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GREEN PRODUCTION AND ECOLOGICAL FOOTPRINT: EVALUATION OF SUSTAINABILITY PERFORMANCE WITH MULTI-CRITERIA DECISION-MAKING METHODS

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Abstract
Purpose: This study seeks to provide a comprehensive assessment of national sustainability performance by integrating green production strategies into the broader discourse of production management. In response to the growing ecological crisis, it addresses a notable gap in the literature concerning the use of advanced multi-criteria decision-making (MCDM) methods to evaluate the interplay between ecological footprint, biocapacity, and ecological deficit.
Methodology: A hybrid methodological framework is employed, combining the TOPSIS technique with time-series analysis, regional and income-based stratifications, and K-Means clustering. This integrative approach allows for a multi-dimensional, data-driven evaluation of sustainability performance across diverse economic contexts, facilitating both temporal and spatial comparisons among countries.
Findings: The empirical findings underscore that high-income nations tend to exhibit disproportionately large ecological footprints and deficits, whereas lower-income countries, despite lower consumption levels, suffer from significant biocapacity constraints. Moreover, a strong positive correlation is observed between GDP growth and ecological degradation, particularly in industrialized economies. Nonetheless, several countries have demonstrated the capacity to decouple economic expansion from environmental deterioration through the implementation of robust green policies.
Originality: This research makes a novel contribution by operationalizing an interdisciplinary analytical framework that bridges production management and environmental sustainability. By synthesizing MCDM techniques with unsupervised learning algorithms, it offers new insights into the role of green production strategies in mitigating ecological disparities, ultimately emphasizing the urgency of aligning economic development with planetary boundaries.

Keywords: Sustainability, Ecological Footprint, Biocapacity, Multi-Criteria Decision Making, Global Sustainability, Green Production, Production Management

JEL Codes: Q01, Q56, M11, C44, L23

Yeşil Üretim ve Ekolojik Ayak İzi: Çok Kriterli Karar Verme Yöntemleriyle Sürdürülebilirlik Performansının Değerlendirilmesi

Özet
Amaç: Bu çalışma, yeşil üretim stratejilerini üretim yönetimi perspektifiyle ilişkilendirerek ülkelerin sürdürülebilirlik performanslarını çok boyutlu bir yaklaşımla değerlendirmeyi amaçlamaktadır. Ekolojik ayak izi, biyokapasite ve ekolojik açık gibi temel çevresel göstergelere dayalı olarak yapılan değerlendirme ile, mevcut literatürdeki çok kriterli karar verme yöntemleriyle yapılan kapsamlı analizlerin eksikliğine çözüm sunulması hedeflenmektedir.
Yöntem: Çalışmada hibrit bir metodolojik çerçeve benimsenmiş ve TOPSIS yöntemi, zaman serisi analizi, bölgesel ve gelir düzeyine dayalı karşılaştırmalar ile K-Means kümeleme analizi birlikte uygulanmıştır. Bu çok katmanlı analiz modeli, ülkelerin sürdürülebilirlik performanslarının mekânsal ve zamansal açıdan kapsamlı bir şekilde karşılaştırılmasına olanak sağlamaktadır.
Bulgular: Elde edilen bulgular, yüksek gelirli ülkelerin genellikle daha yüksek ekolojik ayak izi ve ekolojik açık değerlerine sahip olduğunu, düşük gelirli ülkelerin ise daha sınırlı ayak izine rağmen ciddi biyokapasite kısıtları yaşadığını ortaya koymaktadır. Ayrıca, GSYİH büyümesi ile ekolojik açık arasındaki anlamlı pozitif ilişki, sanayileşmiş ülkelerin çevresel baskıyı artırma eğilimini teyit etmektedir. Bununla birlikte, bazı ülkeler etkin çevre politikaları ve sürdürülebilirlik stratejileriyle bu olumsuz etkileri başarıyla sınırlandırmıştır.
Özgünlük: Bu çalışma, üretim yönetimi ve çevresel sürdürülebilirlik alanlarını disiplinlerarası bir yöntemle bir araya getirerek literatüre özgün bir katkı sunmaktadır. Çok kriterli karar verme tekniklerinin denetimsiz öğrenme algoritmalarıyla entegrasyonu sayesinde, yeşil üretim stratejilerinin ekolojik eşitsizliklerin azaltılmasındaki işlevselliği ve politika yapım sürecindeki rolü yeni bir bakış açısıyla ortaya konmuştur. Bu çerçevede, ekonomik kalkınmanın çevresel sınırlarla uyumlu hale getirilmesi gerekliliği vurgulanmaktadır.
Anahtar Kelimeler: Sürdürülebilirlik, Ekolojik Ayak İzi, Biyokapasite, Çok Kriterli Karar Verme, Küresel Sürdürülebilirlik, Yeşil Üretim, Üretim Yönetimi
JEL Kodları: Q01, Q56, M11, C44, L23

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1. Introduction

The sustainability problem is now a significant concern in the context of the global economy and environmental policy (Feng, Shafiei, Ng, Ren, & Jiang, 2024). Industrialization, economic development, and the rise in the population have raised the use of natural resources and carbon dioxide emissions and have turned into a significant ecological imbalance threat (Ozcan, Tzeremes, & Tzeremes, 2020). The manufacturing sector, particularly in industrialized nations, contributes to the imbalance between ecological footprint and biocapacity (Saqib & Shahzad, 2024). In such a context, it is necessary to be aware of the degree to which the environmental performance of nations is in line with global sustainability goals and the degree to which the ecological balance is influenced by economic growth. However, it is revealed in the literature that few studies assess sustainability performance using multi-criteria decision-making methods. Apart from studies focusing on a specific indicator in evaluating the ecological performance of countries, there is a pressing need for multidimensional and holistic analysis.

The current study aims to assess the sustainability performance of countries with the help of key indicators such as ecological footprint, biocapacity, ecological deficit, and global hectares demand. To achieve this, the study categorizes countries with the help of the TOPSIS approach, examines ecological indicator changes with the help of the time-series analysis, examines regional and income-based discrepancies, and classifies countries with similar sustainability traits with the help of K-Means clustering analysis. The studies help to fill the literature and clarify the effectiveness of sustainable development policy. The present work also attempts to investigate cross-country variations in the sustainable development process by analyzing how sustainability policy differs in various nations with varying income levels and geographical compositions. Based on the stated objectives and the gaps identified in the existing literature, this study is guided by three central research questions: (1) How do ecological sustainability indicators such as ecological footprint, biocapacity, and ecological deficit differ among countries with varying income levels and regional characteristics? (2) What patterns and trends emerge in these ecological indicators over the 2019–2022 period, and how do they reflect the global sustainability trajectory? (3) To what extent can multi-criteria decision-making techniques—particularly the entropy-weighted TOPSIS method—and K-Means clustering analysis be utilized to systematically classify countries according to their sustainability performance? Addressing these questions aims to provide a data-driven foundation for evaluating national sustainability efforts and informing future policy directions.

Ecological sustainability policies' success worldwide depends mainly on the capacity to balance natural resource use and economic development. Though some nations' economic growth is linked to sustainable development models, others' environmental pressures are exacerbated by limited resource use (Hariram, Mekha, Suganthan, & Sudhakar, 2023). Thus, an integrated evaluation of ecological and economic indicators is vital for future sustainable development policymaking. The present work will attempt to determine the long-term effects of the sustainability policy in various nations and offer recommendations for creating more integrated decision-support systems.

An overall evaluation of the ecological performance of countries with different income levels and regional characteristics is given in the paper. This emphasizes how economic growth affects ecological deficits, regional disparities, and the clustering of countries with comparable environmental traits. The study highlights the necessity of reevaluating sustainable development plans and offers insightful information about the future course of sustainability policy.

2. LITERATURE REVIEW

Supply chain management and sustainable production have become increasingly important in today's research and business practices. Most production management and sustainability studies have focused on lowering the carbon footprint, reducing the ecological deficit, and improving resource utilization efficiency (Gallego-Álvarez, Segura & Martínez-Ferrero, 2015).

Key Studies and Findings

Numerous strategies for managing logistics and sustainable production have been put forth due to the scholarly literature's analysis. The following primary thematic categories have been used to group these studies:

No	Researcher(s)	Year	Title	Key Findings	Methodology Used
1	Arsu, T. & Ayçin, E.	2021	Evaluation of OECD Countries with Multi-Criteria Decision-Making Methods in terms of Economic, Social and Environmental Aspects	Assessed OECD countries in terms of economic, social, and environmental aspects; highlighted the need for balanced sustainable development.	TOPSIS (MCDM)
2	Wackernagel, M., Monfreda, C., Schulz, N. B., Erb, K.-H., Haberl, H., & Krausmann, F.	2004	Calculating national and global ecological footprint time series: resolving conceptual challenges	Resolved conceptual challenges in national and global ecological footprint time series estimation.	Ecological footprint accounting
3	Galli, A., Iha, K., Pires, S. M., Mancini, M. S., Alves, A., Zokai, G., Lin, D., Murthy, A., & Wackernagel, M.	2020	Assessing the Ecological Footprint and biocapacity of Portuguese cities: Critical results for environmental awareness and local management	Analyzed ecological footprint and biocapacity in Portuguese cities to support local environmental awareness and management.	Econometric and spatial analysis
4	Govindan, K., Sivakumar, R., Sarkis, J., & Murugesan, P.	2015	Multi criteria decision making approaches for green supplier evaluation and selection: a literature review	Reviewed MCDM approaches for green supplier evaluation and identified critical success factors.	Literature review of MCDM methods
5	Gholizadeh, M.H. et al.	2022	Modelling uncertainty in sustainable-green integrated reverse logistics network using metaheuristics optimization	Modeled uncertainty in green reverse logistics networks using advanced optimization methods.	Robust optimization, scenario analysis
6	Gholizadeh, H., Goh, M., Fazlollahtabar, H., & Mamashli, Z.	2020	Biocapacity—Premise of Sustainable Development in the European Space	Examined biocapacity and ecological reserves in Europe, highlighting regional disparities.	Multivariate statistical analysis
7	Shen, Y., & Yue, S.	2020	Does ecological footprint affect biocapacity? Evidence from the experiences of G20 countries	Forecasted ecological footprint trends in G20 countries for the next 30 years using time series models.	Panel data econometrics

8	Espinosa, R. M., & Koh, L. S. C.	2024	Forecasting the ecological footprint of G20 countries in the next 30 years	They have analyzed the effectiveness of decision support systems in sustainability management.	Time-series forecasting models
9	Li, T., Wang, H., & Lin, Y.	2020	Selection of renewable energy development path for sustainable development using a fuzzy MCDM based on cumulative prospect theory: the case of Malaysia	Developed a fuzzy MCDM framework to select renewable energy paths under uncertainty in Malaysia.	Fuzzy MCDM with Cumulative Prospect Theory
10	Wang, H., Pan, C., Wang, Q., & Zhou, P.	2020	Assessing sustainability performance of global supply chains: An input-output modeling approach.	Assessed global supply chain sustainability using multi-region input-output models integrated with MCDM tools.	Multi-region input-output modeling, DEA, AHP

The literature has expressed diverse opinions about the significance of sustainability assessment and green production. Research has shown that environmental sustainability can boost competitiveness and support sustainable development in general (Arsu & Ayçin, 2021; Wang et al., 2020). Particularly in production and supply chain management, researchers have emphasized the significance of comprehensive evaluation methods considering economic, social, and environmental factors (Govindan et al., 2023).

The field makes a clear distinction between theoretical studies and empirical research. While theoretical concepts have assumed center stage in some paradigms, sustainability performance has in recent times been ascertained with the use of actual figures and statistical analysis (Shen Yue, 2023; Galli et al., 2020). For example, Gogonea et al. (2020) undertook integrated regional examination of deficits in biocapacity in Europe and established disparities and the requirement for specific sustainability policies. In sustainability analysis, multi-criteria decision-making (MCDM) methods have been employed with increasing frequency as an approach (Li, Wang, Lin, 2024; Arsu Ayçin, 2021). Two MCDM methods that have demonstrated utility for ranking countries or alternatives on the basis of ecological performance measures are fuzzy MCDM and TOPSIS, akin to this, Wackernagel et al. In 2004 it established the basis for current environmental accounting methods by tackling the conceptual and methodological issues of time series estimation following ecological footprints on an extensive large-scale, national, and global basis.

In addition to Methods such as MCDM (Multiple Criteria Decision Making), ongoing research is exploring the application of time series models, specifically econometric and clustering models, for forecasting sustainability patterns and grouping countries sharing comparable ecological patterns (Espinosa and Koh, 2024). For example, research has been conducted on green logistics models based on uncertainty by Gholizadeh, Goh, Fazlollahtabar, and Mamashli (2022). Galli and co-authors have also researched on this matter in the recent past. In 2020, the research examined biocapacity patterns using econometric and spatial analysis models.

In addition, application of artificial intelligence, big data analytics, and decision support systems for sustainable production management is on the increase. Wang et al. (2020) and Li et al. (2020) presented advanced modeling frameworks for global supply chain decision-making and renewable energy planning.The recent literature demonstrates a move away from conceptual discussion and toward quantitative, comparative, and decision-making-driven research that produces valuable data on sustainability performance on a national and international scale.

2.1. Research Gaps and Contributions in the Literature

An analysis of the literature demonstrates that estimates of carbon footprints are primarily restricted to particular industrial sectors. However, studies integrating decision-support methods such as TOPSIS and time-series analysis for comparing sustainability across income groups and regions remain scarce. While many studies quantify sustainability performance based on a single indicator, there is a growing need for a multifaceted approach based on several interrelated variables. Furthermore, the limited number of studies that examine the relationship between GDP and ecological deficit in detail limits the achievement of a better understanding of the environmental costs of economic growth. In this context, most of the studies in the literature focus on sectoral sustainability policies, while comparative macroeconomic studies are comparatively less explore.

The present study aims to bridge such gaps with the help of a data-based sustainable production and logistics management approach. Toward this end, TOPSIS and the time-series analysis will be utilized to compare the sustainability performance of nations, the regional and income-based gaps, and the ecological deficit-economic growth relationship. The study will further analyze the application of decision support systems and big data analysis in sustainable logistics management and explore the long-run impact of such applications in the sector.

2.2. Recommendations for Future Research

Existing research on sustainable production and logistics management is primarily sectoral or employs a unidisciplinary approach. Future research should use an integrated approach with ecological and carbon footprint and sustainability policy in an interdisciplinary framework. Future research may employ advanced analysis, such as the model-based analysis of the dynamics of environmental footprints concerning time, to identify long-run sustainability trends. In-depth sectoral studies are required to examine the sustainability gaps among different countries and regions in finer detail.

The development of artificial intelligence-based supply chain optimization algorithms and predictive models would advance the successful implementation of sustainability policy. Applying machine learning and big data analytics would assist in the evolution of advanced forecasting mechanisms to reduce carbon footprint. The efforts will help enhance the extent of the science base in sustainable production management and facilitate the development of new methodologies to guide policymakers and industrial practice toward sustainable options.

3. METHODOLOGY

In this study, a data-driven approach has been adopted to evaluate countries' ecological performance within the context of sustainable production and logistics management. The data were obtained following official correspondence with relevant institutions and shared strictly for scientific research. The methodologies used for data calculation are comprehensively detailed in the corresponding reports, and the analyses in this study have been conducted by referencing these established methods.

The primary data used in this study were provided by the Global Footprint Network (GFN). They were derived from datasets containing key indicators measuring carbon footprint, biocapacity, ecological deficit, and environmental sustainability. The dataset includes ecological indicators for various countries from 2019 to 2022. A total of 153 countries were included in the analysis. The selection was based on data availability and completeness across all four main indicators—ecological footprint, biocapacity, carbon footprint, and ecological deficit—within the 2019–2022 period. Countries with incomplete or missing data for any of these indicators were excluded from the analysis to ensure the consistency and comparability of results. Permission to use these data for research purposes was obtained through official correspondence with the Global Footprint Network.

The calculations provided by GFN assess sustainability by comparing ecological footprint and biocapacity. The Ecological Footprint represents the total demand placed by an individual, society, or country on biologically productive land and water areas. In contrast, Biocapacity refers to the natural resources and absorption capacity that nature can provide to meet this demand. All measurements are expressed in global hectares (gha).

The ecological footprint and biocapacity values calculated by GFN have been standardized using Yield Factors and Equivalence Factors to ensure comparability across different land types and regions.

Yield Factors: alculated as a coefficient that compares a country's productivity in a specific land use type with the global average. The formula is as follows:

$$\mathrm{YF}_{NL} = \frac{Y_{NL}}{Y_{WL}}$$

Here, Y_N^L represents the yield for a specific land use type in a given country, while Y_W^L denotes the global average yield.

For areas containing multiple primary products, such as agricultural land, an extended calculation formula is used:

$$\mathrm{YF}_{NL} = \frac{\sum A_W}{\sum A_N}$$

Here, the harvested area for a specific country is represented, while the corresponding area required on a global scale to produce the same amount of output is also considered.

Equivalence Factors: These are calculated to compare the productivity of different land types relative to the global average. These factors are determined using FAOSTAT and the Global Agro-Ecological Zones (GAEZ) model.

These calculation systems allow for the appraisal of economic activities' impact on the natural world. On the basis of methodologies devised by GFN, multi-criteria decision-making methodologies and statistical techniques have been utilized for the comparison of ecological balance between nations.

3.1. Analysis Methods and Justifications
The analysis methodologies employed in this research have been selected to yield the optimum interpretation of the current data and be in line with the related research in the field. In order to compare nations in terms of sustainability, the TOPSIS technique has been utilized as a viable means of multi-criterion decision-making models in sustainability analysis (Zavadskas, Mardani, Turskis, Jusoh, & Nor, 2016). From time-series analysis, it is viable to compare discrepancies in ecological indicators and identify the long-term effects of sustainability policies (Chatfield, 2016). Comparison of regions and income levels helps identify disparities in sustainability among nations as well as the research of environmental impacts of economic drivers. Among the most important ways to determine the influence of economic growth on ecological imbalances is a correlation study between ecological deficit and GDP (York, Rosa, & Dietz, 2004). K-Means clustering analysis helps to group nations with comparable ecological prints and highlight the commonalities in the sustainability strategies (Al Qahtani & Sankar, 2024).

These techniques were chosen because they can offer a thorough comparison, assist in decision-making, and be founded on proven approaches in the literature. The studies clarify the meaning of the data and highlight essential results for formulating sustainability policy. From this angle, the chosen techniques are seen as necessary components enhancing the dependability of the research and decision support systems.

3.2. Software and Calculation Tools Use
Python was used for the analysis. Pandas and NumPy handled data cleaning, processing, and analysis; Scipy and Statsmodels handled statistical analysis. Scikit-learn was used to model the decision support systems. The Matplotlib and Seaborn libraries were used for graphic and data visualization. The MCDM (Multi-Criteria Decision Making) library, which supports multi-criteria decision-making processes, was used to conduct TOPSIS analysis.

The present study's calculation and procedure steps seek to provide a multi-faceted contribution to the literature such that ecological differentiation among countries can be assessed both statistically and within decision support systems.

4. FINDINGS AND ANALYSIS
This part presents and thoroughly interprets the findings of the analyses performed on the acquired data. Before analysis, the datasets were thoroughly cleaned to remove faulty and missing data, qualifying the data for examination. Classified by technique, the results show the variations between nations in ecological footprint, biocapacity, carbon footprint, and sustainability performance.

4.1. Ecological Footprint and Biocapacity Analysis
The studies revealed notable disparities between the nations' ecological footprint and biocapacity values. Certain countries have significant footprints in natural resource use compared to where they can get those resources from, meaning they're up against a crunch where they don't have enough natural capital. It was observed that biocapacity could not meet consumption demands, especially in developed countries. Data analysis was based on calculations provided by the Global Footprint Network. The carbon footprint increased between 2019 and 2022, according to an analysis of changes in ecological footprint and biocapacity over time. This rise stems from the consistent use of fossil fuels plus this big push towards industrialization that's been going on. This finding is consistent with past studies highlighting the strong connection between environmental overshoot and industrial growth (Wackernagel et al., 2004). The lack of effectiveness of certain countries' biocapacity protection policies was also noted. Nevertheless, the biocapacity deficit normally prevails.

This indicates environmental imbalances exist notwithstanding the impact of government policies because of unsustainability in the production and consumption patterns (Moros Ochoa et al., 2022).

4.1.1. TOPSIS Analysis: Comparison of 2019 and 2022 Result

The studies suggest China and India had the best TOPSIS performances in 2019 and the same ranking would prevail until 2022. Differences from 2019 to 2022 were analyzed and each country's environmental performance and sustainable production management were evaluated using the TOPSIS approach. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is an efficient decision tool for multi-criteria decision problems enabling aggregation of diverse performance indicators into one overall score and its comparison of nations' sustainability performance.

The six chosen key indicators of sustainability in the TOPSIS model in the present research were: ecological footprint and biocapacity on a per capita basis; ecological deficit; renewable energy contribution of consumption; energy intensity (energy/GDP); and overall index of sustainable production. These indicators were selected on the basis of their ability to apply to environmental pressures and consumption of resources and track both the demand and supply sides of sustainability in the environmental context. To attribute each of the criteria their respective weights, Entropy was utilized. Entropy is an objective weighting technique which calculates the spread of each indicator in the dataset and attributes higher weights to more discriminatory variables.The process was to normalize the data and calculate the entropy of each criterion before deriving the weights on the basis of the amount of uncertainty or variation. Utilization of entropy-based weights means the evaluation is not subject to bias and has indicators of higher variation across countries having more impacts on the outcome (Zavadskas & Turskis, 2011). Following weighting, distances to positive and negative ideal solutions were calculated and relative closeness values calculated in order to arrive at the final TOPSIS values for each country.

The study's conclusions show that there have been notable differences in the sustainability performance of some countries. TOPSIS compares the green performance of different places by taking many sustainability yardsticks and averaging them into one overall score. It's like Big Macs averaging all the tasty ingredients into just one tasty average meal. This allowed for identifying countries that have made significant progress in sustainable development. According to the study, China and India had the highest TOPSIS scores in 2019, and by 2022, this ranking had mainly remained stable. However, nations, including the United States, Canada, and Lithuania, were found to have much lower TOPSIS scores. Although an overall rise in ecological footprint and ecological deficit ratios was noted in 2022, certain nations that have carried out sustainability policies more successfully revealed encouraging changes. This lends credence to the idea that national policy initiatives can produce noticeable changes in ecological performance over relatively brief periods (Djordjevic & Krmac, 2019).

Between 2019 and 2022, nations denoted by blue bars in Figure 1 exhibited increases in sustainability performance. These increases are based on changes in the entropy-weighted TOPSIS scores. The use of entropy weighting helped emphasize the most variable and informative indicators in the dataset, which resulted in a fairer evaluation of performance improvements. Lithuania showed the most significant rise in its TOPSIS score; Guyana, Zimbabwe, and Ireland came second. These developments imply the practical application of sustainable development policies, particularly in the resource economy and renewable energy sectors. Particularly in nations where industrialization processes have sped up, ecological footprint values have grown, while nations with favorable biocapacity are implementing more sustainable development policies. This supports earlier research showing that natural capital endowments can support economic development while improving a nation's ability to preserve environmental balance (Hassinein & Elmassah, 2023).

Conversely, some countries demonstrated stagnation in their sustainability performance or decreased their performance, implying the necessity of more in-depth and region-specific environmental policies. These findings highlight the necessity of enhancing the efficiency of sustainable production policies as it indicates that various environmental management strategies vary according to the nation. In this way, the researched studies have made it possible to fairly calculate the impacts of national sustainability policy. The entropy-weighted TOPSIS process employed in the present research offers an open and systematic way to monitor such changes, increasing the validity of findings. The explicit empirical understanding provided by the graphical representation of the TOPSIS score enables one to know how national policies influence environmental outcomes. The findings are crucial for understanding the long-run impacts of environmental management policies and the efficiency of sustainable production policies.

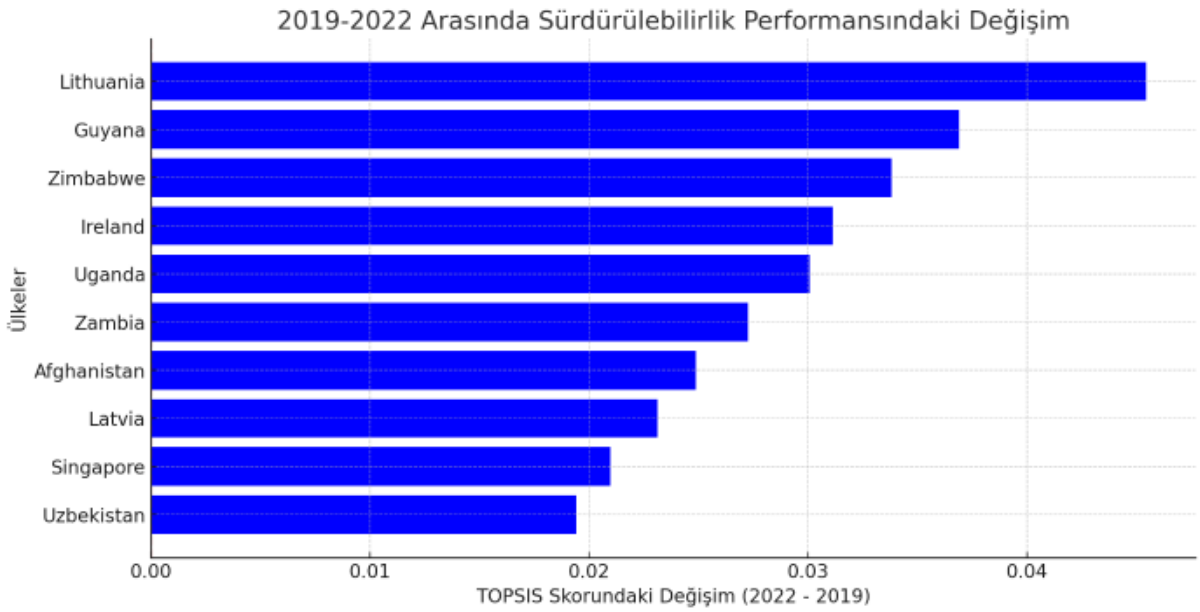

Figure 1: Changes in countries' sustainability performance scores between 2019 and 2022 based on the TOPSIS method

4.2. Time Series Analysis: 2019-2022 Global Trends

The yearly fluctuation of ecological indicators was established through a time series analysis. Yearly comparison of indicators such as environmental footprint, ecological deficit, and global demand from 2019 to 2022 assisted in bringing out global sustainability trends. Results of the analysis indicate a typically negative environmental indicator trend. Driven primarily by ongoing fossil fuel use, rapid urbanization, and industrial growth, the ecological footprint continued to increase each year. As Wackernagel et al. (2004) emphasize—that crossing planetary limits can lead to long-term environmental change—this trend indicates the sustained pressure on planetary limits. Furthermore, the growing ecological deficit in the majority of countries means biocapacity was increasingly unable to meet consumption pressures. Nevertheless, other countries exhibited signs of development due to more strict environmental laws and policy measures. For instance, countries adopting circular economy concepts or investing in renewable energy infrastructure tend to display fairly steady or rising performance in the long run. Time series analysis highlights the need for urgent long-term planning of environmental policy and international cooperation to stop the downward trajectories of sustainability indicators. Collective multilateral efforts are the sole means to deal with the complex problems posed by ecological overshoot and to ensure progress towards the Sustainable Development Goals, as put forward by Saaida (2023).

4.2.1. Changes in Ecological Indicators Between 2019-2022

According to the time series analysis, the global ecological footprint increased steadily between 2019 and 2022, suggesting that planetary resources are under increasing strain. Increased industrial activity, urbanization, and unsustainable consumption patterns are primarily to blame for this increase. Similar trends were seen in the ecological deficit, indicating that many nations use natural resources more quickly than ecosystems can replenish them. These patterns are in accord with the concept of "ecological overshoot" as it has become an important factor in sustainability research (Lin et al., 2018).

But biocapacity remained fairly steady in the period observed, which means the level of resource replenishing has not caught up with consumption. Even though some countries have invested in clean energy sources, afforestation programs, and conservation efforts, these are not yet showing measurable global gain. This verifies previous research that technology solutions cannot be sustained unless systems of production and lifestyle are altered (Espinosa & Koh, 2024).

The notion that current resource use patterns are unsustainable was further supported by a slight increase in the Earth Required indicator, which shows the number of planet Earths required to sustain current consumption levels. A declining ecological balance is reflected in the growing disparity between ecological footprint and biocapacity, as illustrated in Figure 2, particularly in nations with high per capita consumption. This trend emphasizes the urgency of reconsidering growth-driven economic models and carrying out more forceful sustainability transitions.
Furthermore, a closer look was conducted at the connection between ecological indicators and economic development. Although some showed that strategic policy reforms could decouple growth from environmental degradation, nations with higher GDP per capita tended to show more pronounced ecological deficits. According to Öcal, Altınöz, and Aslan (2020), a non-linear relationship exists between income and environmental impact, consistent with the Environmental Kuznets Curve hypothesis. Still, the general global trend indicates that the sustainability gap is growing.

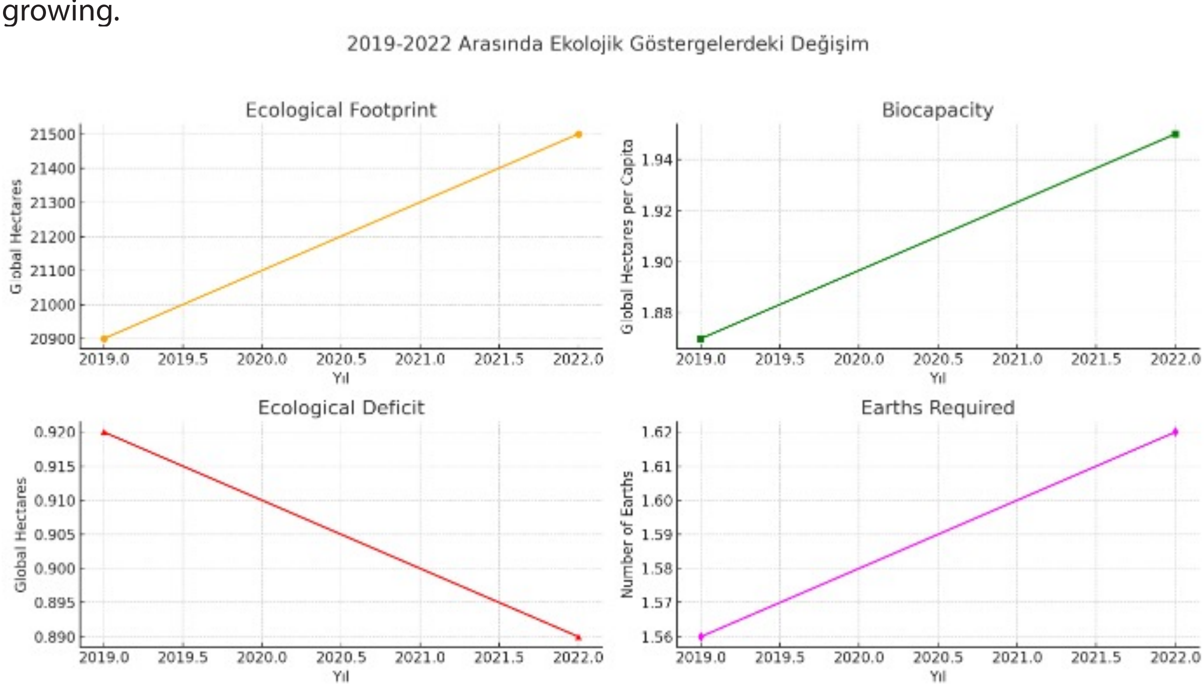

Figure 2 : Change in Ecological Indicators Between 2019 and 2022

4.2.2. Regional Comparison of Countries

The regions of Africa, Europe, Asia, North America, South America, and Oceania were examined to see if sustainability indicators differed by continent. The Earth's Required ratio, ecological deficit, and average ecological footprint were among the evaluation criteria. Europe and North America have the largest average ecological footprints, followed by Oceania and Asia, as Figure 3 illustrates.

According to the analysis, North America and Asia are the areas under the most environmental stress. Because of their vast industrial bases and growing energy needs, China and India, in particular, have a significant ecological footprint in Asia. Similarly, the high energy consumption and resource-intensive lifestyles of the United States and Canada account for a sizable portion of North America's footprint. These results match earlier research stressing that the leading causes of ecological stress are industrialization and income levels (Çelekli & Zariç, 2023).

On the other hand, areas with less ecological impact are Africa and Oceania. Restricted industrial activity and low per capita consumption in Africa help lower environmental pressure. Though some resource-intensive economies exist in Oceania, especially in nations like Australia and New Zealand, they gains fromlow population density and large biocapacity reserves. This supports the idea that, when combined with sustainable land-use practices, biocapacity endowments can at least offset ecological burdens (Hertwich & Peters, 2009).

Regional studies also show that ecological footprints in Europe are increasing, and environmental deficit ratios have developed in several high-income countries. This pattern highlights the necessity of separating environmental deterioration from economic expansion, a problem commonly addressed in the literature on sustainability (Ferreira, Marques, Moreno Pires, Iha, & Galli, 2022). Balancing long-term development objectives and ecological constraints is still crucial for areas with high consumption and environmental impact.

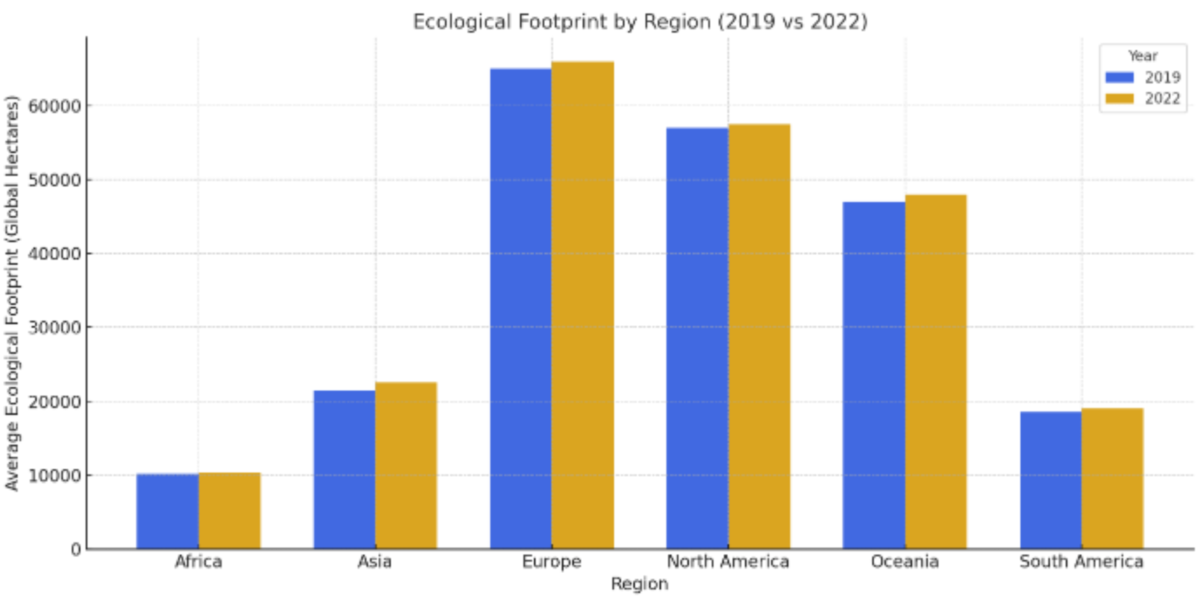

Figure 3: Ecological Footprint by Region (2019 vs 2022)

4.2.3. Sustainability Analysis by Income Groups

Countries may perform differently in terms of sustainability depending on the size and composition of their economies. The low, middle, and high-income groups' ecological footprint, biocapacity, and ecological deficit levels were compared. The environmental footprints of high-income nations are substantially more extensive than those of middle- and low-income countries, as shown in Figure 4.

High-income nations exhibit the most significant ecological footprint and ecological deficit. This group includes countries like the US, Germany, Canada, and Japan, where high production and consumption put more strain on the environment. But despite their massive ecological footprints, developed nations have also made significant strides in reducing ecological deficits through emission reduction initiatives, circular economy models, and policy investments in renewable energy. The Environmental Kuznets Curve hypothesis, which contends that early economic growth accelerates environmental degradation, may eventually stabilize or reverse this trend through technological innovation and environmental regulation, is consistent with this dual reality (Dinda, Coondoo, & Pal, 2000).

Upper-middle-income countries—such as China, Brazil, Mexico, and Turkey—show intermediate sustainability performance. In these countries, ecological deficits are primarily driven by ongoing industrialization and expanding infrastructure development. However, national sustainability plans and international collaboration offer the potential to reduce future environmental pressure. This group represents a critical turning point in global sustainability efforts, where policy effectiveness can significantly alter long-term environmental outcomes (Demirbay & Karakaş, 2024).
Bangladesh, Nepal, Nigeria, and the Democratic Republic of the Congo are examples of low-income nations that belong to a different category. Owing to their low industrialization and consumption levels, these nations have small ecological footprints relative to their population, yet often have low biocapacity. Although contributing minimally to global environmental degradation, this leaves them environmentally exposed. Thus, environmental sustainability must be evaluated via parity in terms of ecological assets and carbon footprint (Menton, Larrea, Latorre et al., 2020). These conclusions highlight the necessity for concerted but separate global sustainability plans in terms of each income level's political, economic, and environmental circumstances.

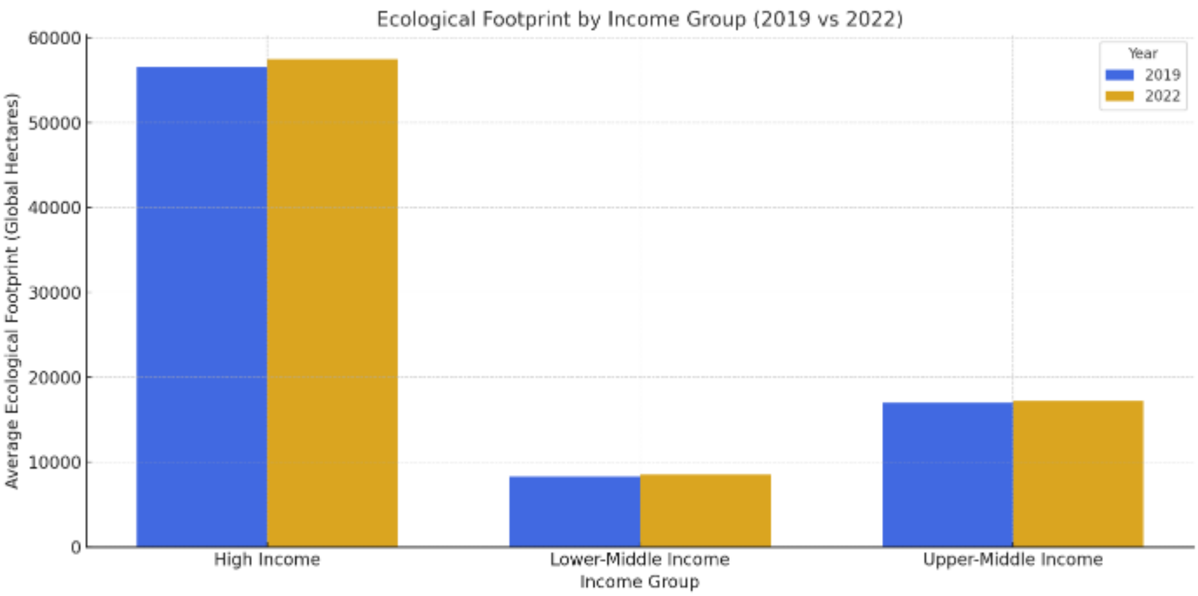

Figure 4: Ecological Footprint by Income Group (2019 vs 2022)

4.2.4. Relationship Between Ecological Deficit and Economic Growth (GDP

The correlation between GDP and ecological deficit was examined in order to explore the impact of economic growth on environmental sustainability. The findings indicated a straightforward pattern: high GDP countries tend to have higher ecological deficits. This is most obvious in countries like the US, Germany, France, and South Korea, where industrialized systems put mounting pressures on ecological stability. This reinforces the established relationship in the literature between industrial production and environmental degradation in developed nations (Toprak, 2023).

Figures 5 and 6 reveal that high-income countries have significant ecological deficits but have a relatively small range of variation. This mirrors the presence of sound institutional structures, long-term environmental planning and infrastructure investment to stabilize ecological performance in the face of ongoing economic growth. In an interesting contrast to Hungary's experience, other outlier cases like Sweden, Norway, and Finland have shown us that economic growth and environmental degradation are not necessarily complementary. Sweden, for example, reduced and stabilized ecological deficits via the implementation of sustainable production practices, efficient energy systems, and long-term environmental policies. This experience can be reconciled with more recent research findings that indicate it is possible to decouple economic growth from environmental degradation in the face of strong environmental regulation and governance (Georgescu, Nica, & Kinnunen, 2024).

In contrast to high-income countries, low- and middle-income countries have less ecological and economic pressures. Even with relatively low ecological footprints, though, these nations tend to experience sustainability issues triggered not by consumption levels, but by structures like lack of well-developed infrastructure, poor environmental management, and dependence on extraction. This suggests that in such nations sustainability performance relies more on institutional resilience and capacity rather than purely on ecological consumption (Denny and Marquart-Pyatt, 2018). Notably, these findings establish that the relationship between GDP and ecological deficit is not only nonlinear but also heterogeneous. Although higher economic performance tends to be associated with higher environmental pressure, it is mediated by how nations approach economic growth and incorporate sustainability in policy.

While the positive relationship between economic growth and ecological pressure has been well documented, the present research introduces a new dimension by emphasizing the stability of ecological deficits in high-income nations despite their powerful impact with the suggestion that ecological outcomes can be buffered by structural investment and maturity in institutions. The difference between growth-driven and governance-driven environmental pressure, particularly in the context of the Global South, also contributes to a more nuanced picture of sustainability dynamics across income levels. This multidimensional insight strengthens arguments that ecological deficit cannot be interpreted solely through the lens of affluence, and must also account for state capacity, resilience, and environmental policy continuity.

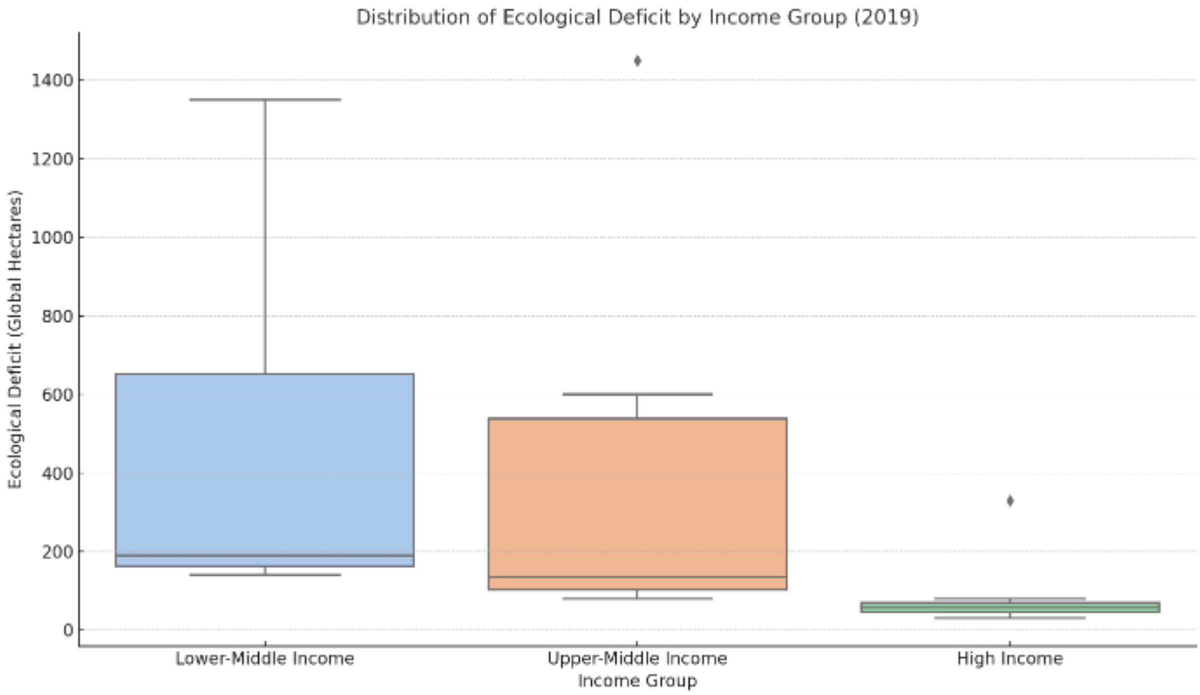

Figure 5: Distribution of Ecological Deficit by Income Group (2019)

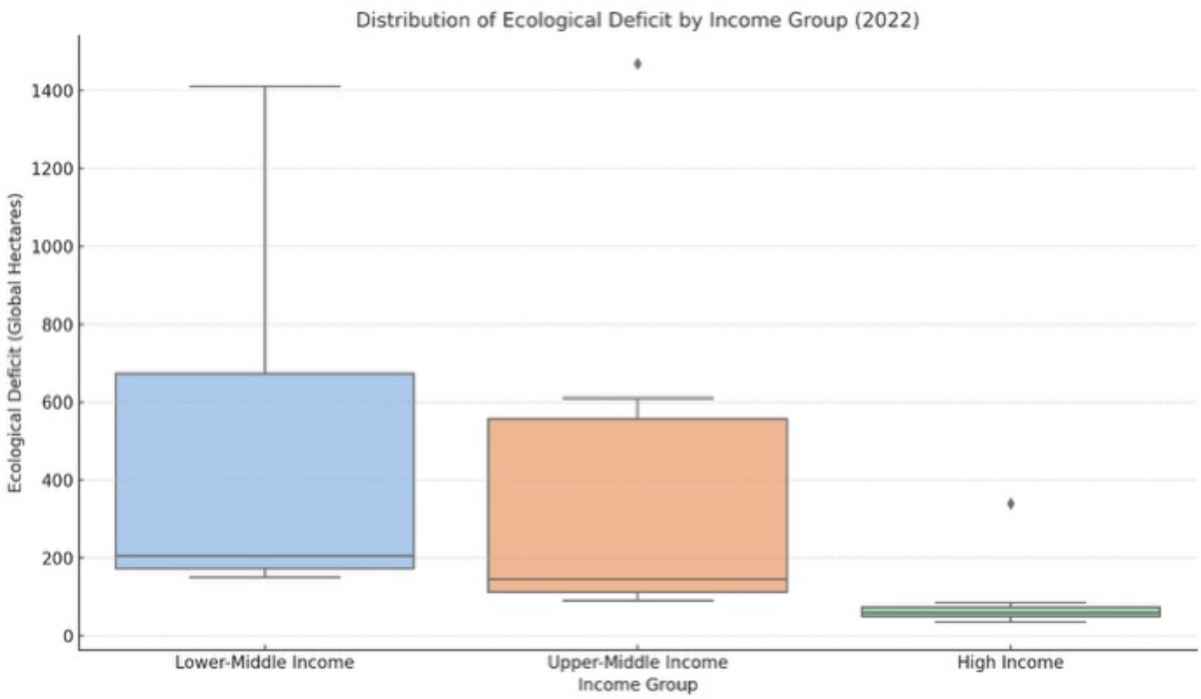

Figure 6: Distribution of Ecological Deficit by Income Group (2022)

4.3. K-Means Clustering Analysis: Sustainability Groups of Countrie

K-Means Clustering Analysis was used to group nations with comparable sustainability traits. Following this analysis, nations were categorized into three groups according to their levels of sustainability: low, medium, and high. To determine the optimal number of clusters (k), both the Elbow Method and the Silhouette Score Analysis were conducted. The Elbow Method revealed a clear inflection point at k = 3, where the reduction in within-cluster sum of squares began to flatten, indicating that three clusters provided a meaningful and efficient classification. Similarly, the average silhouette score peaked at k = 3, confirming that the clustering structure offers strong cohesion within groups and clear separation between them. This dual validation approach ensured the robustness and interpretability of the clustering results.

•Cluster 0 (High Ecological Deficit and Footprint): This cluster comprises industrialized countries with high consumption rates, such as the United States, Canada, Germany, Japan, and France.
•Cluster 1 (Medium-Level Sustainability): This group includes countries undergoing industrialization, such as Brazil, China, Mexico, and Turkey. These countries can reduce their environmental impacts by implementing sustainable development strategies.
•Cluster 2 (Low Ecological Footprint and Deficit): This group includes developing countries, such as Nigeria, Bangladesh, and Nepal, which have low levels of industrialization.

2019–2022 Cluster Changes: Based on the clustering analysis outcome, some nations have experienced changes in their sustainability performance. Algeria, Albania, and Afghanistan shifted from Cluster 2 to Cluster 1 because their ecological deficit ratios increased. Sweden and Norway, on the other hand, remained in favorable clusters by lessening their negative impact on the environment through improvements in sustainability policies.
This comparative temporal analysis highlights that sustainability performance is not static and can shift significantly depending on policy actions and consumption trends. The use of validated clustering methods provides a clear, data-driven categorization that enhances the understanding of global ecological disparities.

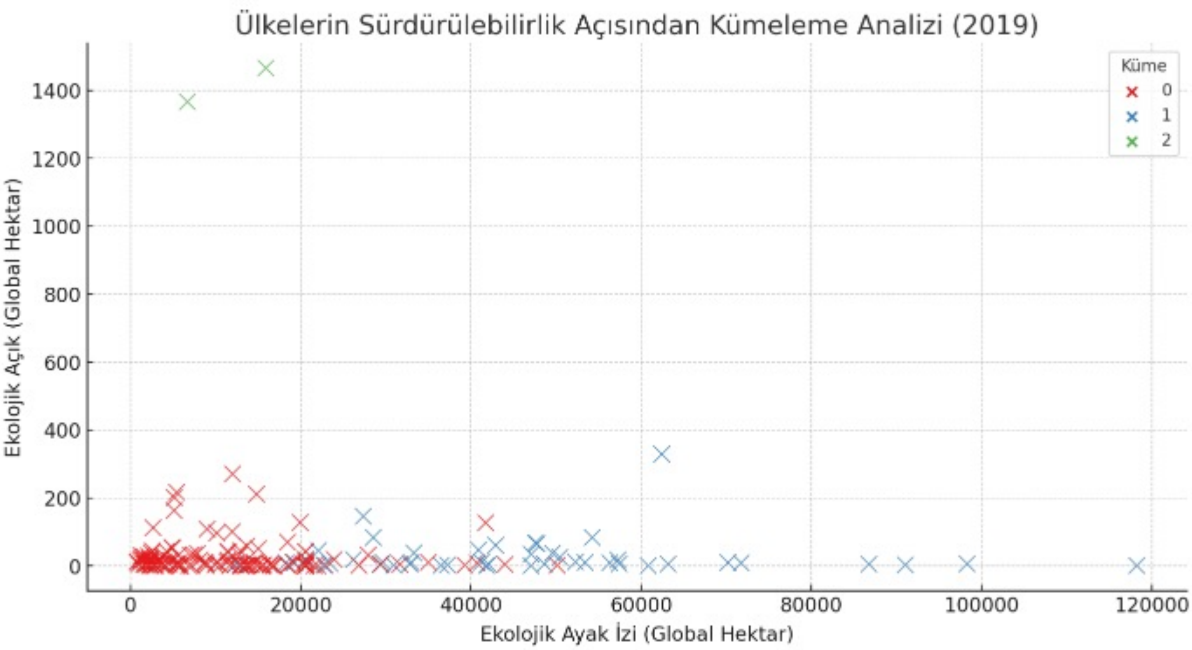

Figure 7: Clustering Analysis of Countries by Sustainability (2019)

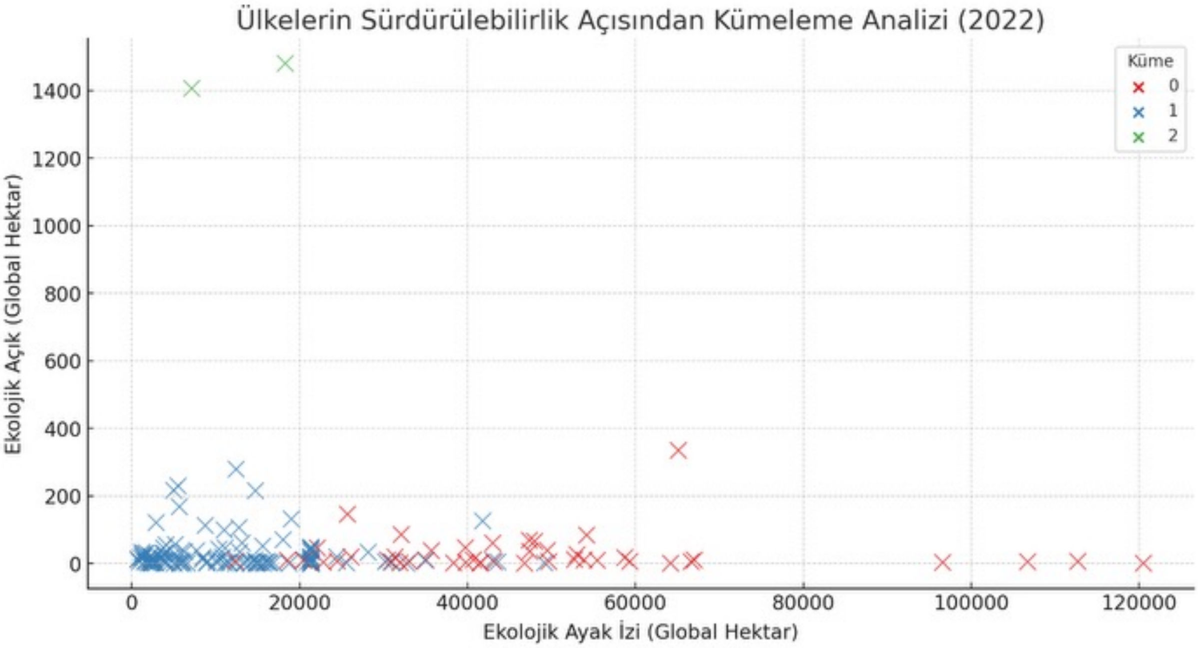

Figure 8: Clustering Analysis of Countries by Sustainability (2022)

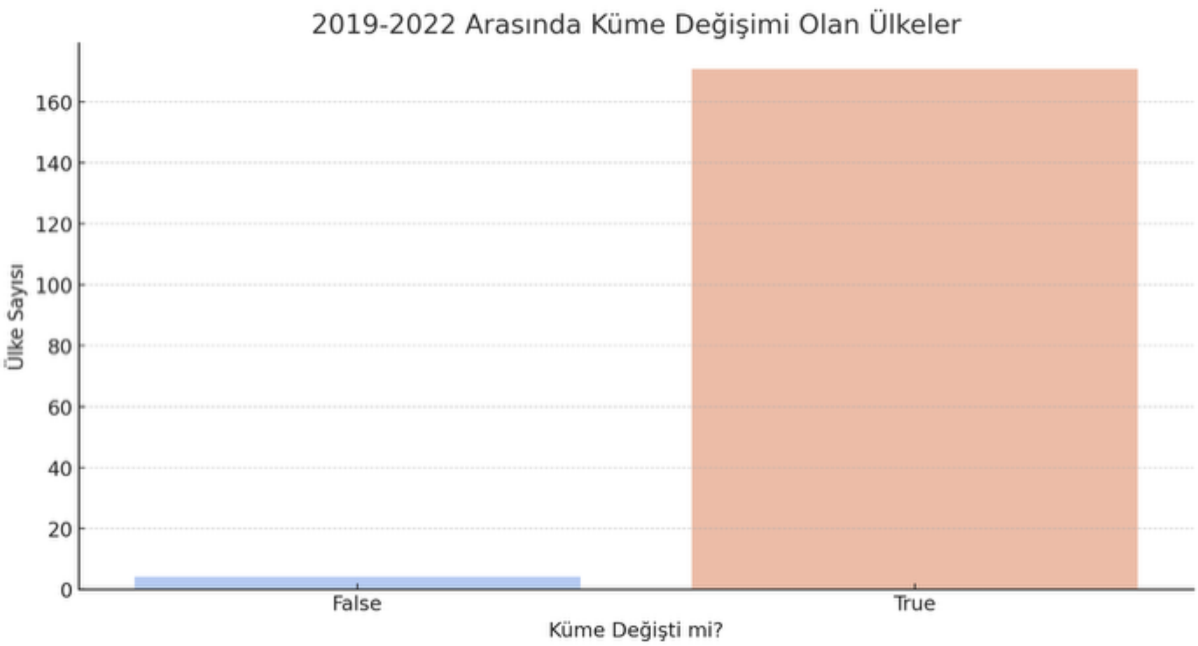

Figure 9: Number of Countries That Changed Clusters (2019–2022)

According to the findings of the analysis, worldwide sustainability indexes vary considerably. Industrialized nations are specifically bogged down in environmental sustainability if we take important indicators like the ecological footprint, biocapacity, or ecological deficit into consideration. Low-income nations are experiencing high levels of inefficient use of natural resources and waste, and high-income nations with high industrial activities and energy consumption are experiencing high ecological deficits. This indicates the need to maintain economic growth balanced with environmental sustainability. Empirical facts support these imbalances and also prove the developed nations have the tendency to outsource their costs to less developed countries (Syrovátka, 2020). This evidence lends credence to the idea that global coordination and collective responsibility are also needed to solve sustainability problems nationally (UNDP & SDSN, 2020).

Regional analysis findings suggest that regions such as Africa and Oceania register lower levels of ecological impact while industrialized areas such as Asia and North America register more remarkable environmental footprints. Low ecological footprints do not always imply sustainability in those regions since, in some countries, a biocapacity shortage hurts environmental sustainability. Income-group-based measures indicate an increase in ecological pressure in correspondence with economic development, although this can be minimized through sustainable production processes. Economic growth is directly related to environmental deterioration, although some industrialized countries have reduced this adverse effect by introducing a green economy. All these findings correlate with the Environmental Kuznets Curve hypothesis that suggests that the deterioration of the environment will reduce after reaching a certain level of income. However, it increases with economic growth (Saraç & Yağlıkara, 2017).

Lastly, clustering analysis has found countries with similar ecological characteristics through their classification into categories of their sustainability levels. This analysis has effectively distinguished countries with superior sustainability conditions and those with more significant ecological deficits and imprints. Environmental balance is directly affected by policy changes regarding sustainability since some countries shifted between 2019 and 2022 between different clusters. All the findings indicate the necessity of increased efficiency and locally applicable policies to achieve sustainable development goals. This dynamic framework shows how short-term policy adjustments can contribute to a quantifiable effect on the sustainability status of a nation (Radácsi & Szigeti, 2024). To be effectively utilized, policy design has to consider both the spatial and temporal aspects of sustainability (Ghita et al., 2018).

5. Conclusion and Evaluation

The analyses conclude that one of the most pressing barriers to sustainable development is the uneven distribution of ecological indicators—namely, ecological footprint, biocapacity, and ecological deficit. Ecological risks tend to arise in developing countries due to their limited biocapacity, while industrialized nations face growing environmental pressures caused by excessive consumption. These findings align with prior studies that emphasize the uneven transgression of planetary boundaries across countries at different stages of development (Galli et al., 2012).

This study offers an original contribution to the literature by adopting an integrated, multi-method approach to sustainability evaluation. Unlike previous research that predominantly relies on single-dimensional indicators, this study implements a composite methodology combining the TOPSIS method for country-level sustainability ranking, time series analysis to examine changes in ecological indicators over time, and K-means clustering to group countries with similar ecological profiles (Tomadon et al., 2024). This comprehensive framework enhances methodological robustness and allows for more accurate policy interpretations.

More specifically, the application of decision-making tools such as TOPSIS addresses the increasing academic interest in employing quantitative, criteria-based models to evaluate ecological performance. The clustering analysis further enriches the assessment by identifying structural patterns of sustainability behavior, revealing how countries evolve in their environmental standing.

The empirical results reinforce the long-debated notion that economic growth often materializes into environmental degradation. Major industrialized economies—despite having policy frameworks in place—continue to show an upward trend in ecological deficits. However, the findings also demonstrate that progress is possible. Countries like Sweden, Norway, and Finland have succeeded in stabilizing or reducing their ecological deficits by integrating sustainable production models and green policy innovations. These observations support earlier research indicating that well-targeted policy interventions and innovation-driven sustainability strategies can significantly mitigate ecological damage (Qamruzzaman & Karim, 2024).

Importantly, this study extends the literature by offering a time-sensitive, structural analysis of sustainability performance. The cluster comparisons between 2019 and 2022 provide evidence of dynamic shifts in national sustainability profiles, underscoring the importance of continuous performance monitoring. While some countries have improved in terms of sustainability, others—such as the United States, Canada, and China—remain in high-impact clusters, highlighting the urgency for stronger, outcome-oriented policy measures.

Ultimately, the findings illustrate a crucial policy trade-off: achieving economic development while maintaining ecological balance. This study underlines the need for tailored environmental strategies that align with a country's developmental context. Future research should further refine this approach by integrating longer-term sustainability data and exploring causal mechanisms linking policy design, innovation, and ecological outcomes. Despite the comprehensive approach employed in this study, several limitations should be acknowledged. First, the study relies exclusively on data from the Global Footprint Network (GFN), which may limit generalizability due to potential methodological constraints inherent to the dataset. Second, the relatively short time span of the analysis (2019–2022) restricts the ability to observe long-term sustainability trends. Third, while the study incorporates robust quantitative methods, it does not account for qualitative dimensions such as institutional quality, governance efficiency, or socio-political stability, all of which may influence ecological outcomes.

Nevertheless, the study contributes significantly to the growing literature on ecological performance assessment by offering a robust, multi-method framework that integrates entropy-based TOPSIS, time-series analysis, and clustering techniques. These methods provide a systematic and replicable way to track sustainability progress across countries. Future research expanding on this model—both in temporal scope and methodological diversity—can enhance the precision and relevance of sustainability diagnostics and guide more effective policy interventions at both national and global levels.

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