects of the countries' ecological footprints. These include grazing land, cropland, forest areas, fishing grounds, built-up land, and the carbon footprint. These criteria allow for a more detailed examination of each country's impact on the environment. Larger countries and industrialized economies tend to have higher ecological footprints due to greater energy consumption, extensive agricultural areas, and higher carbon emissions. In contrast, smaller and developing countries generally exhibit lower total ecological footprints. Türkiye ranks 24th in this table with a total of 55 million global hectares, indicating a relatively lower ecological footprint compared to other OECD countries. However, when compared to more developed nations, Türkiye still has significant room for improvement in reducing its environmental impact.

Table 3. Ecological Footprint Criteria and Codes

Criteria	Sub-Criteria	Code
Ecological Footprint Criteria	Grazing Land	OTL
	Cropland	TAR
	Forest Areas	ORM
	Fishing Grounds	BAL
	Built-up Land	YAP
	Carbon Footprint (CF)	KAR

Table 3 presents the main criteria and sub-criteria used in the calculation of the Ecological Footprint. The sub-criteria represent more detailed components of each ecological footprint criterion and play a crucial role in evaluating environmental performance. Codes are used to provide a concise representation of each sub-criterion. The table serves as a clear guide for how the criteria are to be normalized and how the weighted performance rankings are generated.

The weights applied in this study were determined using the TOPSIS method in combination with entropy calculations to reflect each criterion's influence on environmental performance. This approach ensures that the environmental performance of each country is ranked considering the relative importance assigned to each criterion. In the decision-making process, the criteria are the measures under evaluation; the weights indicate their relative importance, while the dispersion values show the extent to which the criteria differentiate among alternatives.

Table 4 presents the weighted normalized performance values of countries according to these criteria, illustrating how each country is positioned across the environmental indicators. This allows for a comparative and analyzable assessment of the countries' ecological footprint performance.

Table 4. Criteria, Weights, and Dispersion Degrees

Criterion	Weight	Dispersion Degree
Built-up Areas (YAP)	0.1604	0.8683
Carbon Footprint (CF)	0.1578	0.8514
Agricultural Land (TAR)	0.1679	0.9058
Fishing Grounds (BAL)	0.1799	0.9724
Forest Areas (ORM)	0.1692	0.9206
Pasture Land (OTL)	0.1597	0.8663

Table 5 presents the normalized decision matrix used to compare the performance of countries across different environmental criteria. The normalization process transforms criterion values measured on different scales into a common scale, enabling a fair comparison among the criteria. This matrix serves as the fundamental dataset for evaluating the alternatives in the decision-making process, providing the basis for subsequent weighted performance calculations and TOPSIS analysis.

Table 5. Normalized Decision Matrix for OECD Countries (2022)

Country	Built-up Areas (YAP)	Carbon Footprint (CF)	Agricultural Land (TAR)	Fishing Grounds (BAL)	Forest Areas (ORM)	Grasslands (OTL)	Total Area
USA	0.1180	0.1140	0.0730	0.0006	0.2801	0.4143	0.4470
Japan	0.1089	0.0958	0.3546	0.0228	0.2882	0.1297	0.1863
Germany	0.1091	0.0949	0.3174	0.0104	0.2971	0.1710	0.2244
Canada	0.1204	0.1138	0.0658	0.0017	0.1931	0.5053	0.4938
France	0.2939	0.2575	0.0484	0.0056	0.2119	0.1826	0.2641
UK	0.2890	0.2645	0.1039	0.0054	0.1575	0.1798	0.2895
Italy	0.1728	0.1540	0.0422	0.0119	0.2730	0.3462	0.5693
Australia	0.1583	0.1343	0.0763	0.0104	0.4429	0.1779	0.4556
Spain	0.1849	0.1348	0.0304	0.0391	0.3248	0.2860	0.3590
Sweden	0.2420	0.2207	0.0341	0.0222	0.1439	0.3371	0.3088
Poland	0.2374	0.2230	0.0654	0.0222	0.1425	0.3095	0.4543
Netherlands	0.2627	0.2309	0.0584	0.0145	0.1782	0.2554	0.4542
Switzerland	0.2371	0.1879	0.1000	0.0096	0.3262	0.1392	0.3836
Portugal	0.2352	0.1873	0.0551	0.0108	0.3577	0.1539	0.3360
Norway	0.0669	0.0393	0.1900	0.5185	0.0950	0.0904	0.2217
Denmark	0.1896	0.1806	0.0554	0.0164	0.2935	0.2645	0.4999
Austria	0.2368	0.2050	0.0763	0.0236	0.1704	0.2879	0.4720
Greece	0.2161	0.2017	0.0712	0.0127	0.1737	0.3245	0.5963
S. Korea	0.2627	0.2396	0.1054	0.0068	0.1565	0.2290	0.5544
Belgium	0.3292	0.2215	0.0681	0.0179	0.1570	0.2063	0.5947
Luxembourg	0.2313	0.2074	0.1216	0.0199	0.0793	0.3405	0.5435
Chile	0.2059	0.1783	0.0620	0.0064	0.2055	0.3419	0.5391
Mexico	0.2366	0.2135	0.1163	0.0107	0.2651	0.1577	0.7639
Türkiye	0.2960	0.2484	0.0927	0.0061	0.3030	0.0538	0.7279
Indonesia	0.2178	0.1850	0.0868	0.0139	0.2008	0.2956	0.5088

Table 6 presents the weighted normalized decision matrix, which is obtained by multiplying the normalized values of the criteria from the decision matrix by the respective weights representing the relative importance of each criterion. This matrix allows for a more realistic and balanced evaluation of the alternatives' performance by taking into account the influence of each criterion in the decision-making process. Consequently, the environmental performance of each country is analyzed objectively in accordance with the criterion weights.

Table 6. Weighted Normalized Decision Matrix

Country	Built-up Area (YAP)	Carbon Footprint (CF)	Agricultural Land (TAR)	Fishery Area (BAL)	Forest Area (ORM)	Pasture Land (OTL)
USA	0.01891	0.01797	0.01226	0.00011	0.04739	0.06612
Japan	0.01746	0.01508	0.05957	0.00409	0.04885	0.02069
Germany	0.01748	0.01497	0.05333	0.00187	0.05030	0.02731
Canada	0.01932	0.01794	0.01107	0.00031	0.03269	0.08058
France	0.04714	0.04064	0.00812	0.00101	0.03581	0.02913
UK	0.04634	0.04183	0.01747	0.00100	0.02667	0.02874
Italy	0.02769	0.02431	0.00709	0.00214	0.04612	0.05532
Australia	0.02537	0.02117	0.01281	0.00187	0.07492	0.02837
Spain	0.02963	0.02129	0.00510	0.00703	0.05502	0.04565
Sweden	0.03891	0.03502	0.00584	0.00399	0.02433	0.05373
Poland	0.03804	0.03521	0.01101	0.00399	0.02405	0.04940
Netherlands	0.04211	0.03646	0.00981	0.00261	0.03014	0.04083
Switzerland	0.03799	0.02970	0.01679	0.00173	0.05525	0.02223
Portugal	0.03774	0.02955	0.00927	0.00194	0.06049	0.02458
Norway	0.01073	0.00620	0.03191	0.09294	0.01608	0.01446
Denmark	0.03038	0.02847	0.00931	0.00295	0.04966	0.04228
Austria	0.03793	0.03233	0.01281	0.00424	0.02884	0.04600
Greece	0.03467	0.03186	0.01195	0.00229	0.02941	0.05183
South Korea	0.04211	0.03774	0.01768	0.00121	0.02650	0.03656
Belgium	0.05285	0.03494	0.01142	0.00322	0.02657	0.03291
Luxembourg	0.03710	0.03273	0.02042	0.00357	0.01341	0.05433
Chile	0.03299	0.02821	0.01045	0.00115	0.03674	0.05459
Mexico	0.03793	0.03374	0.01957	0.00193	0.04483	0.02518
Türkiye	0.04752	0.03916	0.01557	0.00109	0.05126	0.00860
Indonesia	0.03741	0.02915	0.01463	0.00250	0.03384	0.04717

Table 7. Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS)

Criterion	Positive Ideal Solution (PIS)	Negative Ideal Solution (NIS)
Built-up Area (YAP)	0.3292 (Belgium)	0.0669 (Norway)
Carbon Footprint (CF)	0.2645 (UK)	0.0393 (Norway)
Agricultural Land (TAR)	0.3546 (Japan)	0.0422 (Italy)
Fishery Area (BAL)	0.5185 (Norway)	0.00061 (USA)
Forest Area (ORM)	0.4429 (Australia)	0.0793 (Luxembourg)
Pasture Land (OTL)	0.5053 (Canada)	0.0538 (Türkiye)

The Positive and Negative Ideal Solutions table highlights the countries with the best and worst performance for each criterion. For example, Belgium demonstrates the best performance in built-up areas, whereas Norway shows the worst. In terms of carbon footprint, the United Kingdom exhibits the highest emissions, while Norway adopts an environmentally friendly approach, representing the ideal solution. Regarding agricultural land, Japan has the most productive areas, whereas Italy has less fertile land. For fishery areas, Norway is considered the ideal, while the United States shows the poorest performance. Australia stands out for its extensive forest areas, in contrast to Luxembourg, which has very limited forest coverage. Finally, for pasture lands, Canada represents the ideal, whereas Türkiye has a more restricted area. This table allows for a comparative evaluation of each country's environmental performance and natural resource utilization.

Table 7 shows the distance measures between alternatives for each criterion. For built-up areas, Belgium is closest to the ideal solution, while Norway is the farthest. In terms of the carbon footprint, the United Kingdom performs the worst, whereas Norway represents the ideal solution. Regarding agricultural land, Japan has the most productive areas, while Italy exhibits significantly lower performance. For fishery areas, Norway achieves the ideal solution, whereas the United States is quite close to the negative ideal. In terms of forest areas, Australia stands out with its extensive forests at the ideal solution, while Luxembourg falls near the negative ideal. Concerning pasture areas, Canada possesses the largest areas, whereas Türkiye is positioned near the negative ideal. These distance measures provide insights into each country's environmental efficiency and resource utilization performance.

Table 8. Relative Closeness to the Ideal Solution C_i^+

Rank	Country	C_i^+
1	Norway	0.127
2	Canada	0.079
3	Luxembourg	0.074
4	Japan	0.072
5	Sweden	0.070
6	Poland	0.069
7	USA	0.068
8	Germany	0.067
9	Greece	0.066
10	United Kingdom	0.065
11	Austria	0.065
12	Belgium	0.065
13	South Korea	0.064
14	Netherlands	0.064
15	Italy	0.063
16	Chile	0.063
17	France	0.063
18	Türkiye	0.061
19	Indonesia	0.061
20	Spain	0.061
21	Australia	0.059
22	Denmark	0.059
23	Mexico	0.058
24	Portugal	0.056
25	Switzerland	0.056

Based on the relative closeness (C_i^+) values presented in Table 8 the countries' proximity to the ideal solution can be interpreted as follows: Norway, with a C^+ value of 0.127, exhibits the highest relative closeness, indicating that it performs closest to the ideal solution in terms of environmental criteria. Countries such as Canada (0.079), Luxembourg (0.074), and Japan (0.072) follow, showing relatively high proximity to the ideal solution. In contrast, countries like Türkiye (0.061), Belgium (0.065), and Switzerland (0.056) display lower relative closeness values, positioning them farther from the ideal solution compared to other countries. The overall low and closely clustered C^+ values suggest that the differences in environmental performance among the countries are relatively small. This indicates that, in general, the countries exhibit similar performance regarding natural resource use and environmental sustainability. In summary, while Norway leads in terms of environmental performance, all countries have comparable proximity to the ideal solution, highlighting that there is development potential in this domain for each country.

5.1. Sensitivity Analysis and Robustness of the Findings

To assess the robustness of the results and the potential impact of variations in criterion weights on the rankings, a sensitivity analysis was conducted. The key findings are summarized as follows:

Balance of Criterion Weights: The criterion weights derived from the entropy method (Table 4) range narrowly between 15.78% and 17.99%, indicating that no single criterion disproportionately influences the model. This suggests that small perturbations in the weights are unlikely to cause significant changes in the overall ranking.

Robustness of the Leading Country: The analysis of the relative closeness (C^+) values reveals that Norway (0.127) maintains a substantial lead over its closest competitor, Canada (0.079), with a difference of approximately 60%. This pronounced gap confirms that Norway's leading position remains robust even under potential variations in criterion weights.

Sensitivity of Middle-Ranked Countries: Conversely, countries such as Türkiye, Indonesia, and Spain, with closely aligned C^+ values around 0.061, exhibit greater sensitivity to changes in the weights. This indicates that the rankings of mid- and lower-tier countries are more susceptible to variations in criteria, reflecting the proximity of their environmental sustainability performances and suggesting that minor policy or weight adjustments could alter their relative positions.

Conclusion of Sensitivity Analysis: Overall, the results demonstrate that while the top-ranked country exhibits strong stability, moderate-ranked countries display higher variability, emphasizing the importance of cautious interpretation of rankings in the mid-range and the value of sensitivity analysis in supporting the robustness of MCDM-based evaluations.

Table 9. Robustness and Sensitivity of OECD Countries' Ecological Footprint Rankings

Analysis Category	Key Findings & Data	Result & Robustness (C)*
Balance of Criterion Weights	Entropy-based weights range narrowly between 15.78% and 17.99%.	No criterion exerts a disproportionate influence; small weight changes do not alter overall ranking.
Leading Country Performance (Norway)	Norway has a C* value of 0.127, 60% higher than closest follower Canada (0.079).	Norway's leading position is highly robust against potential changes in criterion weights.

Middle-Ranked Countries (Türkiye, Indonesia, Spain)	C* values are around 0.061 and very close to one another.	High sensitivity to weight changes; minor policy or weight adjustments can easily change rankings.
Overall Ranking Stability	Top-ranked countries show strong stability.	Middle- and lower-ranked countries have similar performances; rankings in this range should be interpreted cautiously.
Summary	Top-ranked countries like Norway are highly reliable and stable. Middle-ranked countries, including Türkiye, are sensitive to criteria changes.	Environmental sustainability performance of middle-ranked countries is very close, indicating potential ranking shifts.

In summary, the analysis results are highly reliable and stable for top-ranked countries such as Norway, whereas middle-ranked countries, including Türkiye, exhibit a sensitive structure that responds to changes in criteria. This indicates that the environmental sustainability performances of middle-ranked countries are very close to one another.

6. Conclusion and Evaluation

In this study, the environmental sustainability performance of 25 OECD countries in 2022 was evaluated objectively based on their ecological footprints and related subcomponents. The findings reveal considerable differences in sustainability performance among countries. Norway, Canada, Luxembourg, and Japan demonstrated relatively strong environmental sustainability performance, whereas Türkiye, Belgium, and Switzerland were found to be farther from the ideal solution. These results support earlier research suggesting that environmental performance indicators are closely linked to country-specific sustainability structures, policy priorities, and resource management strategies.

From a policy perspective, these findings provide meaningful insights for countries that remain relatively distant from the ideal sustainability benchmark. Countries such as Türkiye, Belgium, and Switzerland may particularly benefit from more targeted environmental and energy policies aimed at reducing ecological pressure and strengthening sustainability performance. Policies that encourage the expansion of renewable energy sources, promote sustainable land management practices, and support carbon emission reduction strategies may significantly improve ecological sustainability outcomes. In addition, strengthening environmental regulations, promoting circular economy initiatives, and increasing investments in green technologies may contribute to long-term improvements in ecological footprint indicators. The findings of this study are broadly consistent with previous empirical research. For instance, Shafiei & Salim (2014) demonstrated that renewable energy consumption plays a critical role in reducing carbon emissions in OECD countries, whereas reliance on non-renewable energy sources tends to increase environmental pressure. This observation is closely aligned with the results of the present study, where the carbon footprint appears as one of the most influential determinants of sustainability performance. Similarly, Ifeakor (2023) highlighted the importance of sustainable natural resource management, agricultural land use, and pasture management for improving ecological sustainability. In particular, practices such as organic farming and sustainable land management were shown to enhance environmental quality, which is consistent with the sub-criteria results obtained in this analysis.

In addition, previous research on environmentally friendly urbanization and sustainable urban development indicates that environmental policies integrated into urban planning processes can positively influence sustainability outcomes. Cömertler & Cömertler (2021), for example, emphasize that eco-friendly urbanization practices play an important role in strengthening environmental sustainability performance. Likewise, systematic studies examining the relationship between carbon emissions and sustainability highlight the strong link between carbon footprints and environmental degradation, emphasizing the importance of carbon reduction strategies within global environmental policy frameworks (Durkaya & Kaya, 2024). Empirical studies conducted at both global and national levels also suggest that the relationships among economic growth, renewable energy consumption, and environmental quality may vary across countries depending on their structural characteristics and policy approaches (Akın & Şen, 2024).

Another point emphasized in the literature is that methodological differences in environmental indicators and analytical approaches may produce variations in country rankings. Environmental Kuznets Curve analyses, for instance, suggest that the relationship between economic growth and environmental indicators may differ depending on countries' economic structures and stages of development (Akın & Şen, 2024). Such findings highlight the importance of methodological choices when evaluating sustainability performance.

Despite its contributions, this study has several limitations that should be acknowledged. First, the analysis is limited to data from a single year (2022), which restricts the ability to observe long-term sustainability dynamics across countries. Environmental performance and ecological footprints may change over time due to technological progress, economic transformations, and evolving policy frameworks. Future research may therefore benefit from using panel data sets covering multiple years in order to analyze temporal changes in ecological sustainability performance more comprehensively.

Another limitation relates to the methodological framework used in the analysis. The results are derived from the Entropy-based TOPSIS method and the selected weighting structure. Although this method provides an objective framework for weighting criteria, alternative multi-criteria decision-making (MCDM) methods or weighting techniques may produce different rankings. For this reason, future studies may conduct sensitivity analyses or compare the findings with other MCDM approaches such as AHP, CRITIC, or VIKOR in order to test the robustness and stability of the results.

Beyond its academic contributions, this study also offers practical insights for policymakers seeking to improve environmental sustainability performance. Governments, particularly in countries with relatively lower rankings, may consider strengthening integrated environmental policies that promote renewable energy investments, sustainable land use, and efficient natural resource management. Furthermore, improving environmental governance, supporting green innovation, and encouraging low-carbon economic transitions may play an important role in reducing ecological footprints. In addition, cooperation among OECD countries could facilitate the sharing of policy experiences and best practices, thereby supporting more effective and coordinated sustainability strategies at the international level.

Overall, the findings underline the importance of evaluating ecological sustainability performance through comprehensive and objective analytical frameworks. By identifying the relative strengths and weaknesses of OECD countries in terms of ecological footprint components, this study provides valuable insights for both researchers and policymakers. Strengthening environmental strategies that prioritize renewable energy expansion, efficient resource use, and sustainable land management may contribute significantly to reducing ecological pressure while supporting long-term sustainable development goals.

In conclusion, the results of this study are largely consistent with the existing literature and reaffirm the importance of factors such as carbon emissions, energy consumption, and natural resource management in shaping environmental sustainability performance. At the same time, differences in methodological approaches and data sets help explain the variations observed in rankings across studies. These findings highlight that the selection of indicators and analytical methods plays a crucial role in sustainability assessments. Overall, the study contributes to the literature by offering an objective evaluation of ecological sustainability performance across OECD countries and provides valuable insights for policymakers seeking to design more effective environmental and sustainability-oriented policies.

Future studies could conduct comparative analyses using alternative weighting methods such as AHP or CRITIC, or different multi-criteria decision-making (MCDM) techniques such as VIKOR, PROMETHEE, or ELECTRE, in order to test the methodological robustness of the results obtained in this research. Although the short sensitivity analysis conducted in the present study indicates that the performance of top-ranked countries is relatively stable, the use of different methods would further strengthen the generalizability of the findings.

Declarations

Conflict of interest The author(s) have no competing interests to declare that are relevant to the content of this article.

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