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Examining the Interplay Between Innovation Index, Innovation Efficiency and Sustainability Index: A Cross-Group Analysis of G7 and E7 Countries

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ABSTRACT

Purpose: The main purpose of this study is to examine the innovation, sustainability and innovation efficiencies of G7 and E7 countries and to address the relationship between them. The investigation focuses on exploring the potential impact of innovation productivity on the sustainability index in both developed and emerging economies, along with examining potential underlying factors influencing this relationship.

Methodology: The research employs Data Envelopment Analysis (DEA) to assess the innovation efficiency. This analysis considers two innovation outputs set against five inputs. Statistical methods such as t-test and correlation analysis are also used to investigate the interplay between innovation efficiency and the sustainability.

Findings: The findings of this study reveal interesting results. First, no significant difference is observed regarding innovation efficiency between G7 and E7 groups. For the G7 countries, there is a positive correlation between the sustainability index and innovation efficiency, suggesting that more efficient innovation is associated with sustainability. Contrarily, there is a negative correlation between these indices in E7 countries, implying that effective innovation can lower the sustainability index.

Originality: This study contributes novel insights into the relationship between innovation and sustainability by considering the G7 and E7 countries. Although various countries are evaluated in the literature, no comparison has been made for these two groups. Also, the identification of opposing correlations between two indices in developed and emerging economies constitutes a significant contribution to the literature.

Keywords*:* Innovation Efficiency, Sustainability Index, Data Envelopment Analysis (DEA), Developed and Emerging Economies, Correlation Analysis.

JEL Codes: Q01, O3, O4, R1.

İnovasyon Endeksi, İnovasyon Verimliliği ve Sürdürülebilirlik Endeksi Arasındaki Etkileşimin İncelenmesi: G7 ve E7 Ülkelerinin Gruplar Arası Analizi

ÖZET

Amaç: Bu çalışmanın temel amacı, G7 ve E7 ülkelerinin inovasyon, sürdürülebilirlik ve inovasyon verimliliklerini incelemek ve aralarındaki ilişkiyi ele almaktır. Araştırma hem gelişmiş hem de gelişmekte olan ekonomilerde inovasyon verimliliğinin sürdürülebilirlik endeksi üzerindeki potansiyel etkisini keşfetmeye ve bu ilişkiyi etkileyen potansiyel faktörlerin incelenmesine odaklanmaktadır.

Yöntem: Araştırma, inovasyon etkinliğini değerlendirmek için Veri Zarflama Analizi (VZA) kullanmaktadır. Bu analizde beş girdiye karşı iki yenilik çıktısını dikkate almaktadır. İnovasyon verimliliği ile sürdürülebilirlik arasındaki etkileşimi araştırmak için t-testi ve korelasyon analizi gibi istatistiksel yöntemler de kullanılmıştır.

Bulgular: Bu çalışmanın bulguları ilginç sonuçlar ortaya koymaktadır. İlk olarak, G7 ve E7 grupları arasında inovasyon verimliliği açısından anlamlı bir fark gözlenmemiştir. G7 ülkelerinde, sürdürülebilirlik endeksi ile inovasyon verimliliği arasında pozitif bir ilişki vardır, bu da daha verimli inovasyonun sürdürülebilirlik ile ilişkili olduğunu ortaya koyar. Bunun aksine, E7 ülkelerinde ise bu endeksler arasında negatif bir korelasyon vardır, bu da etkin bir inovasyon sürecinin sürdürülebilirlik endeksini düşürebileceğini göstermektedir.

Özgünlük: Bu çalışma, G7 ve E7 ülkelerini dikkate alarak inovasyon ve sürdürülebilirlik arasındaki ilişkiye yeni bakış açıları katmaktadır. Literatürde çok farklı ülkeler değerlendirilmesi karşın bu iki ekonomik grup için karşılaştırma yapılmamıştır. Ayrıca gelişmiş ve gelişmekte olan ekonomilerde iki endeks arasındaki zıt korelasyonların tespit edilmesi literatüre önemli bir katkı oluşturmaktadır.

Anahtar Kelimeler*:* İnovasyon Verimliliği, Sürdürülebilirlik İndeksi, Veri Zarflama Yöntemi, Gelişmiş ve Gelişmekte Olan Ekonomiler, Korelasyon Analizi.

JEL Kodları: Q01, O3, O4, R1.

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1. INTRODUCTION

Sustainability and innovation are among the most prominent themes on the agenda of countries. Industrial processes, which began with the invention of the steam engine, have continued to evolve at an accelerated pace due to advancing technological developments. However, in an increasingly competitive environment, merely following technological advancements is no longer sufficient. Innovation activities are essential to be at the forefront of technological progress. Simultaneously, global issues such as climate change, depletion of natural resources, environmental pollution, and social inequality threaten the future of humanity, prompting countries to embrace sustainable activities across economic, ecological, and social areas. Innovation stands as a fundamental driving force for both competitiveness and sustainable development (Erdin and Çağlar, 2023).

The concept of sustainability refers to the maintenance of a balance between the environment, economy, and society to effectively utilize natural resources and meet the needs of future generations. Sustainability ensures the long-term well-being of our planet and society through smart resource management, reduction of environmental footprint, and the establishment of social justice. Viewing sustainability solely as the prevention of resource depletion or a green manner falls short of grasping the full extent of the matter. Sustainability aims not only to foster economic and environmental growth but also to uphold social justice. To this end, the United Nations' Sustainable Development Goals encompass targets related to poverty, quality education, zero hunger, gender equality, inequality reduction, peace, and justice.

Innovation means enhancing the current state, creating new technologies and business models, and generating fresh opportunities. Historically, innovation has primarily revolved around economically-focused objectives, often disregarding environmental and social considerations. However, the recognition of the significance of sustainability has led to the integration of eco-friendly technologies, renewable energy sources, efficient production methods, and social innovations as core elements of innovation. Consequently, innovation possesses substantial potential to contribute to sustainability by producing novel solutions, utilizing resources more effectively, and mitigating social inequalities.

Research and development activities, especially in the field of energy and the environment, and the budget allocated for these are very important in achieving the sustainability goals determined by the UN (Jiang, 2023). This study investigates the examination of the innovation, innovation efficiency, and sustainability indices between the Group of Seven (G7) countries, representing the world's most advanced economies, and the Emerging 7 (E7), comprising developing nations. While developed economies are expected to rank higher on the innovation index, their innovation efficiency necessitates separate evaluation. Similarly, developing countries, although ranked lower on the innovation index, may yield a more efficient innovation output relative to their inputs. To analyze this, Data Envelopment Analysis has been employed to calculate the efficiencies of G7 and E7 countries based on their innovation inputs and corresponding outputs. Subsequently, the relationship between this efficiency and sustainability has been examined and compared across years between these two groups.

This study is organized as follows: Section 2 presents a review of literature in the areas of innovation efficiency and sustainability. Section 3 provides a detailed description of the data and methodology employed in the study. Descriptive statistics of the selected data, calculations of innovation efficiency, and the results of statistical analyses are presented in Section 4. Section 5 concludes the paper by summarizing the key findings and limitations of the study including some future research ideas.

2. RELATED RESEARCH

This study, which investigates the relationship between innovation and sustainability, entails a literature review encompassing the areas of innovation, innovation efficiency, and sustainable development.

Innovation efficiency embodies the effectiveness within the process of transforming innovation inputs, such as resources, knowledge, and investments, into valuable and impactful outputs. Improved innovation efficiency denotes generating more outputs with the same size of inputs or achieving the same output with reduced inputs. The measure of innovation efficiency is pivotal in assessing the utilization of innovation resources. The evaluation of innovation performance is monitored and indexed by various international bodies, including prominent instances like The European Innovation Scoreboard (EIS), formulated by the European Union, and the Global Innovation Index (GII), endorsed by the UN General Assembly (Murat, 2020).

Usman and Liu (2015) conduct an assessment of innovation capacity and efficiency for SAARC countries. This research aims to unveil deficiencies within the innovation systems of these countries and identify requisite innovation inputs to solve the problems. Innovation efficiency is calculated as the ratio of the innovation output to the input index. It is noteworthy that among the methodologies extensively employed for calculating innovation efficiency, Data Envelopment Analysis (DEA) occupies a prominent position. For example, Erdin and Çağlar (2022) employ the DEA to compute the innovation efficiency of OECD countries using data from the Global Innovation Index (GII). Andrijauskiene et al. (2023) evaluate the innovation efficiency of the European Union between 2000 and 2020 using the DEA method. Their analysis indicates variations in efficiency within the Union countries, with DEA results serving as guidelines for overcoming such disparities. Altıntaş (2020) considers the innovation efficiency of G7 countries in their 2019 study, employing both DEA and the Criteria Importance Through Intercriteria Correlation (CRITIC) methodologies. Luo et al. (2019) quantify the efficiency of green technology innovation for strategically emerging industries between 2004 and 2015, employing the Malmquist index and DEA techniques. Alnafrah (2021) utilizes the bias-corrected network DEA to evaluate the efficiency of national innovation systems within BRICS economies. Alongside assessments of national innovation performance, some studies have investigated the impact of innovation activities on firm efficiency using the DEA method (Pham and Quddus, 2021). Aldieri et al. (2022) study the alterations in energy efficiency within developing economies due to renewable energy innovations by applying DEA methodology. Jiang et al. (2021) employ DEA to evaluate the efficiency of green technology innovations in renewable energy enterprises. Belgin (2019), on the other hand, used DEA to analyze the efficiencies of research and development which is a crucial component of innovation for various regions of Türkiye. We refer readers Narayanan et al. (2022) for a detailed review of DEA based innovation performance measurements and Sherman and Zhu (2006: 49-89) for details of DEA.

Innovation traditionally centered on economic advantages, with a primary emphasis on improving product or service quality. However, the scope and objectives of innovation have evolved to encompass broader societal concerns, notably addressing critical issues such as climate change, environmental sustainability, and public health (Wintjes, 2016). Therefore, the relationship between innovation and sustainability has been extensively explored by numerous researchers in the literature. Seclen-Luna et al. (2021) evaluate the impact of innovation activities on firms' productivity and the environment. They conclude that innovation activities, particularly for large firms, have a positive effect on the environment. Yurdakul (2020) emphasize the critical significance of the sustainability concept due to the substantial increase in greenhouse gas emissions, the prevalence of hunger affecting one in nine individuals, and excessive resource consumption in industrialized nations. Consequently, the study details the influence of eco-innovation on sustainability from environmental, economic, and social dimensions. Yücel and Terzioğlu (2023) highlight a meaningful spatial relationship between eco-innovation and sustainable development indicators, and underscore the necessity of aligning eco-innovation and development policies within a spatial context. Çalık (2021) deliberates on sustainable innovation activities within the manufacturing sector, discussing innovation and sustainability facets while contextualizing firm scale through average scores. Long et al. (2019) highlight the significance of measuring green innovation efficiencies across different regions in China as a mean to mitigate greenhouse gas emissions. Luo et al. (2019) discuss the pivotal role of green technology innovation efficiency in realizing China's sustainability targets. Shin et al. (2018) assess sustainability as an objective of innovation and examine the relationship between innovation efficiency and sustainability using data from manufacturing companies in Korea. Akyol (2020) demonstrate that technological innovation serves as a powerful catalyst for promoting sustainable development, both in developed and developing nations. Jiang et al. (2023) reveal that green innovation activities in developed countries effectively reduce carbon emissions. Omri (2020) examines the ability of technological innovation to stimulate economic growth, increase human development and reduce carbon emissions in low, middle and high-income countries. According to the results of the analysis, technological innovation in high-income countries simultaneously improves economic growth, environmental quality and human development. However, the same improvement cannot be achieved in other countries Similarly, examining data from eighty both advanced and emerging economies, Kumar and Managi (2010) observe that technological innovation leads to a decrease in environmental degradation within developed nations, but tends to contribute to increased environmental harm in the majority of developing countries.

The measurement of innovation efficiency has been explored in the literature from a comprehensive perspective, encompassing the utilization of various input-output criteria and diverse methodologies for efficiency assessment. In this study, the widely employed Data Envelopment Analysis (DEA) is applied. The analysis focuses on G7 economies, representing advanced economies, and E7 economies, which are emerging economies. The contribution of this study is twofold. Firstly, a comparative analysis of innovation and sustainability indices is undertaken between two distinct economic groups. This analysis aims to explore the relationship between economic development and these variables through the comparison of countries within these groups. Subsequently, the study examines the relationship between innovation efficiency, calculated using the DEA, and sustainability indices. Unlike the innovation index, innovation efficiency pertains to the outputs of innovation relative to inputs independently of a country's economic condition. Consequently, certain E7 countries might exhibit greater efficiency compared to G7 countries. Hence, the correlation examination between this efficiency and the sustainability index holds the potential to yield unique insights. In essence, this study employs the DEA to provide insights into the potential interplay between innovation efficiency and sustainability indices within the selected economies, offering a perspective that could lead to help policy makers.

3. DATA and METHODOLOGY

In this section, GII (Global Innovation Index) and Sustainability Index are introduced for the selected G7 countries (Germany, United States, United Kingdom, Italy, France, Japan, and Canada) along with E7 countries (China, India, Russia, Brazil, Mexico, Indonesia, and Türkiye). Data spanning from 2013 to 2022 will be analyzed using the Data Envelopment Analysis (DEA) method and various statistical tests. Elaboration on the parameters to be employed in the research is presented in Table 1.

Table 1. Global innovation index and sustainability index

Index	*Details*	*Reference*
Sustainability Index (SI)	It is the average of the scores a country receives in achieving the 17 goals set by the UN.	Sachs et al. (2023)
Innovation efficiency (IE)	It represents a country's innovation efficiency calculated using DEA based on innovation inputs and outputs.	-
Innovation Index (II)	It is the average of scores from innovation input and output sub-indices.	GII
Innovation input sub-index	It signifies the inputs utilized in the innovation process.	GII
Institutions	This aspect encompasses the institutional framework of an economy, encompassing elements such as the political, regulatory, and business environment.	GII
Human capital and research	This category includes education, tertiary education, and research and development (including metrics like the number of researchers and gross expenditure on R&D).	GII
Infrastructure	It covers infrastructure aspects such as IT technology infrastructure, energy and logistics infrastructure, as well as environmental sustainability.	GII
Market sophistication	It encompasses market conditions such as credit, investment, trade, and market size, including overall transactions.	GII
Business sophistication	It includes expert labour, innovation linkages such as university-industry collaboration, and access to knowledge.	GII
Innovation output sub-index	It represents the outcomes that emerge after the innovation process.	GII
Knowledge and technology outputs	It is scored based on knowledge and technological outputs, including patents, scientific and technical articles, H-index, labour productivity, high-tech manufacturing, and high-tech exports.	GII
Creative outputs	It contains creative outputs such as trademarks, industrial designs, creative products and services, top-level domains, and developed mobile applications.	GII

3.1 Data Envelopment Analysis

Data Envelopment Analysis (DEA) is a non-parametric method based on linear programming used to measure relative efficiency and it was first introduced by Charnes et al. (1978). Unlike other methods, DEA evaluates relative efficiency using empirical inputs and outputs without being dependent on any specific functional form (Shin et al., 2018). Its strength lies in its linear programming-based approach, which proves more effective for complex scenarios involving multiple inputs and outputs (Sherman and Zhu, 2006). Consequently, it is widely employed in assessing efficiency and measuring innovation efficiency due to its robustness.

DEA aims to determine the most advantageous combination of weights for input and output variables, with the objective of maximizing output while minimizing input utilization. Let's consider a decision-making unit (DMUs) with a set of $j = 1, .., n$ and an input vector, x_{ij} $where\ i \in \{1, .., m\}$ and output vector, y_{rj} $where\ r \in \{1, .., s\}$. The weights for input and output vectors are v_i and u_r respectively. Then the objective function is the maximization of weighted efficiency as in set of Equation 1-3. The weighted efficiency has to be less than equal to "1" and the weights for input and outputs are nonnegative

$$E_j = Max\ \frac{\sum_r u_r y_{rj}}{\sum_i v_i x_{ij}} \tag{1}$$

$$\frac{\sum_r u_r y_{rj}}{\sum_i v_i x_{ij}} \leq 1, \ \forall j \tag{2}$$

$$u_r, v_i \geq 0, \ \forall r, i \tag{3}$$

This is the fundamental input oriented CRR model introduced by Charnes et al. (1978) and it can be converted to a linear model as in set of Equation 4-7.

$$e_j = Max \sum_r u_r y_{rj} \tag{4}$$

$$\sum_r u_r y_{rj} - \sum_i v_i x_{ij} <= 0 , \ \forall j \tag{5}$$

$$\sum_i v_i x_{ij} = 1, \ \forall j \tag{6}$$

$$u_r, v_i \geq 0, \ \forall r, i \tag{7}$$

The model is run "*n*" times to derive the weights for each DMUs. When the outcome is 1, we can classify the DMU as efficient. Conversely, if the result is otherwise, it indicates that the DMU operates inefficiently. In the context of the problem under consideration in this research, the CRR input-oriented DEA model has been employed. This model calculates the efficiency of a total of 14 countries for each year within the period spanning from 2013 to 2022.

4. EMPIRICAL RESULTS

In this section, empirical results obtained based on the data of the G7 and E7 countries, which are the focus of the study, between the years 2013-2022 are presented. These data include analysis of important factors such as innovation index, sustainability index and innovation efficiency. These analyses allow us to both understand the innovation and sustainability performance of countries and examine the differences in this performance between different economic groups.

4.1 Descriptive Statistics

We discuss the innovation and sustainability performance of G7 and E7 countries between 2013 and 2022 with descriptive statistics. The average values of the Global Innovation Index (GII) scores, sustainability indices and other related variables of each country by years are analyzed. These statistical results help us to understand the situation of both groups of countries in the fields of innovation and sustainability. The yearly scores of the SI and II for both G7 and E7 countries are visualized in Figure 1 and Figure 2.

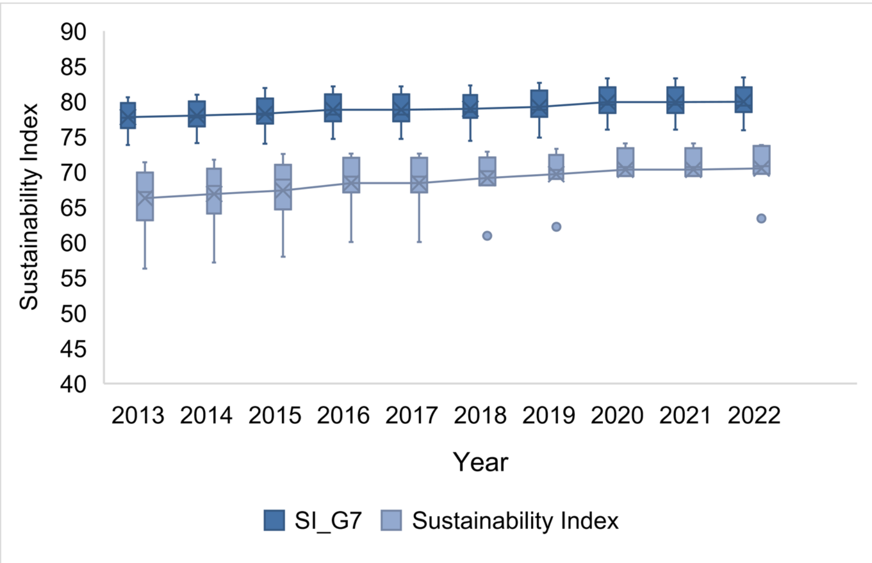

Figure 1. Sustainability index of G7 and E7 countries over years

Figure 1 reveals a noticeable upward trajectory in the sustainable index for both G7 and E7 nations across the assessed years. Particularly attributed to lower energy and production efficiency, developing economies exhibit a potential for achieving swifter advancements in terms of sustainability. Conversely, established economies exhibit a relatively gradual progression. Examining the data presented in Figure 1 for the E7 countries, it is evident that a single country (Indonesia) stands significantly behind the group averages in terms of sustainable scores.

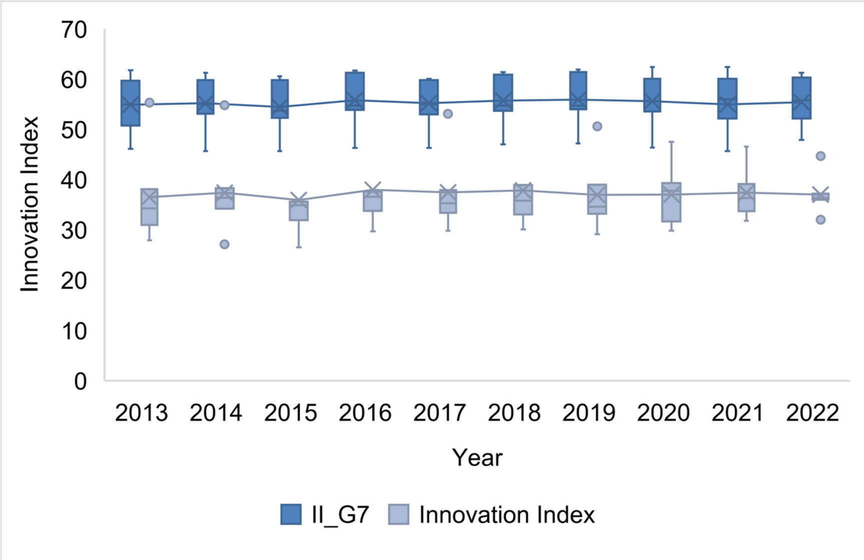

Figure 2. Innovation Index of G7 and E7 countries over years

Turning to the evaluation of the innovation index illustrated in Figure 2, minimal fluctuations are observed over the selected time frame. Notably, China secures a significantly higher innovation score compared to E7 nations and even outperforms some of the G7 countries. Indonesia's innovation score also falls below the group average. Among the G7 nations, Italy notably lags behind the group average in terms of innovation score. The summarized outcomes depicted in Table 2 are derived from the examination of descriptive statistics capturing the average trends across different years.

Tablo 2. Descriptive statistics

	Index	*Mean*	*Std. Dev.*	*Min*	*Max*
G7 countries	Sustainability Index	78.96	2.51	73.83	83.4
	Innovation Index	55.33	4.80	45.7	62.4
E7 countries	Sustainability Index	68.68	4.23	56.28	74.05
	Innovation Index	37.14	6.67	26.5	55.3

As can be clearly seen in Table 2, G7 countries exhibit superior scores across both indices. However, statistical analysis is required to determine whether these score differences are statistically significant. In pursuit of this goal, the two-sample t-test is employed to investigate whether the mean values of the G7 countries exhibit statistically significant distinctions. This analysis was conducted utilizing the Minitab software, employing a confidence interval of 95%. The comprehensive findings resulting from the analysis are presented in Table 3.

Table 3. Two-sample t-test results

Sustainability Index			*Innovation Index*		
Null hypothesis		H_0: $\mu_{G7} - \mu_{E7} = 0$	Null hypothesis		H_0: $\mu_{G7} - \mu_{E7} = 0$
Alternative hypothesis		H_1: $\mu_{G7} - \mu_{E7} > 0$	Alternative hypothesis		H_1: $\mu_{G7} - \mu_{E7} > 0$
T-Value	*DF*	*P-Value*	*T-Value*	*DF*	*P-Value*
17.46	138	0.000	18,52	138	0.000

The t-test outcomes reveal that the obtained p-value significantly falls below the established significance level of 0.05. Consequently, the null hypothesis is rejected, leading to the inference that the mean value of the sustainability index for G7 countries is statistically higher than that of E7 countries. In the context of comparing mean values subject to the innovation index, the null hypothesis is similarly rejected, as the computed p-value remains below the 0.05 threshold. These results support the statement that, based on the data spanning the past decade, G7 countries achieve greater success in both sustainability and innovation indices as compared to their E7 counterparts.

4.2 Innovation efficiency analysis

Between 2013 and 2022, the innovation efficiency of G7 and E7 countries was assessed based on the innovation input sub-index and output sub-index parameters, as outlined in Table 1. This assessment was conducted by employing the Data Envelopment Analysis (DEA) model, as expressed in Equation 2. The results of innovation efficiency scores are presented in Table 4.

Table 4. Innovation efficiencies by DEA

Country	*2022*	*2021*	*2020*	*2019*	*2018*	*2017*	*2016*	*2015*	*2014*	*2013*
Germany	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
United States	1.000	1.000	0.982	1.000	0.995	1.000	1.000	0.972	0.871	0.785
United Kingdom	1.000	1.000	1.000	1.000	1.000	0.970	0.984	1.000	0.898	0.838
Italy	1.000	1.000	1.000	0.933	0.965	0.925	0.957	0.914	0.921	0.947
France	1.000	1.000	0.979	0.917	0.920	0.871	0.878	0.971	0.885	0.899
Japan	0.933	0.894	0.879	0.869	0.897	0.842	0.847	0.799	0.744	0.763
Canada	0.761	0.856	0.847	0.882	0.845	0.818	0.873	0.917	0.773	0.821
China	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
India	0.988	1.000	1.000	1.000	1.000	0.852	0.927	1.000	1.000	1.000
Russia	0.711	0.786	0.706	0.674	0.726	0.732	0.824	0.882	0.920	0.820
Brazil	0.712	0.685	0.607	0.656	0.685	0.670	0.739	0.881	0.884	0.885
Mexico	0.891	0.958	0.936	0.948	0.848	0.831	0.836	0.934	0.828	0.939
Indonesia	0.868	0.962	0.968	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Türkiye	1.000	1.000	0.951	1.000	1.000	1.000	1.000	1.000	1.000	1.000

When the results in Table 4 are examined, it can be seen that the innovation systems of all G7 countries, with the exception of Japan and Canada, exhibit efficient functioning in the year 2022. In the same year, among the E7 countries, only China and Türkiye demonstrated efficient innovation processes, while the rest faced challenges in achieving effective innovation process. Notably, despite its relatively low innovation score, Indonesia maintained an efficient innovation process until 2019; however, its efficiency has experienced a decline in more recent years as seen in Table 4. Conversely, Italy and France, both belonging to the G7 countries, have displayed improved productivity in recent years. To facilitate a comprehensive comparison of productivity between the two groups, the average innovation productivity of G7 and E7 countries is calculated for each year and visually depicted in Figure 3. These results show how efficiently the countries of both groups use innovation inputs with corresponding outputs and reveal the differences between economic groups.

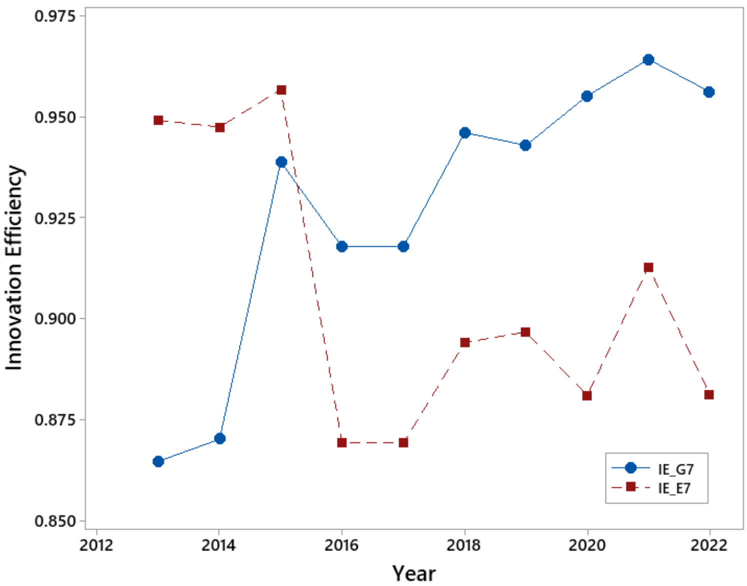

Figure 3. Mean of innovation efficiency over years

Although the mean innovation efficiency of E7 countries exceeds that of G7 countries until 2015, a notable decline is observed after 2015, causing it to lag behind the G7 averages. Statistical analysis through a t-test was conducted on the data from both groups, yielding a result of p=0.103, which is greater than the significance level of 0.05. This outcome implies that the null hypothesis, asserting the equality of innovation efficiency averages between the two groups, cannot be rejected. In other words, no statistically significant distinction in terms of innovation efficiency performance exists between the two groups. The minor discrepancy between these groups could potentially be due to chance or random sampling variations.

Expecting improved sustainability outcomes in line with high innovation efficiency is a valid presumption. This situation suggests a positive correlation between these two variables. To test this assumption, the correlation between innovation efficiency and sustainability indices for both the G7 and E7 groups is investigated. First, by visually presenting innovation efficiency and sustainability index data, we gained an initial observation regarding to the relationship between them. Figure 4 and Figure 5 depict scatter plots with trendlines for the G7 and E7 groups, respectively. Notably, an upward trendline is observed for the G7 group, whereas an opposing trendline is observed for the E7 group.

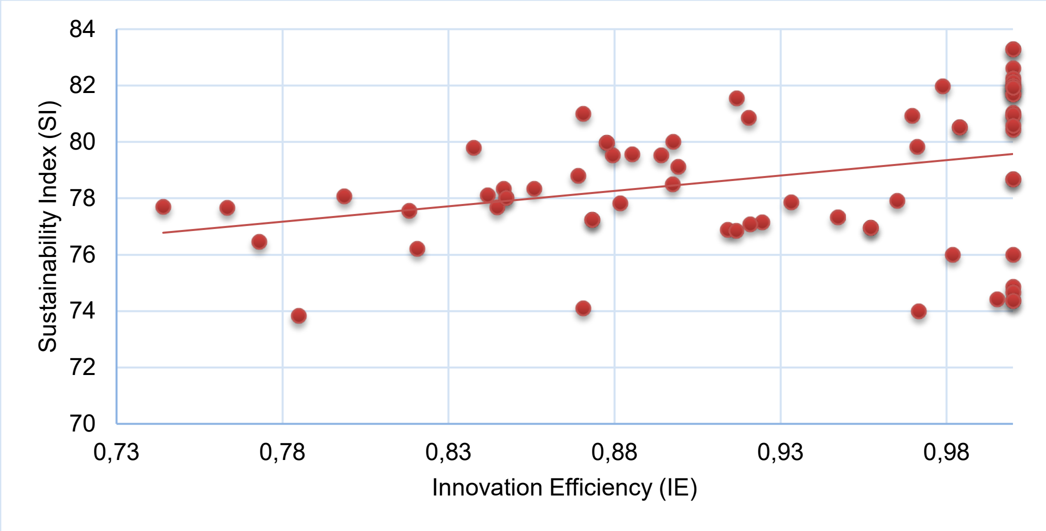

Figure 4. Scatter plot of SI vs II for G7 countries (2013-2022)

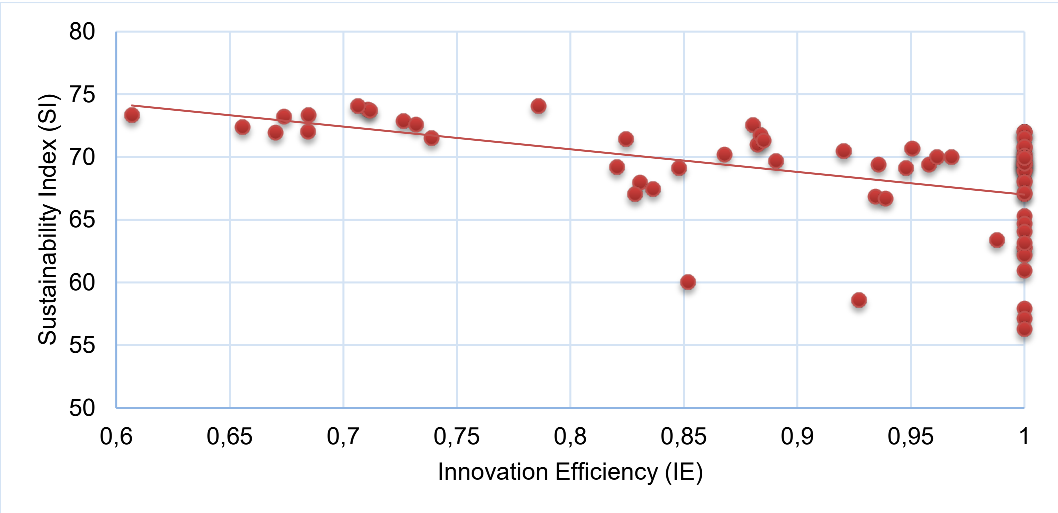

Figure 5. Scatter plot of SI vs II for E7 countries (2013-2022)

As observed in Figures 4 and 5, different patterns of relationship emerge for two distinct groups. To determine whether this constitutes a statistically significant relationship, Pearson and Spearman correlation coefficients are calculated, along with their corresponding p-values. The values for the correlation analysis are presented in Table 5.

Table 5. Correlation analysis of Innovation Efficiency (2013-2022) for G7 and E7

	Pearson Correlation		*Spearman Correlation*	
Group	*Coefficient*	*p value*	*Coefficient*	*p value*
G7	0.321	0.007	0.386	0.001
E7	-0.494	0.000	-0.518	0.000

Since the correlation coefficients are not close to “1” or “-1”, we do not conclude that there is a strong correlation between these two variables. Yet, it is important to note the contrasting correlation patterns for G7 and E7 countries. Since p values for each case is less than 0.05, we can conclude that these correlation coefficients are statistically significant within the %95 confidence interval. In Table 5, G7 countries show a consistent positive correlation between the two variables, whereas E7 countries display a consistent negative correlation-a noteworthy observation.

A positive correlation implies a direct relationship between the variables: as one increases, the other does as well. Conversely, a negative correlation indicates that as one variable increases, the other decreases. For G7 countries, the positive correlation between innovation efficiency and sustainability indices highlights that innovation efficiency positively impacts sustainability performance. In other words, increased innovation efficiency in these countries contributes to advancing sustainability goals.

In contrast, the negative correlation seen for E7 countries suggests that innovation efficiency growth may lead to reduce sustainability outcomes. The increase in innovation in these economies could potentially hinder progress toward sustainability objectives. The underlying reasons for this situation may be depend on each country's economic, social, and political situation. For instance, innovation in advanced economies often aligns with environmentally-focused and sustainable solutions, whereas in developing economies, innovation processes may have more significant environmental consequences. Another influencing factor could be the carbon quota or carbon taxation policies applied in advanced economies, which might encourage innovation efforts toward more sustainable avenues.

Omri (2020) states that the relationship between innovation activities and sustainability differs across countries with high, middle, and low-income levels. Similarly, Kumar and Managi (2010) presents that innovation activities reduced environmental degradation in developed countries but increased it in others. When compared to these studies, the different correlation patterns of G7 and E7 groups revealed in this paper carry significant implications. Similar to Omri (2020) and Kumar and Managi (2010), it can be inferred that innovation contributes positively to sustainability in developed countries but has a negative impact in developing ones.

Based on the findings, the following conclusions and policy suggestions can be drawn:

1. Innovation and Sustainability (G7): The positive relationship between innovation efficiency and sustainability index in G7 countries underscores the need for these countries to further align innovation with sustainability. Since the correlation is relatively low, policymakers can work on developing policies and incentives to make their innovations more environmentally and socially sustainable.
2. Innovation and Sustainability (E7): The negative relationship between innovation efficiency and sustainability index in E7 countries highlights the incongruity between innovation and sustainability in these nations. They can consider policy measures to orient their innovation processes more towards sustainability. Given that economic objectives are given higher priority in these nations, innovation efforts primarily aim to address economic concerns.
3. International Collaboration: International cooperation is crucial in supporting innovation and sustainability efforts. Developing mechanisms for experience sharing and collaboration between G7 and E7 countries can promote the exchange of best practices and foster sustainable innovation.
4. Improving Innovation Quality: The findings reveal fluctuations in innovation efficiency in some countries over the years. These nations should review their policies to stabilize and enhance the quality of their innovations. This can lead to more effective innovation processes and outcomes.

5. CONCLUSION

In summary, this study investigates the relationship between innovation efficiency and sustainability indices of G7 and E7 countries over the period 2013-2022. Findings obtained through the application of DEA and a range of statistical tests reveal significant trends and differences within these two groups, representing developed and emerging economies.

The findings indicate that G7 countries outperform E7 countries in terms of both innovation index and sustainability index. Innovation efficiency results suggest that G7 countries tend to maintain high and relatively stable innovation efficiency scores over the years, indicating their strong innovation capabilities and resource utilization. In contrast, the E7 countries, as a group, show more significant variations in innovation efficiency, reflecting the challenges and diversity in innovation practices among emerging economies. It's important to note that individual country-specific factors, such as government policies, infrastructure, education, and industry composition, can contribute to these variations within each group. Although these disparities, it has concluded that there is not statistically significant difference between the innovation efficiencies of two groups based on t-test. Correlation tests between innovation efficiency and sustainability index, on the other hand, produce more interesting results. The positive correlation suggests that in developed economies, increased innovation efficiency tends to align with higher sustainability achievements. On the other hand, E7 countries exhibit a negative correlation between innovation efficiency and sustainability, indicating that their innovation process might not be fully aligned with their sustainability objectives.

The difference pattern of correlation between G7 and E7 countries can be due to a variety of factors, including economic development levels, technological capabilities, regulatory frameworks, and resource availability. While G7 countries leverage their technological advancements to enhance both innovation and sustainability, E7 countries might face challenges in achieving this due to their economic development priorities and resource limitations. Besides, carbon pricing and quota policies applied in developed economies might also pressure the innovation process in these countries to focus on more sustainable solutions. Shifting innovation activities from economic priorities to the field of sustainability, improving international collaboration and reducing fluctuations in innovation efficiency for some countries will be effective in achieving sustainability goals.

This study has some potential limitations. The specified time frame might not consider the impact of recent events or changing economic conditions. Some regional conflicts and pandemic might have affected some countries more than others. Also, the classification of countries into G7 and E7 groups might oversimplify their diversity, and the findings may not be universally applicable. Yet, this could still be a good beginning point for further research as these groups are accepted by a wide range.

In light of the outcomes of this research, several future research directions emerge. First, a detailed exploration of differing correlations in G7 and E7 countries could provide valuable insights into the factors shaping innovation and sustainability linkages. Additionally, investigating the role of policy interventions and regulatory frameworks in influencing the relationship between innovation and sustainability across different country groups would be insightful. In particular, examining the impact of carbon policies will be very useful in terms of evaluating the consequences of adopting these policies in developing economies. This could offer valuable insights for policy-makers and stakeholders seeking to enhance their national innovation systems while advancing sustainability goals.

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Compliance with Ethical Standards
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It was declared by the author that scientific and ethical principles have been followed in this study and all the sources used have been properly cited.

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