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Innovation Performance Analysis of G20 Countries: A Novel Integrated LOPCOW-MAIRCA MCDM Approach Including the COVID-19 Period

Tayfun Öztaş[1], Gülin Zeynep Öztaş[1]

ABSTRACT
Purpose: This study aims to examine the innovation performance of G20 countries in 2018-2022 with multi criteria decision making methods. When the 5-year performance was analyzed, it was also revealed whether the COVID-19 outbreak has an impact on the innovation performance of the countries.
Methodology: An integrated LOPCOW (Logarithmic Percentage Change-driven Objective Weighting) - MAIRCA (Multi Attribute Ideal-Real Comparative Analysis) method was applied in the study. First, the indicators representing innovation performance (institutions, human capital, and research, infrastructure, market sophistication, business sophistication, knowledge and technology outputs, creative outputs) was objectively weighted by the LOPCOW method. Then, the innovation performance of G20 countries was calculated with the MAIRCA method. Finally, a comparative analysis was also presented to support the findings.
Findings: As a result of the innovation performance analysis using multi criteria decision making methods, human capital, and research were found to be the most important indicators, and the United States was found to be the country with the best innovation performance. In the sensitivity and comparative analysis, it was concluded that the integrated LOPCOW-MAIRCA method provides robust outputs.
Originality: This study makes original contributions by analyzing the impact of the COVID-19 pandemic on the innovation performance of countries considering the 2018-2022 period and the integrated multi criteria decision making methods it uses that have not yet been applied in the literature.
Keywords*:* Innovation Productivity, Performance Analysis, MCDM, LOPCOW, MAIRCA.
JEL Codes: O31, H11, C44.

G20 Ülkelerinin İnovasyon Performans Analizi: COVID-19 Dönemini İçeren Yeni Bütünleşik LOPCOW-MAIRCA ÇKKV Yaklaşımı

ÖZET
Amaç: Bu çalışmada G20 ülkelerinin 2018-2022 yılları içerisindeki inovasyon performanslarının çok kriterli karar verme yöntemleri ile ele alınması amaçlanmaktadır. Ayrıca ülkelerin 5 yıllık performansları incelenerek COVID-19 salgınının inovasyon performanslarına bir etkisinin olup olmadığı da irdelenmektedir.
Yöntem: Çalışmada bütünleşik bir LOPCOW (LOgarithmic Percentage Change-driven Objective Weighting) - MAIRCA (Multi Attribute Ideal-Real Comparative Analysis) yöntemi uygulanmıştır. İlk olarak inovasyon performansını temsil eden göstergeler (kurumlar, beşerî sermaye ve araştırma, altyapı, pazar gelişmişliği, iş gelişmişliği, bilgi ve teknoloji çıktıları, yaratıcı çıktılar) LOPCOW yöntemi ile objektif olarak ağırlıklandırılmıştır. Daha sonra G20 ülkelerinin inovasyon performansları MAIRCA yöntemi ile hesaplanmıştır. Son olarak, elde edilen bulguları desteklemek için karşılaştırmalı bir analiz de sunulmuştur.
Bulgular: Çok kriterli karar verme yöntemleriyle ele alınan inovasyon performans analizi sonucunda, beşerî sermaye ve araştırma en önemli gösterge, Birleşik Devletler de en iyi inovasyon performansına sahip ülke olarak elde edilmiştir. Duyarlılık ve karşılaştırmalı analiz sonucunda ise, bütünleşik LOPCOW-MAIRCA yönteminin güçlü ve güvenilir çıktılar sunduğu sonucuna varılmıştır.
Özgünlük: Bu çalışma 2018-2022 dönemini göz önünde bulundurarak COVID-19 salgınının ülkelerin inovasyon performansı üzerindeki etkisini incelemesi ve kullandığı bütünleşik çok kriterli karar verme yöntemlerinin literatürde henüz uygulanmamış olması nedenleriyle özgün katkılar sunmaktadır.
Anahtar Kelimeler*:* İnovasyon Verimliliği, Performans Analizi, ÇKKV, LOPCOW, MAIRCA.
JEL Kodları: O31, H11, C44.

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1. INTRODUCTION

In a competitive world, countries need to be dynamic and sustainable by embracing technological developments. The construction of a competitive economy relies crucially on a nation's ability to foster a high degree of innovative activity. So, one of the decisive factors which determines the potential economic development is innovativeness (Alnafrah, 2021). Innovation is the process of creating new ideas, products, or services for adding value or solving problems within an organization. The concept of innovation plays a vital role in the evolution of industries and economic growth. It is widely acknowledged that innovation acts as a driving force behind productivity and competitiveness for organizations, regions, and nations (Murat, 2020). As globalization and technological advancements continue to accelerate, innovation has emerged as a fundamental pillar within a country's production factors. Therefore, nations have to be aware of their innovation capabilities (Oturakci, 2023).

Measurement is vital for effective management. Evaluating innovation performance provides valuable insights into the level of national growth and welfare (Murat, 2020). Recognizing the current situation is necessary to determine innovation productivity and make recommendations for improvement. However, how to measure the performance of innovation is an ongoing discussion in the literature (Garcia-Bernabeu et al., 2020). Halkos and Tzeremes (2013) and Garcia-Bernabeu et al. (2020) summarize some challenges and various approaches for measuring innovation. Additionally, the literature presents numerous studies that explore comprehensive approaches to measuring innovation from various perspectives. The debate and challenge in innovation measurement include the identification of measurement indicators, their importance, and their impact on overall performance. Since innovation performance is a multi-dimensional structure, the assessment of innovation must be addressed inclusively. Evaluating and selecting the best option from a set of alternatives based on multiple criteria is known as a multi-criteria decision-making procedure. Therefore, it is clear that Multi Criteria Decision Making (MCDM) approaches can be one of the methodologies that can contribute to innovation measurement.

In this study, we aim to provide a robust framework for measuring the innovation performance of G20 countries from MCDM perspective for the period of 2018-2022. The study presents the integrated LOPCOW (LOgarithmic Percentage Change-driven Objective Weighting) - MAIRCA (Multi Attribute Ideal-Real Comparative Analysis) method. First, the indicators measuring innovation performance are objectively weighted with the LOPCOW method. Then, G20 countries are ranked in terms of their innovation performance using the MAIRCA method. Furthermore, sensitivity and a comparative analysis are conducted to assert that the proposed methodology is robust and valid. Although various studies have focused on countries' innovation performance, there is still a gap in the literature that our study will address. Particularly, our study will examine the period covering the COVID-19 pandemic, which has been the most catastrophic event in recent years in terms of both health and the economy. The impact of COVID-19 on countries' innovation performance has not been adequately examined in the existing literature. As stated by Jewell (2021), the investments in innovation reached record levels in 2019 prior to COVID-19 and it was expected that the innovation investments would likely suffer because of the pandemic. Nevertheless, throughout 2020, essential indicators of innovation investment continued to increase. This study examines the research question of how the 5-year innovation performance of G20 countries varies. Additionally, the research question revolves around the effects of COVID-19 on the innovation performance of countries as well. Our study will contribute to the literature by identifying the strengths, and weaknesses of countries and revealing dimensions committed to innovation-driven growth by considering the COVID-19 pandemic. Furthermore, the methodology (LOPCOW-MAIRCA) applied in our study has never been used in literature. The reason to prefer these methods is that the LOPCOW method is relatively novel and has not been integrated with the MAIRCA method yet. Also, since they are objective MCDM methods and they have notable features, an integrated LOPCOW-MAIRCA method is presented for the problem of innovation performance. Due to the novelty and uniqueness of the proposed methodology, a comprehensive two-step analysis was conducted to evaluate the reliability and validity of its generated results. In the first step, the influence of criteria weights, which directly affect the outcomes of MCDM methods, was assessed. Subsequently, in the second step, a comparison was drawn between the results yielded by the proposed methodology and those generated by other established MCDM methods in the existing literature. This process served to demonstrate the robustness of the proposed methodology in producing dependable and credible outcomes.

To address the research question, data including innovation indicators of countries is essential. Therefore, the reports published under the leadership of WIPO have been utilized to perform an objective analysis. Although each report includes 132 economies, our study will focus on the innovation performance of G20 countries. Since the member nations of the G20, representing around two-thirds of the world's population, account for approximately 85% of the global GDP and over 75% of the global trade (G20, 2023), we preferred to investigate G20 countries' performance in terms of innovation. Furthermore, as stated in the report (G20, 2023), the Digital Economy Working Group was established in 2021 to reveal the digital potential of economies. This indicates that the analysis of innovation performance will provide valuable insights for policymakers to contribute to economic growth.

The aims and motivation of the study can be highlighted as follows:

- A novel integrated MCDM approach has been proposed for the innovation performance analysis of G20 countries.
- The proposed approach combines the LOPCOW and MAIRCA methods, which, to the best of our knowledge, have never been applied together before.
- The approach has been employed over 5 years, including the COVID-19 pandemic, to comprehensively investigate the performance of countries.
- The LOPCOW method has been utilized for weighting innovation performance indicators in an objective manner.
- The MAIRCA method has been used to rank countries for each year.
- The novel integrated methodology has been tested for robustness and validation through sensitivity and comparative analysis.

In the following sections of the study, the literature review, methodology, and findings sections will be presented respectively. Finally, the findings will be discussed in the conclusion section.

2. LITERATURE REVIEW

The literature review section is organized under 3 sub-headings by considering the topic and the methodology of this study. In the first part, the studies focused on innovation productivity were handled. In the second and third parts, the studies that applied the same methodologies were summarized.

2.1. Literature of Innovation Performance

The literature was reviewed by considering the “innovation productivity”, “innovation performance”, “multi-criteria decision-making”, “data envelopment analysis” keywords in Scopus database. Care was taken to ensure that the publications are up-to-date and high quality. It should be noted that the studies analyzed are not only conceptual studies, but also methodological ones. The summarized literature is given in Table 1 in the following.

According to Table 1, it is seen that there are studies that address innovation performance from different perspectives. For instance, city performance (Broekel et al. (2018), Deng et al. (2019), Chen et al. (2020), Garcia-Bernabeu et al. (2020)), country performance (Roszko-Wójtowicz and Białek (2016), Kaynak et al. (2017), Namazi and Mohammadi (2018), Alnafrah (2021), Aytekin et al. (2022), Robertson et al. (2023)) are topics which attract attention more. In addition, China, and Europe stand out as the most preferred locations in the studies focused on innovation performance in the literature. When the years covered in the studies are analyzed, it is seen that studies examining a specific time interval were last conducted in 2020. Moreover, innovation performance was analyzed by various methodologies. Data Envelopment Analysis (DEA), Multi-Criteria Decision-Making (MCDM), and statistical analysis such as Canonical correlation, PLS, SEM, Clustering, and Factor analysis were applied. Especially, DEA is the most preferred methodology in the literature on innovation performance. For a detailed review, one can see Narayanan et al. (2022). Moreover, it is obvious that recently published MCDM methods are very limited in the field of innovation.

It should be noted that there are still gaps in the literature in terms of both the scope (countries, timespan) and the methodology. One of the most striking gaps is that there is no study handling the COVID-19 effect on countries’ innovation performance. The other gap is that MCDM methods are very limited in the field of innovation performance. There are various novel objective MCDM methods that have not been applied yet. Therefore, we hope that our study contributes to the related literature in terms of both the scope and the methodology.

Table 1. Innovation performance studies

Author(s)	*Topic*	*Method*	*Timespan*
Robertson et al. (2023)	Analyzing the effect of knowledge-based dynamic capabilities of 129 countries	PLS-SEM	2019
Oturakci (2023)	Examination of the relationship between innovation factors	Canonical correlation	2013-2020
Erdin and Çağlar (2023)	Evaluation of 36 OECD countries' innovation efficiency	DEA	2019
Xu et al. (2023)	Measuring sustainable innovation performance of 27 EU countries	Slack-based DEA	2000-2017
Huang (2023)	Evaluation of Chinese manufacturing firms' innovation performance	Feasible Generalized Least Squares	2005-2007
Ecer and Aycin (2023)	Evaluation of G7 Countries' innovation performance	MEREC	2020
Aytekin et al. (2022)	Measuring of innovation efficiency for EU member and candidate countries	DEA-EATWIOS	2020
Ali et al. (2021)	Investigation of the impact on innovation performance for 24 Iraqi banks	CFA-SEM	2020
Yu et al. (2021)	Evaluation of high-tech companies' innovation performance in China	Dynamic Network DEA	2014-2017
Alnafrah (2021)	Assessment of national innovation systems for BRICS	Bias-corrected Network DEA	-
Chen et al. (2020)	Evaluation of city innovation capability in China, Liaoning	TOPSIS-ORM	2012-2016
Garcia-Bernabeu et al. (2020)	Analyzing regional innovation performance in Spain	MRP-WSCI	2019
Yin et al. (2020)	Measuring innovation performances in terms of green technology in China	Inter-indicator correlation & EFA & TOPSIS	-
Deng et al. (2019)	Investigation of innovation performance of Chinese Provinces	Super-efficiency DEA	2001-2016
Namazi and Mohammadi (2018)	Evaluation of innovation efficiency of 141 countries	TOPSIS/DEA	2015
Hájek et al. (2018)	Evaluation of innovation performance of European companies	Fuzzy TOPSIS & BSC	2010-2012
Broekel et al. (2018)	Evaluation of innovation efficiency of German regions	Shared-input DEA	1999-2008
Kaynak et al. (2017)	Evaluation of innovation performance of EU Candidate countries	Entropy-based TOPSIS	2012
Roszko-Wójtowicz and Białek (2016)	Measuring innovation performance of EU countries	Cluster & Factor analysis	2015
Lu et al. (2013)	Investigation of the effects of environmental strategic orientation on innovation performance	Fuzzy DEMATEL & Fuzzy DANP & VIKOR	-
Chang and Tzeng (2010)	Measuring innovation performances of high-tech industries	DEMATEL	-

2.2. Literature of the LOPCOW method

Due to LOPCOW being considered as one of the state-of-the-art MCDM methods, the number of studies in literature is limited. Table 2 presents the studies that applied the LOPCOW method.

Table 2. LOPCOW method studies

Author(s)	*Topic*	*Method*
Kahreman (2023)	Economic performance analysis in economic crisis period for G20 countries	LOPCOW, CoCoSo
Keleş (2023)	Evaluation of livable power center cities in G7 countries and Türkiye	LOPCOW, CRADIS
Ersoy (2023)	Performance analysis of Borsa İstanbul retail and trade sector	LOPCOW, RSMVC
Nila and Roy (2023)	Third-party logistics provider selection	Fuzzy LOPCOW, fuzzy FUCOM, fuzzy DOBI
Simic et al. (2023)	Material handling technology prioritizing for smart and sustainable warehouses	Neutrosophic LOPCOW, ARAS
Ecer et al. (2023a)	Sustainability performance analysis in urban transportation	IVFNN Delphi, LOPCOW, CoCoSo
Ulutaş et al. (2023)	Building insulation materials selection	PSI, MEREC, LOPCOW, MCRAT
Demir et al. (2023)	Open government performance analysis	LMAW, LOPCOW, WASPAS
Ecer et al. (2023b)	Unmanned aerial vehicle performance assessment	q-rung fuzzy LOPCOW, VIKOR
Biswas et al. (2022)	Dividend pay capability comparison of firms	LOPCOW, EDAS, Borda Count, Copeland, SAW, MABAC, COPRAS
Niu et al. (2022)	Site selection	Fermatean Cubic LOPCOW, EDAS
Ecer and Pamucar (2022)	Sustainability performance analysis	LOPCOW, DOBI

The findings of the related literature can be summarized as follows: Sustainability has gained significant attention in various domains including urban transportation, particularly in terms of micro-mobility, the banking sector in developing countries, and industry 4.0-based material technology, with a specific focus on warehouse management systems (Ecer et al., 2023a; Ecer and Pamucar, 2022; Simic et al., 2023). Performance analysis, as explored by Kahreman (2023), Ersoy (2023), Demir et al. (2023) and Ecer et al. (2023b) represents another prominent application of the LOPCOW method. These studies investigate measuring economic performance in 2018 economic crisis for G20 countries, analyzing performance of Borsa İstanbul retail and trade sector firms, the utilization of open government data in G20 countries for performance analysis, and assess the precision of unmanned aerial vehicles in the Agri-Food 4.0 perspective respectively. Selection problems addressing third-party logistics provider selection under sustainability perspectives for a cake manufacturer (Nila and Roy, 2023), material selection for determining the most suitable natural fiber for buildings (Ulutaş et al., 2023) and site selection for the construction of intercity railways (Niu et al., 2022) are noteworthy real-world challenges that benefit from the LOPCOW method. The LOPCOW method is also applied in the field of financial analysis, as highlighted by (Biswas et al., 2022). Urbanism is another important research area in literature, and it may also appear for several purposes such as evaluation of livable power center cities (Keleş, 2023). These findings collectively demonstrate the attention that the LOPCOW method has garnered among scholars in their quest to address current challenges. Additionally, the LOPCOW method can be effectively integrated with other MCDM methods and offers various extensions, including neutrosophic or fuzzy approaches, etc.

2.3. Literature of the MAIRCA method

In the third subsection, the literature is reviewed in terms of MAIRCA studies. Table 3 presents the studies that applied the MAIRCA method in various fields.

When Table 3 was thoroughly investigated it became apparent that the MAIRCA method has gained popularity among scholars since 2016. The findings of related literature of the MAIRCA can be grouped as follows: Technology selection has attracted attention in studies including blockchain technology selection in the logistics industry (Görçün et al., 2023), filtration technology selection for contamination control (Fetanat and Tayebi, 2023), recommender system selection for consumer decision support systems (Bączkiewicz et al., 2021), energy storage technology selection for sustainable energy systems (Pamucar et al., 2020). As environmental concerns increase due to the climate crisis, sustainability has become another prominent research topic. Assessment of sustainability factors in biofuel industry (Hezam et al., 2023), sustainable material selection for human-powered aircraft (Ul Haq et al., 2023) and sustainable energy storage system selection in India (Narayanamoorthy et al., 2023) have been notable applications recently. The MAIRCA method has been also implemented in financial studies such as critical success factor analysis of blockchain technology for agri-food supply chain management (Yontar, 2023), macroeconomic performance analysis of various countries (Bektaş and Baykuş, 2023), selecting the most proper cryptocurrencies from the investment perspective (Ecer et al. 2022), and measuring the effect of the COVID-19 pandemic on the performance of participation banking sector (Işık, 2022). Vaccine selection for the COVID-19 pandemic (Ecer, 2022), and determining the most suitable waste treatment technology (Adar and Delice, 2019) are some of the applications in the healthcare industry. Decision makers confront some real-world problems due to the new technologies. Performance evaluation of electric vehicle batteries (Ecer, 2021) and performance analysis of suppliers in the electronics sector (Chatterjee et al., 2018) are representative studies that emerge in performance analysis. Location selection and supplier selection are another important research area in literature, and it may also appear for several purposes such as location selection for wind farms (Pamučar et al., 2017), location selection for military purposes (Gigović et al., 2016) or supplier selection for dairy products (Şahin Macit, 2023). To sum it all up, it is clear that the MAIRCA method has a vast application area. The method has been integrated with various methods such as ANP, BWM, etc. It also has various extensions that use fuzzy or neutrosophic numbers.

Table 3. MAIRCA method studies

Author(s)	*Topic*	*Method*
Görçün et al. (2023)	Blockchain technology selection	Fermatian fuzzy FUCOM, Fermatian fuzzy MAIRCA
Hezam et al. (2023)	Evaluation of sustainability factors in biofuel industry	Intuitionistic fuzzy symmetry point of Criterion, Rank-Sum-Based MAIRCA
Şahin Macit (2023)	Supplier selection	AHP, MAIRCA
Bektaş and Baykuş (2023)	Macroeconomic performance analysis of selected countries	CRITIC, MAIRCA
Ul Haq et al. (2023)	Sustainable material selection	Interval-valued neutrosophic MAIRCA
Yontar (2023)	Blockchain technology	ANP, MAIRCA
Narayanamoorthy et al. (2023)	Sustainable energy storage technology selection	LDHF SOWIA, MAIRCA
Fetanat and Tayebi (2023)	Industrial filtration technology selection	q-rung orthopair fuzzy set-based MAIRCA
Işık (2022)	Analyzing effect of the COVID-19 on the performance of participation banking sector	MEREC, PSI, MAIRCA
Ecer et al. (2022)	Analyzing investment decisions in cryptocurrencies	EDAS, MAIRCA, MARCOS
Ecer (2022)	Vaccine selection	Intuitionistic fuzzy MAIRCA
Bączkiewicz et al. (2021)	E-Commerce recommender selection	TOPSIS, COMET, COCOSO, EDAS, MAIRCA, MABAC
Ecer (2021)	Performance evaluation of electric vehicle batteries	SECA, MARCOS, MAIRCA, COCOSO, ARAS, COPRAS
Pamucar et al. (2020)	Prioritization of the energy storage technologies	Dombi weighted geometric averaging operator, MAIRCA
Adar and Delice (2019)	Healthcare waste treatment technology selection	MABAC, MAIRCA, TOPSIS, VIKOR
Chatterjee et al. (2018)	Performance analysis of suppliers	R’AMATEL, MAIRCA
Pamučar et al. (2017)	Location selection for wind farms	GIS, BWM, MAIRCA
Gigović et al. (2016)	Location selection for ammunition depots	GIS, DEMATAL, ANP, MAIRCA

Overall, the comprehensive review points out that there is a gap in the literature both in terms of application area and methodology. We hope that our study will contribute to the innovation analysis based on MCDM literature.

3. METHODOLOGY

In this study, a novel hybrid methodology has been employed to compare the innovation performance of G20 countries utilizing the MCDM approach. The methodology consists of two stages. In the first stage, criteria weights are determined with the LOPCOW method, a state-of-the-art objective criterion weighting method. This method provides a robust framework for assigning weights to the criteria based on their relative importance. Then the innovation performance scores of G20 countries are measured with the MAIRCA method. This section provides the details of MCDM methods that form the basis of the methodology in this study. The MAIRCA method is a widely recognized MCDM method that allows for a comprehensive evaluation of multiple criteria and alternatives. It provides a systematic approach to assess the innovation performance of countries based on various factors such as human capital and research, infrastructure, etc. In this section, detailed explanations of the MCDM methods that form the foundation of the methodology used in this study will be provided. These methods have been preferred based on their effectiveness in handling complex decision-making problems and their relevance to the research objective of comparing innovation performance among G20 countries.

3.1. LOPCOW method

Criteria weighting is a crucial aspect in the process of solving problems using MCDM methods. The method chosen to assign values to the criteria directly impacts the ranking of the methodology. Thus, researchers have extensively investigated this issue, as demonstrated by studies conducted by Ayan et al. (2023), Durmuş and Tayyar (2017), Keskin and Kılıç Delice (2022), and Mahmoodi et al. (2023). Hence, there are scores of weighting methods that can be grouped as objective methods and subjective methods.

In this study, the LOPCOW method has been employed to objectively assign weights to the criteria that have been proposed by Ecer and Pamucar (2022) recently. The LOPCOW method offers significant advantages, such as the ability to handle negative values in the initial decision matrix (Ecer et al., 2023a). Since negativity often arises in real-world problems, the methodology must address this issue to provide effective solutions. Additionally, the method mitigates the impact of unusual values in the dataset by employing the logarithmic operator (Ecer, et al., 2023b). It also considers whether a criterion is beneficial or cost-based and removes differences in the data set by including the percentage of the mean square of measurements to their standard deviations (Ecer and Pamucar, 2022). Furthermore, the LOPCOW method demonstrates its efficacy even when dealing with large datasets (Biswas et al., 2022). The following steps are involved in determining criteria weights using the LOPCOW method (Ecer and Pamucar, 2022):

Step 1. An initial decision matrix (X) is generated (Equation 1). This matrix consists of m alternatives and n criteria.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \tag{1}$$

Step 2. A normalized matrix (N) is required to remove measurement differences among criteria. Consequently, the elements of X are transformed to non-dimensional values within $[0, 1]$ interval. This process is implemented whether the criterion is considered as beneficial, or cost-based. The element n_{ij} ($n_{ij} \epsilon N$) is calculated using Equation 2 or Equation 3.

$$n_{ij} = \frac{x_{ij} - x_{min}}{x_{max} - x_{min}} \quad \text{(For benefit type criteria)} \tag{2}$$

$$n_{ij} = \frac{x_{max} - x_{ij}}{x_{max} - x_{min}} \quad \text{(For cost type criteria)} \tag{3}$$

Step 3. The percentage value (PV) is calculated for each criterion. To compute PV, elements of normalized matrix N (n_{ij}), the standard deviation of the criterion (σ), and the number of alternatives (m) are required. The PV values are calculated using Equation 4.

$$PV_{ij} = \left| \ln \left(\frac{\sqrt{\frac{\sum_{i=1}^{m} n_{ij}^2}{m}}}{\sigma} \right) \times 100 \right| \tag{4}$$

Step 4. The of each criterion is calculated using the PV values. The criteria weights (w_j) are obtained using Equation 5.

$$w_j = \frac{PV_{ij}}{\sum_{i=1}^{n} PV_{ij}} \tag{5}$$

3.2. MAIRCA method

The MAIRCA method was proposed by Pamučar et al. (2014). The method originates from the idea of measurement of gaps ideal between observational ratings (Yontar, 2023). In the method, a total gap is calculated for each alternative under evaluated criteria, and the alternative that has a minimal total gap is considered as the best one among its competitors (Ul Haq et al., 2023). As Gul and Ak (2020) stated the MAIRCA method resembles the TOPSIS method with its core idea. The method obtains rankings by applying the following steps (Gigović et al., 2016):

Step 1. The initial decision matrix (X) is generated as in the LOPCOW method.

Step 2. The alternative selection probability is determined. In fact, it is assumed that the decision-maker gives equal probability to select the alternatives. Thus, preference whatsoever alternative among all the alternatives is as follows (Equation 6):

$$P_{A_i} = \frac{1}{m} \tag{6}$$

Here, m is the number of alternatives and $\sum_{i=1}^{m} P_{A_i}$ equals to 1. This issue means the decision maker is neutral and the preference probability of each alternative is equal (Equation 7).

$$P_{A_1} = P_{A_2} = \cdots = P_{A_m} \tag{7}$$

Step 3. The theoretical (ideal) evaluation matrix T_p is generated (Equation 8). Elements of T_p is obtained with a multiplication of P_{A_i} and criteria weights w_j $(j = 1,2, \dots, n)$. As stated in Step 2 all P_{A_i} values are equal, T_p can written as in Equation 9.

$$T_p = \begin{bmatrix} t_{p11} & \cdots & t_{p1n} \\ \vdots & \ddots & \vdots \\ t_{pm1} & \cdots & t_{pmn} \end{bmatrix} = \begin{bmatrix} P_{A_1}w_1 & P_{A_1}w_2 & \cdots & P_{A_1}w_n \\ P_{A_2}w_1 & P_{A_2}w_2 & \dots & P_{A_2}w_n \\ \vdots & \vdots & \vdots & \vdots \\ P_{A_m}w_1 & P_{A_m}w_2 & \cdots & P_{A_m}w_n \end{bmatrix} \tag{8}$$

$$T_p = [P_{A_i}w_1 \quad \dots \quad P_{A_i}w_n] \tag{9}$$

Step 4. Real evaluation (observational) matrix T_r is generated (Equation 10).

$$T_r = \begin{bmatrix} t_{r11} & \cdots & t_{r1n} \\ \vdots & \ddots & \vdots \\ t_{rm1} & \cdots & t_{rmn} \end{bmatrix} \tag{10}$$

The elements of T_r (t_{rij}) is calculated considering the criterion as beneficial, or cost-based. The elements are obtained by multiplying the elements of T_p and initial decision matrix X. The element t_{rij} $(t_{rij} \epsilon T_r)$ is calculated using Equation 11 or Equation 12.

$$t_{rij} = t_{pij}\left(\frac{x_{ij}-x_i^-}{x_i^+-x_i^-}\right) \quad \text{(For benefit type criteria)} \tag{11}$$

$$t_{rij} = t_{pij}\left(\frac{x_{ij}-x_i^+}{x_i^- -x_i^+}\right) \quad \text{(For cost type criteria)} \tag{12}$$

Here, x_i^- and x_i^+ are elements of X. x_i^- means the minimum value of relevant criterion and x_i^+ means the maximum value of the relevant criterion.

Step 5. The total gap matrix G is generated (Equation 13). Elements of G (g_{ij}) are obtained with the subtraction of T_p and T_r.

$$G = T_p - T_r = \begin{bmatrix} g_{11} & \cdots & g_{1n} \\ \vdots & \ddots & \vdots \\ g_{m1} & \cdots & g_{mn} \end{bmatrix} = \begin{bmatrix} tp_{11} - tr_{11} & \cdots & tp_{1n} - tr_{1n} \\ \vdots & \ddots & \vdots \\ tp_{m1} - t_{m1} & \cdots & tp_{mn} - tr_{mn} \end{bmatrix} \tag{13}$$

The value of g_{ij} should equal zero or $(tp_{ij} - tr_{ij})$. Due to g_{ij} means gap if the value of g_{ij} equal to zero, it makes alternative i under the criterion j makes ideal. Or, if the value of g_{ij} equal to tp_{ij}, it makes alternative i under the criterion j makes anti-ideal.

Step 6. The criteria function (Q_i) are calculated for alternatives using their gaps. The calculation of each Q_i is given in Equation 14.

$$Q_i = \sum_{j=1}^{n} g_{ij}, i = 1,2, \dots, m \tag{14}$$

Once the criteria functions are obtained, the scores are ranked from smallest to largest. The alternative with the smaller value has a better position in the ranking.

4. NUMERICAL IMPLICATION

This study aims to assess and compare the innovation performance of G20 countries. The analysis covers the period between 2018 and 2022. Considering the COVID-19 pandemic outbreak in 2019, it will be possible to monitor changes in the innovation performance of countries. Thus, the analysis also helps to reveal the significant changes in innovation performance in the long term. The related data was gathered from the Global Innovation Index 2018 (Cornell University et al., 2018), 2019 (Cornell University et al., 2019), 2020 (Cornell University et al., 2020), 2021 (WIPO, 2021), and 2022 (WIPO, 2022) reports. The countries included in the analysis are as follows: Argentina, France, Japan, South Africa, Australia, Germany, Mexico, Türkiye, Brazil, India, South Korea, United Kingdom, Canada, Indonesia, Russia, United States, China, Italy, and Saudi Arabia. It also should be noted that the European Union was excluded from the context of the study though it is a member of G20 due to it is a political and economic union rather than a country.

The explanation of each criterion included in the analysis is as follows (WIPO, 2022):

- Institutions (C_1) pertains to the political, regulatory, and business environments.
- Human capital and research (C_2) involve education, tertiary education, research, and development (R&D).
- Infrastructure (C_3) takes into consideration information and communication technologies (ICTs), general infrastructure, and ecological sustainability.
- Market sophistication (C_4) considers aspects such as credit, investment, trade, diversification, and market scale.
- Business sophistication (C_5) addresses knowledge workers, innovation linkages, and knowledge absorption.
- Knowledge and technology outputs (C_6) focus on knowledge creation, knowledge impact, and knowledge diffusion.
- Creative outputs (C_7) encompass intangible assets, creative goods, and services, and online creativity.

The reason for preferring the LOPCOW and MAIRCA methods should be clarified. Although there is no rule of thumb for selecting the most appropriate MCDM method for any problem, the reason to prefer them would better to be underlined. The objectivity of these methods and the absence of their integration in the literature are the main reasons. Furthermore, the ability to reduce the effect of unusual values in the data set and the fact that it works effectively with large data sets are important factors in choosing the LOPCOW method. Whereas MAIRCA was preferred because of its similarity to TOPSIS which is one of the cornerstones among MCDM methods.

In the calculations, it is assumed that all criteria are of the benefit type, since the higher the values of all these criteria, the better for the relevant alternative. After determining the type of criterion, the innovation performance of countries was analyzed with a four-stage approach. In the first stage criteria weights were calculated using the LOPCOW method. The obtained criteria weights were used in the second stage with the MAIRCA method. In the third stage, a sensitivity analysis was performed to test the robustness of the approach. In the fourth and final stage, a comparative analysis was conducted with MARCOS, TOPSIS, MABAC, and EDAS methods to validate the approach adopted in this study. The mentioned stages applied in this study are illustrated comprehensively in Figure 1. It should be noted that the results of the computational steps could not be included due to the word limit in the paper.

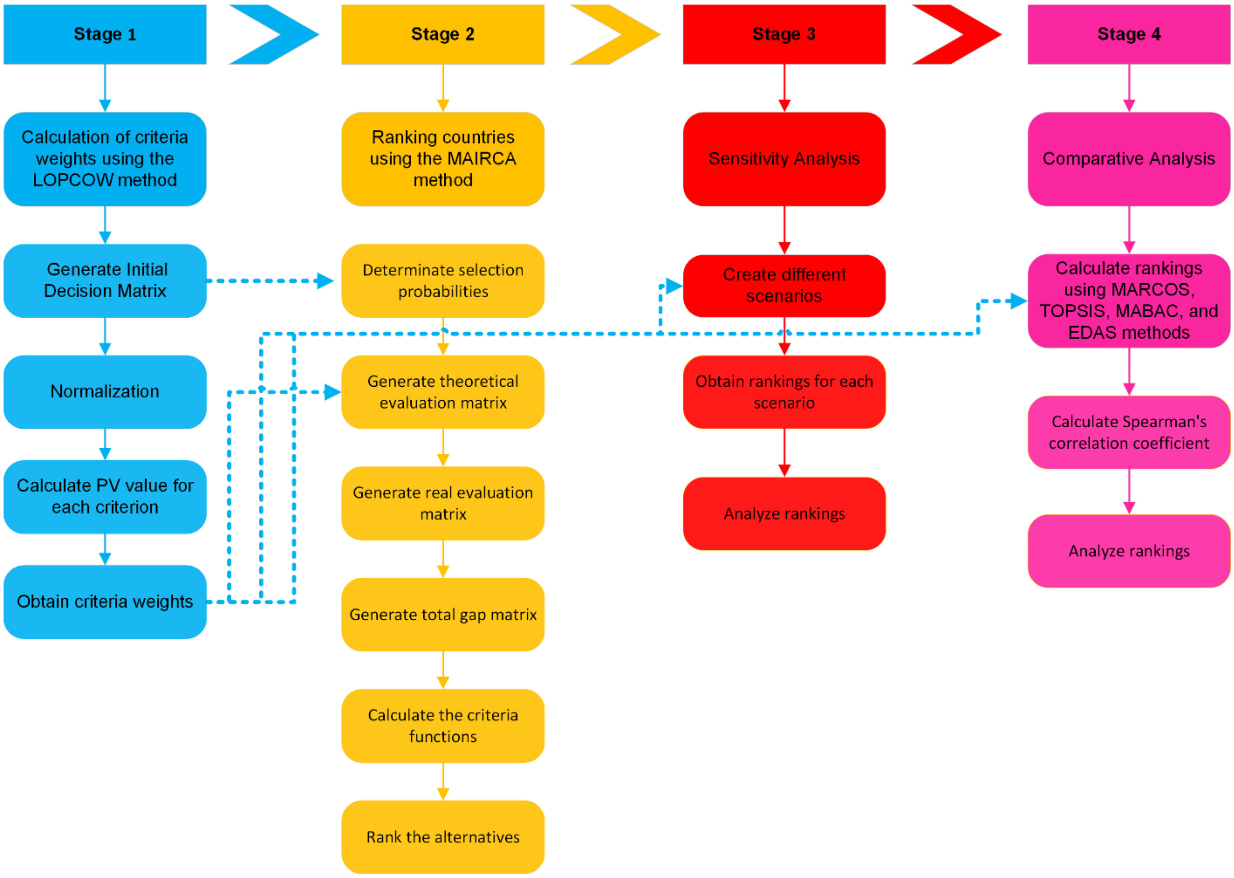

Figure 1. Flow chart of the LOPCOW-MAIRCA method

Stage 1. Determination of criteria weights: The criteria weights were calculated using the LOPCOW method. To determine the criteria weights, Equations (1) to (5) were applied. Since the analysis covers a five-year period between 2018 and 2022, each year has unique data, criteria weights were calculated for each year which makes it possible. This approach allows for monitoring significant changes in criteria weights on a yearly basis. The results of the criteria weight calculations are presented in Table 4.

Table 4. Criteria weights by year

Year	C_1	C_2	C_3	C_4	C_5	C_6	C_7
2018	0.1126	0.1948	0.1456	**0.1620**	0.1487	0.1232	0.1132
2019	0.1266	**0.1919**	0.1512	0.1573	0.1378	0.1172	0.1180
2020	0.1264	**0.1828**	0.1198	0.1791	0.1582	0.1278	0.1059
2021	0.1301	0.1601	**0.1722**	0.1507	0.1192	0.1347	0.1330
2022	0.1176	**0.1807**	0.1340	0.1806	0.1486	0.1155	0.1230
Average	0.1227	**0.1821**	0.1446	0.1659	0.1425	0.1237	0.1186

Table 4 indicates that Human capital and research (C_2) is consistently the most important criterion for the years 2019, 2020, and 2021, and the average. Market sophistication (C_4) takes precedence as the most important criterion for the year 2018. Similarly, Infrastructure (C_3) holds the highest importance for the year 2021. None of the other criteria were determined as the most important in any year. It is noteworthy that Institutions (C_1) had the least significance in 2018, Business sophistication (C_5) in 2021, Knowledge and technology outputs (C_6) in 2019 and 2022, and Creative outputs (C_7) in 2020 and on average. Moreover, Human capital and research (C_2) has gained increasing importance since the onset of the pandemic. For a more detailed visual representation, refer to Figure 2.

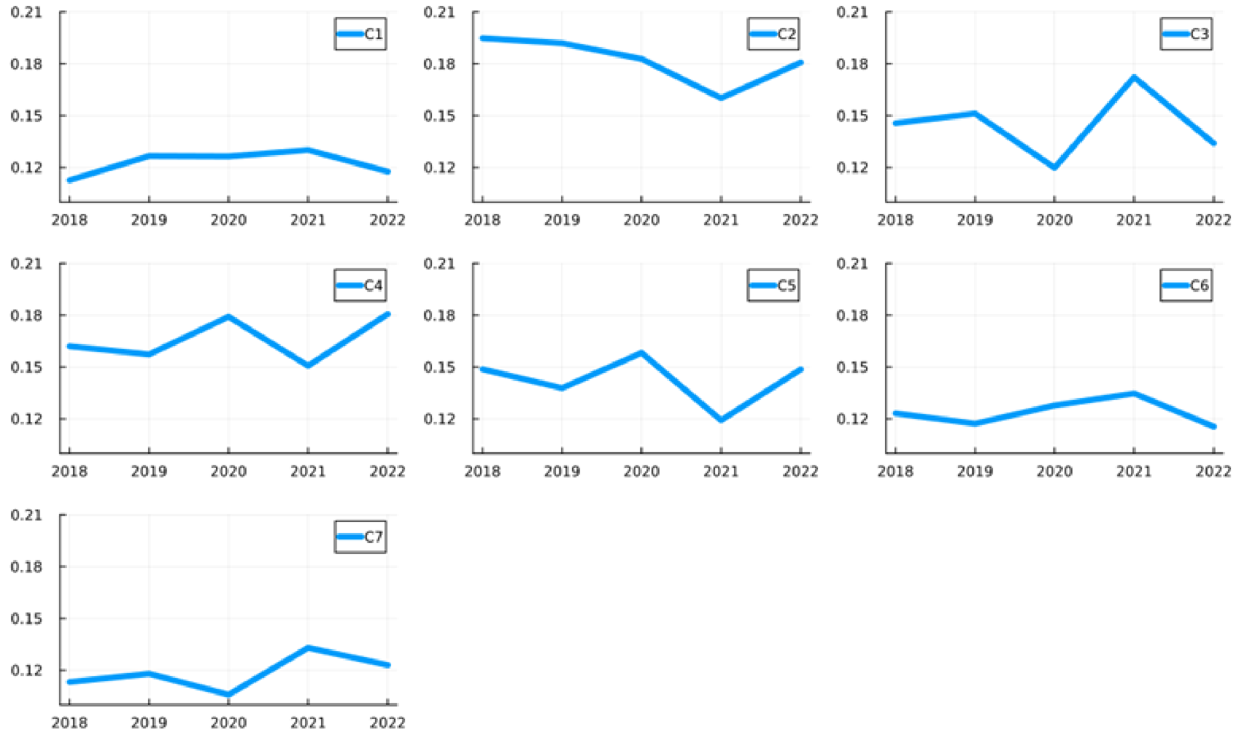

Figure 2. Breakdown of criteria weights changes

The changes in criteria weights can be easily observed with the assistance of Figure 2. The figure presents information about each criterion for each year. The figure allows for the confirmation of trends, as well as the identification of minimum and maximum values. For example, C_1 (Institutions) does not exhibit a distinct trend, but the minimum value of the criterion was recorded in 2018, likewise, the maximum value was observed in 2021. Similar observations can be made from Figure 2 regarding other criteria. As of 2020, Infrastructure (C_3) and Creative outputs (C_7) are seen as criteria with increased importance due to the COVID-19 pandemic. This can be considered as a suggestion to investors and policymakers. It would be appropriate to direct more investments to criteria whose importance level has increased with COVID-19.

Stage 2. Ranking countries using the MAIRCA method: In the second stage, the MAIRCA method was employed to rank the G20 countries. The method utilizes Equations (6)-(14) to determine the rankings. The criteria weights obtained in the first stage were utilized in the calculation of the theoretical evaluation matrix T_p. The criteria function, which assesses the total gap between alternatives and the ranking of countries, is provided in Table 5.

Based on the data presented in Table 5, The United States has consistently held the top position for the past four years. The United Kingdom, which held the first position in 2018, dropped to the second position and has maintained that rank ever since. Germany and South Korea have consistently vied for the third and fourth positions in the ranking, demonstrating a similar level of competitiveness. Moreover, Indonesia has consistently shown the poorest performance among the countries throughout most of the years. An illustrative plot would facilitate a clear understanding of the performance changes among the countries.

Upon analyzing Figure 3, it can be inferred that several countries, such as the United States, United Kingdom, Germany, South Korea, Argentina, and Indonesia, have experienced minimal changes in their performance over time, often gaining or losing just one position in the ranking. Italy has consistently maintained its position in the ranking throughout the entire period. On the other hand, countries like South Africa, Saudi Arabia, Brazil, Russia, Canada, and Japan have exhibited inconsistent performance in the ranking, showing fluctuations over time. Furthermore, it is noteworthy to mention Türkiye's performance. Türkiye's initially held the 13^{th} position in the ranking but has progressively improved its performance over time, attributed to its investments in innovation.

Table 5. Rankings based on the MAIRCA method

	LOPCOW-MAIRCA									
	2018		*2019*		*2020*		*2021*		*2022*	
Country	*Score*	*Ranking*	*Score*	*Ranking*	*Score*	*Ranking*	*Score*	*Ranking*	*Score*	*Ranking*
Argentina	0.0462	18	0.0440	18	0.0459	18	0.0526	**19**	0.0470	18
Australia	0.0139	7	0.0164	8	0.0160	8	0.0139	9	0.0184	9
Brazil	0.0420	16	0.0415	16	0.0405	17	0.0313	14	0.0418	15
Canada	0.0141	8	0.0139	6	0.0125	5	0.0100	6	0.0149	7
China	0.0188	9	0.0181	9	0.0177	9	0.0130	8	0.0150	8
France	0.0134	6	0.0140	7	0.0134	7	0.0105	7	0.0127	5
Germany	0.0110	3	0.0101	3	0.0107	4	0.0087	4	0.0112	4
India	0.0426	17	0.0409	15	0.0382	13	0.0306	13	0.0377	13
Indonesia	0.0501	**19**	0.0487	**19**	0.0494	**19**	0.0385	18	0.0474	**19**
Italy	0.0253	10	0.0253	10	0.0244	10	0.0198	10	0.0260	10
Japan	0.0119	5	0.0133	5	0.0128	6	0.0098	5	0.0134	6
Mexico	0.0409	14	0.0400	13	0.0397	16	0.0316	15	0.0445	16
South Korea	0.0114	4	0.0108	4	0.0093	3	0.0064	3	0.0105	3
Russia	0.0358	11	0.0359	11	0.0355	11	0.0285	12	0.0390	14
Saudi Arabia	0.0388	12	0.0403	14	0.0395	15	0.0322	16	0.0369	12
South Africa	0.0413	15	0.0424	17	0.0393	14	0.0325	17	0.0461	17
Türkiye	0.0397	13	0.0381	12	0.0371	12	0.0270	11	0.0364	11
United Kingdom	0.0063	**1**	0.0064	2	0.0062	2	0.0054	2	0.0076	2
United States	0.0077	2	0.0059	**1**	0.0045	**1**	0.0043	**1**	0.0041	**1**

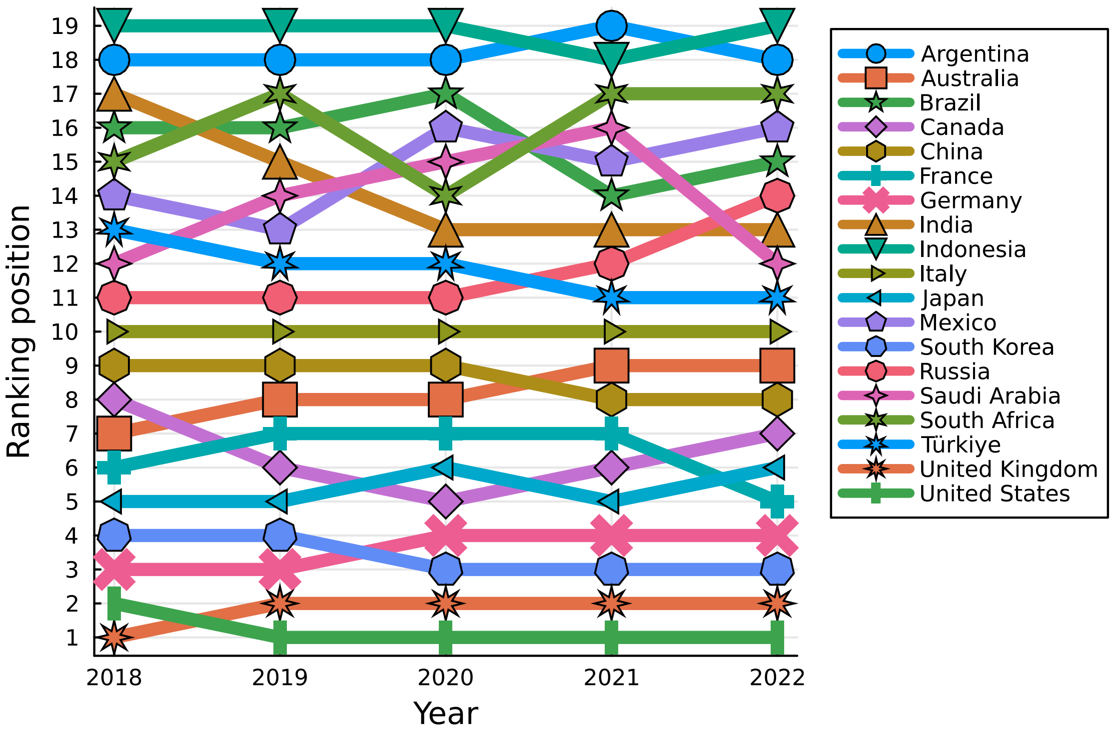

Figure 3. Country ranking changes as a result of the LOPCOW-MAIRCA methodology

When the innovation performance of countries as of COVID-19 is analyzed, we see those 6 countries (United States, United Kingdom, South Korea, Germany, Italy, and India) have maintained their place in the ranking. In addition to these countries, 5 countries (France, China, Türkiye, Saudi Arabia, and Brazil) have improved their performance until 2022. 4 countries (Japan, Mexico, Indonesia, and Argentina) returned to their performance in 2020, albeit with a change in 2021. Canada, Australia, Russia, South Africa, Russia, South Africa are seen as countries with deteriorating innovation performance. Overall, in total, 14 countries either maintained their position, improved, or returned to their previous performance in the following year after the outbreak of the COVID-19 pandemic. These findings are in line with the interpretation of Jewell (2019) mentioned in the introduction. In other words, the expectation that investments in innovation would decrease due to the COVID-19 was not met and investments continued to increase. Therefore, it can be interpreted that through innovation investments the negative effects of COVID-19 were eliminated in the innovation performances of countries.

Stage 3. Sensitivity analysis: The changes in the parameters of MCDM approaches may have an enormous effect on the rankings. Sensitivity analysis helps researchers to detect the robustness of their adopted methodologies. To conduct a sensitivity analysis, some scenarios were generated and tested in this study. Furthermore, the sensitivity analysis specifically focuses on the year 2022, allowing for insights based on the most current period. The generated scenarios and relevant criteria weights are provided in Table 6.

Table 6. Criteria weights by scenarios

Scenario	w_1	w_2	w_3	w_4	w_5	w_6	w_7
Scenario 1	0.1176	0.1807	0.1340	0.1806	0.1486	0.1155	0.1230
Scenario 2	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429
Scenario 3	0.1230	0.1155	0.1486	0.1806	0.1340	0.1807	0.1176
Scenario 4	0.1250	0.2500	0.1250	0.1250	0.1250	0.1250	0.1250
Scenario 5	0.1250	0.1250	0.1250	0.1250	0.1250	0.2500	0.1250

Scenario 1 represents the criteria weights obtained using the LOPCOW method for the year 2022. Scenario 2 involves assigning equal weights to all criteria. Scenario 3 is the reverse of Scenario 1, where the weights are flipped. Scenario 4 assigns a weight of 0.25 to the most important criterion of Scenario 1 and 0.125 to the rest. Similarly, Scenario 5 assigns a weight of 0.25 to the least important criterion of Scenario 1 and 0.125 to the rest. The results of the LOPCOW-MAIRCA approach using these criteria weights in the respective scenarios are visualized in Figure 4.

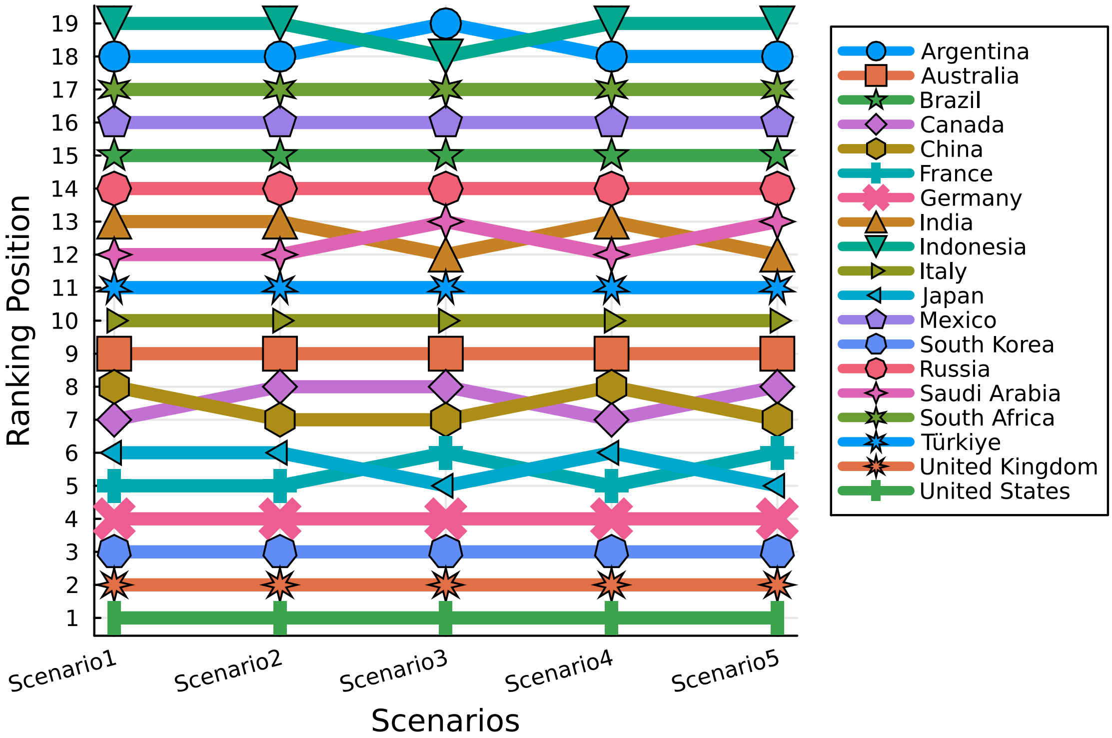

Figure 4. Sensitivity analysis results

After analyzing Figure 4, it can be concluded that the LOPCOW-MAIRCA approach consistently produces robust ranking results. Out of the 19 countries, 11 of them maintained their positions in the ranking across all scenarios. The remaining countries showed minor variations, with only a one-position difference in the overall ranking. These findings indicate that the methodology is not significantly influenced by changes in criteria weights.

Stage 4. Comparative analysis: To investigate the results of an MCDM approach is essential in terms of validating and ensuring the reliability of the rankings. Conducting a comparative analysis is a common practice among researchers to address validation and reliability issues, as this helps prevent potentially misleading results. In this study, the LOPCOW-MAIRCA approach is compared with other prominent methods in the MCDM literature, namely MARCOS, TOPSIS, MABAC, and EDAS methods. Since there is no widely accepted metric in the field of MCDM to measure the relative performance of methods, these types of comparisons between methods are often employed. When choosing the methods for comparison, selecting those with similar principles makes it easier to illustrate how well the results of the proposed methodology align with the outcomes of other methodologies.

The analysis was carried out using the same set of criteria weights for all methods, which were obtained using the LOPCOW method. The comparative analysis focuses on the year 2022 like the sensitivity analysis. The results of all the methods are presented in Table 7.

Based on the data presented in Table 7, it is evident that the United States and the United Kingdom consistently occupy the top two positions across all the methods. Similar rankings can also be observed for other countries such as Australia, Brazil, and South Africa. Notably, the rankings obtained from LOPCOW-MAIRCA, LOPCOW-MARCOS, and LOPCOW-MABAC methods are identical, indicating a high degree of agreement among these approaches. Furthermore, Spearman's rank correlation between LOPCOW-MAIRCA and LOPCOW-TOPSIS is found to be 0.98, while the correlation between LOPCOW-MAIRCA and LOPCOW-EDAS is 0.99. These high correlation values suggest a strong consistency between the rankings produced by the LOPCOW-MAIRCA approach and the other methods. These findings support the assertion made by Ecer (2022) that the LOPCOW-MAIRCA approach yields reliable and valuable results similar to those obtained by other approaches.

Table 7. Results of the comparative analysis

Country	*LOPCOW-MAIRCA*	*LOPCOW -MARCOS*	*LOPCOW -TOPSIS*	*LOPCOW -MABAC*	*LOPCOW -EDAS*
Argentina	18	18	19	18	18
Australia	9	9	9	9	9
Brazil	15	15	15	15	15
Canada	7	8	8	7	8
China	8	7	6	8	6
France	5	5	4	5	5
Germany	4	4	3	4	4
India	13	12	11	13	12
Indonesia	19	19	18	19	19
Italy	10	10	10	10	10
Japan	6	6	7	6	7
Mexico	16	16	16	16	16
South Korea	3	3	5	3	3
Russia	14	14	14	14	14
Saudi Arabia	12	13	13	12	13
South Africa	17	17	17	17	17
Türkiye	11	11	12	11	11
United Kingdom	2	2	2	2	2
United States	**1**	**1**	**1**	**1**	**1**

5. DISCUSSION

This study analyzed the innovation performance of G20 countries in the period covering 2018-2022. According to the findings, in 2018, Infrastructure (C_3) was determined as the most important criterion. In the subsequent years of 2019, 2020, and 2022, Human capital and research (C_2) took precedence, indicating a shift in focus toward education and R&D. Similarly, in 2021, Market sophistication (C_4) emerged as the criterion with the highest importance. When analyzing the changes in the most important criteria over time, it is evident that the emphasis has shifted from infrastructure to education and R&D. These criteria collectively contribute to a country's innovation capabilities, and it is reasonable for their priorities to change over time. As one factor reaches its saturation point, another factor becomes prominent in attracting investments and driving societal transformation. Factors such as new technologies, the impact of the COVID-19 pandemic, and the ongoing process of digital transformation shape the global landscape. The ranking of countries in terms of innovation is not an ultimate and definitive representation. Conversely, the proposed approach should be considered as an alternative method that encompasses the diverse aspects of innovation. However, through the proposed methodology, some outcomes can be provided. In light of the findings obtained in our study, we can say that the continuation of innovation investments despite the COVID-19 pandemic has positive effects on the innovation performance of countries. However, each country will be able to decide which sub-dimension of innovation to invest in with priority using the approach we proposed in this study. Consequently, countries should prioritize education and R&D activities to foster an innovative ecosystem. When shifting the focus from criteria to alternatives, it is expected that developed countries would demonstrate superior performance compared to their less-developed counterparts. The findings confirm this expectation, as the United States, the United Kingdom, Germany, and South Korea showcase the most successful innovation performance within the scope of this analysis. Economic and technological advantages provide these countries with a conducive environment for innovation. Furthermore, the findings of the study confirm that as long as investment in innovation continues, countries' innovation performance will not be affected by universal catastrophic events such as COVID-19.

It is important to support the findings of our study with the findings of other studies in literature. Studies on innovation performance in literature are discussed in the literature section. However, it is not possible to make a detailed comparison due to the differences in the scope (countries, periods, approaches) of these studies. Nevertheless, when the findings of the study by Ecer and Aycin (2023) are analyzed, it is seen that the innovation performances of the US and UK countries are in parallel with the results of our study and that they are in the first two places in both studies.

6. CONCLUSION

A novel integrated MCDM approach was proposed to assess and compare comprehensively the innovation performance of G20 countries. The proposed approach comprises four stages. In the first stage, the LOPCOW method procured needed criteria weights in an objective way. Also, this method is one of the state-of-the-art MCDM methods that doesn’t require individual evaluations of the decision maker(s). The countries were ranked using the MAIRCA method in the second stage. The final two stages were conducted to test the robustness, reliability, and validation of the proposed approach. To achieve this, prominent MCDM methods, namely TOPSIS, MARCOS, MABAC, and EDAS were involved in a detailed comparative analysis. The susceptibility to criteria weight changes was also analyzed under five different scenarios. Moreover, the analysis conducted in this study is comprehensive both in terms of the methodology employed and the period of the analysis. The study covers a five-year period, allowing for the monitoring of the impact of the pandemic on innovation performance. The adopted approach in this study is expected to make a valuable contribution to the literature in the mentioned aspects.

As in every scientific study, there are some limitations in this study. Since the data used in the study are available at the end of annual reporting periods, it is not possible to analyze countries in narrower time windows (monthly, quarterly, semi-annually). Moreover, the importance levels of the criteria included in the analysis were obtained using the information contained in the data set. The fact that the assessments of experts in the field are not included in the calculation of these importance levels can be interpreted as a limitation. Finally, since the innovation performance rankings of countries are obtained only in line with the content of the data set, different findings may emerge from this study using different data sets.

In further studies, there is potential to broaden the scope by including countries from different regions around the world. Additionally, apart from the information provided in the dataset, incorporating the expertise of innovation experts could enhance the analysis process. This could be achieved by utilizing different weighting methods or MCDM methods that incorporate extensions of uncertainty theories. By incorporating these elements, the assessment of innovation performance can be further refined and provide more comprehensive insights.

Author Contributions

Tayfun Öztaş: Literature Review, Methodology, Modelling, Analysis, Writing-original draft, Writing-review, and editing. *Gülin Zeynep Öztaş*: Literature Review, Conceptualization, Writing-original draft, Writing-review, and editing

Conflict of Interest

No potential conflict of interest was declared by the authors.

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Compliance with Ethical Standards
It was declared by the authors that the tools and methods used in the study do not require the permission of the Ethics Committee.

Ethical Statement
It was declared by the authors that scientific and ethical principles have been followed in this study and all the sources used have been properly cited.

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VERİMLİLİK DERGİSİ
JOURNAL OF PRODUCTIVITY

Sustainability in Industry, Innovation and Infrastructure: A MCDM Based Performance Evaluation of European Union and Türkiye for Sustainable Development Goal 9 (SDG 9)

Hasan Arda Burhan[1]

ABSTRACT

Purpose: The aim of this study is to perform two distinct cross-country evaluations including European Union (EU) countries and Türkiye, focusing on Sustainable Development Goal 9 (SDG 9): Industry, innovation and infrastructure. The study aims to obtain rankings that display the relative standings of countries and identify areas for potential enhancement.

Methodology: An integrated objective criteria weighting, VIKOR, and MAIRCA based Multi-Criteria Decision Making (MCDM) approach has been employed.

Findings: Based on the first analysis, high speed internet coverage (HSI) and the share of rail and inland waterways in inland freight transport (SRI) were prominent criteria, and in the MCDM analysis, Sweden displayed the highest performance, while Greece and Croatia showed the lowest performance. In the second analysis, which included Türkiye, tertiary educational attainment (TEA) criteria stood out; while, Sweden maintained its leading position. Türkiye initially had poor performance in the early years but later improved, reaching a mid-level position among 26 countries by 2020. However, a significant decline in performance was observed in the last two years. In addition, during the handled period Türkiye witnessed a decline in both the number of patent applications and the share of buses and trains in inland passenger transport. Thereby, novel policies and incentives could be formulated to overcome these issues.

Originality: Two distinct cross-country analyses were conducted in accordance with the SDG 9 by adopting the most recent data and an integrated methodology. Within this context, EU countries were compared both among themselves and with Türkiye, and valuable findings were presented.

Keywords: Sustainable Development Goals, SDG 9, Objective Criteria Weighting, VIKOR, MAIRCA.
JEL Codes: C60, O30, R11.

Sanayi, İnovasyon ve Altyapıda Sürdürülebilirlik: 9. Sürdürülebilir Kalkınma Hedefi (SKH 9) Açısından Avrupa Birliği ve Türkiye'nin ÇKKV Temelli Performans Değerlendirmesi

ÖZET

Amaç: Bu çalışmanın amacı, Avrupa Birliği ülkeleri ve Türkiye için iki farklı değerlendirme yapmak ve Sürdürülebilir Kalkınma Hedefi 9 (SKH 9): Sanayi, inovasyon (yenilikçilik) ve altyapı üzerinde odaklanarak ülkelerin göreceli performanslarını ve potansiyel iyileştirme alanlarını sergileyen sıralamalar elde etmektir.

Yöntem: Bu çalışmada bütünleşik nesnel kriter ağırlıklandırma, VIKOR ve MAIRCA temelli Çok Kriterli Karar Verme (ÇKKV) yaklaşımı benimsenmiştir.

Bulgular: İlk analizde yüksek hızlı internet kapsamı ile kara taşımacılığında demiryolları ve su yollarının payı öne çıkan kriterler olarak belirlenirken, ÇKKV analizinde İsveç'in en yüksek performansı, Yunanistan ve Hırvatistan'ın ise en düşük performansı gösteren ülkeler olduğu görülmüştür. İkinci analizde Yükseköğrenim Eğitim Düzeyi en önemli kriter olarak belirlenirken, yine İsveç lider konumunu korumuştur. Ele alınan dönemin ilk yıllarında kötü bir performans gösteren Türkiye, sonrasında ilerleme kaydetmiş, 2020 yılında 26 ülke arasında orta düzeyde bir konuma ulaşmıştır. Öte yandan son iki yılda Türkiye'nin genel performansı ve patent başvurularının sayısı ile karayolu ve demiryolu taşımacılığındaki otobüs ve tren payında bir düşüş yaşandığı görülmüş olup, bu doğrultuda yeni politika ve teşvikler geliştirilebilir.

Özgünlük: Çalışmada en güncel veriler ve bütünleşik bir metodoloji benimsenerek 9. sürdürülebilir kalkınma hedefi doğrultusunda iki ayrı ülkeler arası analiz yapılmış, bu bağlamda Avrupa Birliği ülkeleri hem kendi içinde hem Türkiye ile karşılaştırılmış ve elde edilen önemli bulgular paylaşılmıştır.

Anahtar Kelimeler: Sürdürülebilir Kalkınma Hedefleri, SKH 9, Objektif Kriter Ağırlıklandırma, VIKOR, MAIRCA.
JEL Kodları: C60, O30, R11.

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1. INTRODUCTION

Sustainable development (SD) which has gained widespread popularity as an objective for many societies in the 21st century, can be portrayed as the means to achieve a wide array of positive and desirable goals. The initial definition of the notion of SD was introduced in the Brundtland Report of 1987 by the World Commission for Environment and Development (WCED), as the endeavor to fulfill the requirements of the present generation while protecting the interests and well-being of future generations (WCED, 1987). In 2015, the United Nations (UN) General Assembly introduced the 2030 development agenda titled "Transforming Our World: The 2030 Agenda for Sustainable Development" including 17 Sustainable Development Goals (SDGs) (UN, 2015). This agenda and the designated SDGs hold significant importance as the global population is projected to increase from the current 8 billion to 8.55 billion by 2030 (UN, 2022). Thereby, it can be clearly stated that SD, which is inherently linked with innovation, creativity, and productivity, will form the foundation for supporting the world population. In addition, the SDGs introduce these 17 non-legally binding objectives to address economic, social, and environmental aspects of sustainability; nevertheless, it was anticipated that governments will assume responsibility and create country-level plans to attain them. These main indicators involve a broad spectrum of topics, ranging from poverty, inequality, health, industry, innovation, climate action, and others. Furthermore, it is also stated that, in certain instances, the fulfillment of one SDG target is a prerequisite for the attainment of another SDG (Le Blanc, 2015). However, it is also a well-known fact that neglecting the interconnectedness of SDGs and adopting a fragmented approach to target fulfillment may lead to unintended adverse outcomes for countries. For instance, it is stated that prioritizing energy access through coal usage to boost the access to energy (SDG 7) could compromise SDG 13 and SDG 14 (climate action and life below water goals respectively) (Nilsson et al., 2016). Therefore, through harmonious and synergistic actions that minimize trade-offs, the SDG agenda is considered to have the potential to fulfill its objectives effectively.

On the other hand, as not all UN indicators were relevant in the European Union (EU) context, the union determined its SDG indicators which align with various EU policy initiatives (EU, 2023a). The implementation of the SDGs within the EU has been influenced by these several significant policy documents such as 2016's "Next Steps for a Sustainable European Future: European Action for Sustainability", the "Towards a Sustainable Europe by 2030" report of 2019, in addition to strategy and target plans such as the "European Green Deal" in 2019, "Circular Economy Action Plan" of March 2020, and the 2030 Climate Target Plan, etc. (EU, 2023a). In this respect, the EU also presented the first instance of a voluntary review in July 2023, which includes comprehensive and item-by-item evaluation of the collaborative endeavors undertaken by the EU in pursuit of the implementation of the SDGs (EU, 2023b). According to this review report, it is stated that since 2015, the EU has exhibited advancements in all SDGs, albeit not consistently and as per the latest available data in the Eurostat portal, it is mentioned that the EU excelled in ensuring sustainable employment and economic growth, alleviate poverty, and promoting peace (EU, 2023b). Moreover, as economies strive for SD, industrialization has progressed in various nations. While it plays a significant role in fostering economic growth, its consequences vary according to a country's level of development. For instance, in developed economies, industrial growth hinges on the adoption of cutting-edge technologies and mitigate the impact of industrial activities on ecosystems and the climate; on the other hand, for developing economies, industrialization entails transitioning from traditional sectors to a modern industry centered on infrastructure, technology and innovation (Kynčlová et al., 2020). Hence, it can be clearly stated that the primary concern for many countries centers on interlinking industry, innovation, and infrastructure to successfully accomplish SDGs, as it is seen that the innovation brought by the technological progressions of the Fourth Industrial Revolution (Industry 4.0) have profoundly transformed countries and society, (Frankelius, 2009; Silvestre and Ţîrcă, 2019). Additionally, a crucial aspect in the advancement of economies involves establishing a stable infrastructure involving various transportation modalities such as roads, railways, waterways, airways, etc. (Yin, 2019; Stoenoiu, 2022). However, although infrastructure plays a pivotal role for nations, it is noted that the incorporation of state-of-the-art technologies into planning, development, and implementation of the infrastructures lags behind other sectors, whereas limited or inadequate access to infrastructure, encompassing transportation, energy, and information and communication technology (ICT) is perceived as an obstacle to development (Bose et al., 2019). Thereby, it can be stated that regarding both domestic and international links, infrastructure assumes a crucial role in fostering investment generation and attraction, supporting economic development and advancement, and facilitating global integration (Haghshenas and Vaziri, 2012; Zhou, 2012; Alonso et al., 2015).

However, as technologies are not exogenous to environmental and social structures, their impact is also particularly evident. Furthermore, recent events, including the COVID-19 pandemic, global supply chain interruptions, and the energy crisis resulting from Russia's military attacks against Ukraine, have significantly affected the well-being of millions of households, impeding business activities, and revealed vulnerabilities in current social protection and healthcare systems (EU, 2023b). It is also stated that these crises have further intensified the effects of the Fourth Industrial Revolution on employment, competition, trade, digitization, skills, and it has also brought attention to the separation between global economic and environmental systems and the capacity of society to cope with challenges (Schwab and Zahidi, 2020). In this context, it can be asserted that SDGs provide a comprehensive and multidimensional perspective on the development and well-being of nations (Pradhan et al., 2017). Moreover, in line with the above mentioned aspects, one particular SD goal, SDG 9, attracts significant attention. With 8 sub-targets (9.1 to 9.5 and 9.A to 9.C) included, SDG 9 can be succinctly summarized as fostering the development of durable and eco-friendly infrastructure, promoting inclusive and environment-conscious industrialization, and acknowledging the crucial role of research and innovation in addressing social, economic, and environmental challenges (EU, 2023a). Furthermore, the EU SDG 9 includes 9 indicators (6 main, 3 multi-purpose indicators) namely, gross domestic expenditure on research and development (R&D), R&D personnel, patent applications to the European Patent Office (EPO), tertiary educational attainment, share of busses and trains in inland passenger transport, share of rail and inland waterways in total freight transport, air emission intensity from industry, gross value added in the environmental goods and services sector and high speed internet coverage (EU, 2023a). By considering the recently published voluntary review, between 2015 and 2022, the EU's innovation performance witnessed a 9.9% increase; while, expenditure on R&D showed modest growth, rising from 2.02% to 2.26% between 2011 and 2021 (EU, 2023b). Furthermore, over the past 15 years, there was a notable increase of 10,000 patent applications from within the EU submitted to the EPO, while the proportion of individuals aged 25 to 34 with a university degree or equivalent rose from 28.9% to 42.0% (EU, 2023a). Additionally, during the same period, the air emissions intensity of the EU's manufacturing sector declined by 36.4%, noteworthy improvements in high capacity network connectivity were observed in the EU in recent years, however, the share of buses and trains in inland passenger transport decreased to 12.8% in 2020, down from 17.5% in 2019 (EU, 2023a).

When evaluated from the perspective of Türkiye, it is specified in the current 11th National Development Plan (NDP) for 2019-2023 that cultivating SD and promoting inclusive growth require a well-coordinated implementation of efficient economic policies to ensure a stable economy, alongside social policies that foster harmony within society (PSB, 2019a). By considering the SDG 9, available official reports and latest statistics indicate that, in Türkiye, the proportion of R&D expenditure in gross domestic product (GDP) rose from 0.51% in 2002 to 1.40% in 2021 (TSI, 2023b). Moreover, in 2021, 93.0% of enterprises utilized fixed broadband connections, and during the 2018-2020 period, 38.5% of enterprises with ten or more employees were classified as innovation-active (TSI, 2021a; TSI, 2021b). In addition, it is stated that total greenhouse gas (GHG) emissions for the year 2021 exhibited a 7.7% increase compared to the previous year, while based on the 2017 data, the railway's contribution to domestic freight transportation was 4.1%, and its share in passenger transportation was 1% (PSB, 2020; TSI, 2023a). As of 2022, Türkiye 's existing railway network spanned around 13,000 km, with anticipated substantial expansions in the length of electrified and signalized tracks through ongoing projects (TSI, 2023c). Aside from the NDPs and strategic plans of pertinent public institutions, crucial policies and strategies concerning SDG 9 encompass the 2023 Türkiye Export Strategy, Information Society Strategy, National Broadband Strategy, Energy Efficiency Strategy, Combined Transportation Strategy, and action plans (PSB, 2019b).

Furthermore, in the past decade, multi-criteria decision-making (MCDM) methods have gained considerable attention from researchers. As a subfield of operational research, MCDM methods allows decision-makers to make informed choices while considering various and sometimes conflicting criteria, and applied in various areas such as engineering, business, management, also issues of SD (Sousa et al., 2021). In addition, a critical aspect of the MCDM process involves prioritizing the criteria, which is often referred to as the weighting process. This step can be accomplished through subjective weighting, where experts handle the process, or through objective weighting, which relies on the values of the quantities associated with the criteria. However, subjective criteria weighting methods tend to be less preferred due to a variety of factors. These include their time-consuming nature, inherent subjectivity, vulnerability to manipulation, as well as concerns regarding transparency and the potential oversight of critical criteria (Radulescu and Radulescu, 2018; Odu, 2019).

In this context, this study enables assessments of progress towards SDG 9 among both EU countries and Türkiye for 2013-2022 period by utilizing objective criteria weighting approaches and MCDM analysis in which two different methods were compared. By means of the notable and intensive efforts of the EU in tracking and monitoring the SDG indicators, the datasets provided by Eurostat were included in the study. Due to the lack of Cyprus and Malta country data, 25 of the EU countries and all SDG 9 indicators were included in the first analysis. For this initial one, the Criteria Importance Through Intercriteria Correlation (CRITIC) objective criteria weighting method was used because of conflicting criteria. For the second analysis, Türkiye is added to the country list; however, the number of indicators was reduced to 5 because of data constraints. Since there were not any conflicting criteria in this dataset, the Entropy method was used. According to Opricovic (2007) and Taherdoost and Madanchian (2023), the VIKOR method is highly effective in addressing multi-criteria decision-making (MCDM) problems, particularly when dealing with conflicting criteria. Additionally, it stands out for its straightforward ranking process, requiring only a minimal number of steps and eliminating the need for consistency checks. Furthermore, as pointed out by Qahtan et al. (2023), the MAIRCA method has demonstrated greater stability compared to other commonly used MCDM ranking methods and its ability to calculate the probability associated with each alternative can also be stated as the superiority of this method.Therefore, to provide an alternative approach in alignment with the methodologies found in existing literature and facilitate comparative analysis, this study employs both VIKOR and MAIRCA methods in its final phase. Due to the presence of missing values in the dataset, it is essential to regard the calculations for both criteria weighting and country rankings for the year 2022 as projections, since these analyses heavily rely on estimated average values derived from the given time period. Thereby, the objective of this study can be stated as to conduct two distinct cross-country assessments employing a methodology based on objective criteria-weighting and MCDM methods that will facilitate the ranking of countries in the context of SDG 9 in particular and demonstrate their placement in areas of progress. The remainder of the paper is organized as follows: The subsequent section comprises a review of the relevant literature. In the third section, a concise explanation of the employed methodology is presented. Section four encompasses two empirical analyses aimed at obtaining the rankings, along with the corresponding results. The final section provides an overview and brief analysis of these findings.

2. LITERATURE REVIEW

The United Nations (UN) policy framework for sustainable development (SD) endeavors to eradicate poverty, hunger, inequality, and address climate change by the year 2030, utilizing a set of goals known as the SD goals (SDGs). The achievement of these is anticipated to foster development and innovation while ensuring environmental preservation and enhancements in the quality of life for all living beings (Hák et al., 2016). As one of the significant goals, SDG-9 emphasizes the establishment of economies with inclusive industries, stimulating innovation, and ensuring sustainable and resilient infrastructure (Stoenoiu, 2022). In this respect, it can be stated that the impact of these three factors on SD has gained substantial attention in the literature in recent years. In addition, as Sousa et al. (2021) have highlighted the efficient utilization of Multi-Criteria Decision-Making (MCDM) methods in studies focusing on the SDGs in a comprehensive literature review.

Therefore, most related studies, in parallel with the content of this paper, are given as follows: Szopik-Depczyńska et al. (2018) conducted an evaluation of the innovation level among EU countries, utilizing Eurostat's indicators to monitor the progress of SDG 9 of the 2030 Agenda, employing the taxonomic measure of development. The analysis covered the data from 2010 to 2015, revealing that only three countries experienced growth in their innovativeness level: Sweden exhibited the most substantial increase, with an average annual growth of 1.09%, followed by the United Kingdom (0.76%) and Slovakia (0.72%). Hametner and Kostetckaia (2020) undertook a study based on the EU SDG indicator set to evaluate the progress of EU countries towards achieving the SDGs over a 15-year period. The assessment involved analyzing changes over time using both the compound annual growth rate (CAGR) and simple mean (SM) methods. The findings revealed that Sweden, the Netherlands, and Denmark exhibited simultaneous strong sustainable and unsustainable trends across the EU. Furthermore, significant progress was observed in addressing poverty alleviation (SDG 1) and promoting health and well-being (SDG 3). However, developments were less favorable in the economic and environmental dimensions of SD, particularly concerning the goals related to innovation, hence SDG 9. Stanujkic et al. (2020) employed a MCDM method, namely Combined Compromise Solution (CoCoSo), and Entropy to determine the positions of EU countries in relation to the SDGs during the period 2015-2018. Additionally, two more MCDM methods were used to validate the outcomes.The final results indicate that Sweden emerged as the top-performing country in implementing the SDGs, while Romania ranked last. Stoenoiu (2022) conducted an analysis utilizing nine indicators from SDG 9 to assess the performance of eight Eastern European countries in 2013 and 2019. A mathematical model was employed to test the proposed hypotheses and classify the countries based on their progress. The results revealed that Lithuania ranked first in industrialization for both 2019 and 2013, Estonia was the leader in research and innovation for both years, and in terms of infrastructure, Lithuania took the top spot in 2019, which Hungary led in 2013. Brodny and Tutak (2023) undertook an analysis of the EU-27 countries' level of SDG 9 using 14 indicators between 2015-2020. The study employed various MCDM methodologies including Evaluation based on Distance from Average Solution (EDAS), along with objective criteria weighting approaches. The results demonstrated significant variations among the countries in terms of their implementation of SDG 9. Denmark, Germany, Luxembourg, the Netherlands, Finland, and Sweden emerged as the most advanced in this aspect, while Bulgaria, Greece, Portugal, and Lithuania faced substantial challenges in their progress toward SDG 9. Kuc-Czarnecka et al. (2023) conducted an evaluation of the level of SDGs implementation in EU countries and investigated the interrelationships between goals using a composite indicator. The calculation of this indicator was based on an innovative method that incorporated sensitivity analysis (SA) tools and data from the Eurostat database for the year 2020. The results revealed the dominant presence of Scandinavian countries in the top positions, with Sweden securing eight and Denmark earning four (including three as the leader). Notably, the Netherlands stood out, occupying a superior position in terms of the performance of SDG 9.

Regarding studies involving Türkiye, Karaşan and Kahraman (2018) utilized a novel interval-valued neutrosophic EDAS method to assess the prioritization of UN's SDGs for Türkiye and determined the most crucial goal that should be addressed first. The results were also compared with an intuitionistic fuzzy Technique For Order Preference By Similarity To An Ideal Solution (TOPSIS) application and indicated that goals related to poverty were deemed the most significant among the SDGs for Türkiye. However, SDG 9 was ranked 14th out of 15 indicators. Ozkaya et al. (2021) evaluated 40 countries, primarily European, based on 115 science, technology, and innovation (STI) indicators (that are closely related with SDG 9) from 2019. Authors employed various MCDM approaches, and the countries were assessed within 10 dimensions and 115 criteria, which were determined based on data from organizations like the OECD, the World Bank, and the Global Innovation Indices (GIIs). The results revealed that Northern European countries emerged as the leading performers in the rankings based on STI indicators, with Switzerland, the Netherlands, and Germany also securing positions in the top ten. In contrast, Türkiye demonstrated comparatively low values in terms of the included STI indicators. Aytekin et al. (2022) conducted a comprehensive investigation comparing the global innovation efficiency of EU member and candidate countries, which is closely linked to SD and SDG 9. The study utilized the GII and employed Data Envelopment Analysis (DEA) and Efficiency Analysis Technique with Input and Output Satisficing (EATWIOS) methods, analyzing data from the year 2020. The results of the study highlighted the Netherlands, Germany, and Sweden as the top-performing countries in terms of global innovation efficiency. However, Türkiye ranked 20th out of the 32 countries, indicating potential areas for enhancement in its global innovation endeavors. Özarı et al. (2023) conducted a prospective analysis to project the advancement in nations' development by employing a hybrid model, which combined both MCDM and machine learning techniques. Initially, the M-EDAS method was applied to rank selected Asian countries based on their progress towards the SDGs during the years 2017–2020. Subsequently, in predicting the countries' development trajectory for 2019-2020, authors utilized key indicators like gross domestic product (GDP) per capita growth and total unemployment rate, employing the k-NN algorithm. The outcomes from the M-EDAS method revealed Singapore as the most developed country for 2017 and 2018, whereas Japan led the list for 2019 and 2020. On the other hand, Türkiye ranked 11th among 13 countries for 2017 and 2018, and 9th for 2019 and 2020.However, in the following k-NN phase, the predictions were accurate for Hong Kong, the Philippines, Japan, and Singapore. In contrast, the prediction for Türkiye was inaccurate.

Taking into account the works of Szopik-Depczyńska et al. (2018) and Stoenoiu (2022), it can be asserted that the primary objective of the first analysis in this study is to present an updated version using the most recent dataset and employing a distinct methodological approach. Similarly, by utilizing VIKOR and MAIRCA methods, this research offers an alternative analysis compared to the study conducted by Brodny and Tutak (2023), which employed TOPSIS, Weighted Aggregated Sum Product Assessment (WASPAS), and EDAS methods. Regarding the second analysis, which also includes Türkiye and the available dataset, this study aims to investigate Türkiye's current ranking in comparison to the EU countries. Thus, with a specific focus on SDG 9, this study contributes to the research conducted by Ozkaya et al. (2021) and Aytekin et al. (2022), both of which conducted cross-country performance evaluations encompassing European states and Türkiye using different methodologies, which are presented in this research.

3. DATA & METHODOLOGY

3.1. Data

The analysis and evaluation of the implementation of Goal 9 of the Agenda 2030 for sustainable development (SD) in the European Union (EU) countries and Türkiye were conducted using data from Eurostat's SD indicators dataset, specifically focusing on Goal 9: Industry, innovation, and infrastructure (SDG 9). Due to the lack of Cyprus and Malta country data, 25 of the EU countries were included in the analysis. The dataset comprised 9 criteria for the first; and 5 out of 9 for the second analysis. The selected time frame for the study covered years between 2013 and 2022. This timeframe was chosen to assess the years leading up to the 2030 Agenda. The criteria set with abbreviations is given in Table 1.

Table 1. Industry, innovation and infrastructure (SDG 9) criteria

No	*Criteria*	*Abbreviation*
1	Air emission intensity from industry	AEI
2	Gross domestic expenditure on research and development (R&D)	GDE
3	Gross value added in environmental goods and services sector	GVA
4	High-speed internet coverage	HSI
5	Patent applications to the European Patent Office	PA
6	R&D personnel	RDP
7	Share of buses and trains in inland passenger transport	SBT
8	Share of rail and inland waterways in inland freight transport	SRI
9	Tertiary educational attainment	TEA

Source: Eurostat

Firstly, a data preparation and pre-processing approach was conducted to handle missing values in the dataset following the data acquisition step. This phase involved using the Python programming language, and the Scikit-learn library's Simple Imputer class was utilized to address and handle the missing values present in the dataset mostly for 2022.

3.2. Methodology

3.2.1. Criteria Importance Through Intercriteria Correlation (CRITIC) Method

To ascertain the objective weights for the specified criteria, the CRITIC method, proposed by Diakoulaki et al. (1995), employs standard deviation and correlation values. The procedural steps of this method are outlined below (Žižović and Marinković, 2020):

- After establishing the decision matrix, the performance measures in this matrix are subjected to normalization through Equation 1.

$$x_{ij}^{T} = \begin{cases} \frac{x_{ij}-x_j^-}{x_j^+-x_j^-}, x_j^+ = \max_i x_{ij}, x_j^- = \min_i x_{ij} \\ \frac{x_j^- - x_{ij}}{x_j^+-x_j^-}, x_j^+ = \min_i x_{ij}, x_j^- = \max_i x_{ij} \end{cases} \tag{1}$$

where x_{ij}^{T} is the normalized value of i^{th} alternative on j^{th} criterion.

- Standard deviation values are computed for each criterion within the normalized matrix.
- The correlation of each criterion in the normalized matrix is also calculated.
- Using each element of the correlation matrix (r_{jk}), the measure of conflict of a given criterion concerning other criteria is computed using the formula provided below (Equation 2).

$$\sum_{j'=1}^{n}(1 - r_{jk}) \tag{2}$$

- By integrating the two aforementioned measures, the quantity of information contained within criterion j (C_j) is computed as in Equation 3.

$$C_j = \sigma \sum_{j'=1}^{n}\left(1 - r_{jk}\right), j = 1, \ldots, n \tag{3}$$

- To determine the weights of criteria (W_j), the sums of C_j values are computed as in Equation 4.

$$C_k = \sum_{k=1}^{m} C_j \tag{4}$$

- The criteria weights are obtained by the formula given below (Equation 5).

$$W_j = \frac{C_j}{\sum_{k=1}^{n} C_k}, j, k = 1, \ldots, n \tag{5}$$

3.2.2. Entropy Method

The entropy method, developed by C.E. Shannon was originally termed “information entropy” (Shannon, 1948). In essence, entropy serves as a parameter that measures the extent of differentiation between specific criteria (Cavallaro et al., 2016). As the entropy value increases, the entropy weight decreases, indicating that the alternatives are considered less distinguishable with respect to certain criteria (Wang and Lee, 2009). The steps involved in the entropy method are outlined below (Cavallaro et al., 2016; Li et al., 2020):

- The normalization of the decision matrix is carried out using Equation 6.

$$P_{ij} = \frac{x_{ij}}{\sum_{i}^{m} x_{ij}} \tag{6}$$

where x_{ij} represents the performance rating or value of the *i^th^* alternative with respect to the *j^th^* criterion.

- Entropy values E_j are computed for each criteria by Equation 7.

$$E_j = -k \sum_{j=1}^{n} P_{ij} \ \ln(P_{ij}) \tag{7}$$

where $k = \frac{1}{\ln m}$, *m* is the number of alternatives.

- Calculating the degree of divergence (d_j) value using Equation 8.

$$d_j = 1 - E_j \tag{8}$$

where larger the d_j values, moe important the j^{th} criteria.

- Objective weights of the criterion are obtained by Equation 9.

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{9}$$

and the sum of all W_j should be equal to 1.

3.2.3. VIKOR Method

Opricovic and Tzeng (2002) introduced the VIKOR method, which stands for "VIseKriterijumska Optimizacija I Kompromisno Resenje," meaning multi-criteria optimization and compromise solution. This method aids decision-makers in reaching a final decision by identifying compromise solutions, which are feasible options closest to the ideal solution. The steps are given below (Devi, 2011; San Cristóbal, 2011):

- Identify the best (r_j^+) and the worst (r_j^-) values for all criterion functions (Equation 10), where *j* = 1, 2, ..., n. If the j^{th} function represents a benefit (maximization criteria), then,

$$r_j^+ = \max_i r_{ij},\ r_j^- = \min_i r_{ij} \tag{10}$$

otherwise (non-beneficial criteria) the reverse applies.

- S_i and R_i values are calculated by Equations 11 and 12.

$$S_i = \sum_{j=1}^{n} \frac{w_j\left(r_j^+ - r_{ij}\right)}{r_j^+ - r_j^-} \tag{11}$$

$$R_i = \max_j \frac{w_j\left(r_j^+ - r_{ij}\right)}{r_j^+ - r_j^-} \tag{12}$$

where W_j are the criteria weights.

- The Q_i values are obtained by the Equation 13.

$$Q_i = \frac{\vartheta(S_i - S^+)}{S^- - S^+} + (1 - \vartheta)\frac{R_i - R^+}{R^- - R^+} \tag{13}$$

where $S^+ = \min_j S_i$, $S^- = \max_j S_i$, $R^+ = \min_j R_i$, $R^- = \max_j R_i$,

the weight ϑ is assigned to represent the strategy of 'the majority of criteria' (or 'the maximum group utility'), and in this case, it is set as ϑ = 0.5.

- The alternatives are ranked based on their preference order determined by the value of Q_i. The alternative with the smallest Q_i value is identified as the optimal choice if the following two conditions are satisfied:
    1. Acceptable advantage: $Q\left(A^{(2)}\right) - Q\left(A^{(1)}\right) \geq DQ$, where $DQ = \frac{1}{j-1}$, j is the number of alternatives and $A^{(2)}$ is the second best alternative.
    2. Acceptable stability in decision making: The alternative $A^{(1)}$ must also achieve the highest ranking in terms of S_i and/or R_i. If any of the conditions is not met, a set of compromise solutions is proposed, including:

Alternatives $A^{(1)}$ and $A^{(2)}$ are chosen if only the second condition is not met. Alternatives $A^{(1)}$, $A^{(2)}$, ... $A^{(j)}$ are chosen by the relation $Q(A^{(j)}) - Q(A^{(1)}) < DQ$ for maximum *j* until it is satisfied.

3.2.4. Multi-Atributive Ideal-Real Comparative Analysis (MAIRCA) Method

The MAIRCA method, introduced by Pamučar et al. (2014) primarily relies on the disparity between the ideal and real solutions. The method's steps are outlined below (Trung and Thinh, 2021; Günay and Ecer, 2022):

- Once the decision matrix is constructed, the preference values of alternatives (P_{Aj}) are obtained using Equation 14.

$$P_{Aj} = \frac{1}{m} \text{ and } \sum_{i=1}^{m} P_{Aj} = 1, i = 1, \dots, m \tag{14}$$

where *m* is the number of alternatives.

- Theoretical ranking matrix (K_p) is obtained by Equation 15.

$$K_p = P_{Aj} * W_j \tag{15}$$

where W_j is the weight of the *j^th^* criteria.

- By the use of the normalized decision matrix (x_{ij}^T) in equation (1), and K_p values in equation (15), actual evaluation matrix is computed by Equation 16.

$$K_r = K_{pij} * x_{ij}^T \tag{16}$$

- This is followed by the calculation of the gap matrix (F) as in Equation 17.

$$F = K_p - K_r \tag{17}$$

- Considering the alternatives, the criteria function values are determined using Equation 18.

$$Q_i = \sum_{j=1}^{n} f_{ij} \tag{18}$$

- Finally, the alternatives are ranked based on the ascending order of the Q_i values to determine the best option.

4. EMPIRICAL FINDINGS

This study includes two separate analyses intended for evaluating and comparing the progress towards SDG 9 among EU countries solely, as well as including both EU countries and Türkiye, for the period 2013-2022. The steps of the both analysis is given below in Figure 1.

Figure 1. Steps of the performed analysis

Following the outlined steps in Figure 1, in this study, firstly, the necessary datasets were collected, and missing values were handled. In the Analysis 1, to address conflicting criteria, the CRITIC method was employed to derive the criteria weights. As all criteria were beneficial, weights were calculated by the Entropy method in the Analysis 2. In continuation, the rankings of countries based on SDG 9 criteria for both analysis were determined through the application of both VIKOR and MAIRCA methods. In addition, after each MCDM applications, a sensitivity analysis (SA) including the Equal Weights Method (EWM) is conducted.

To assess the robustness and reliability of outcomes generated by MCDM models, SA serves as a valuable tool. However, it's worth noting that in the literature, the utilization of SA in the context of MCDM models varies, with some researchers incorporating it into their analyses while others do not (Delgado and Sendra, 2004). The literature has introduced a range of approaches, exemplified by Demir and Arslan (2022), which encompass techniques like adjusting criterion weights, altering the order of criteria, and cross-comparing outcomes across various MCDM methods. According to Al Garni and Awasthi (2020), the SA helps collecting valuable insights into the reliability and robustness of the results, ultimately enhancing the transparency and trustworthiness of the decision-making process. Also the EWM in particular present a valid methodology due to its simplicity and transparency and makes it easier to comprehend how alterations in criteria weights influence the decision Kumar et al. (2021). In this context EWM and the cross-comparisons with two different MCDM methods has been applied in this study.

The criteria weighting values derived from the CRITIC method for Analysis 1 are provided in Table 2.

Table 2. Weights of the SDG 9 criteria during 2013-2022

Criteria	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022ᵅ*
AEI	0.092	0.099	0.093	0.090	0.091	0.086	0.086	0.090	0.093	0.093
GDE	0.113	0.110	0.109	0.112	0.105	0.106	0.103	0.106	0.111	0.108
GVA	0.103	0.103	0.104	0.102	0.099	0.103	0.103	0.098	0.106	0.103
HSI	0.127	0.133*	0.135*	0.139*	0.147*	0.152*	0.141	0.129	0.124	0.131
PA	0.081	0.082	0.083	0.083	0.081	0.079	0.079	0.081	0.081	0.082
RDP	0.112	0.109	0.106	0.104	0.104	0.101	0.097	0.099	0.098	0.103
SBT	0.108	0.105	0.111	0.110	0.110	0.116	0.123	0.125	0.110	0.114
SRI	0.131*	0.129	0.131	0.132	0.135	0.133	0.142*	0.154*	0.155*	0.143*
TEA	0.129	0.126	0.124	0.124	0.122	0.119	0.121	0.115	0.119	0.119

* The highest value, ᵅ Projection based on estimated values

Based on the findings presented in Table 2, the analysis reveals that the criteria set obtained close values. However, two criteria, namely high-speed internet coverage (HSI) and the share of rail and inland waterways in inland freight transport (SRI), emerge as the most significant factors among others. Notably, HSI obtained the top ranking from 2014 to 2018, while SRI held the first position from 2019 to 2022, as well as in 2013. Additionally, the criterion of tertiary educational attainment (TEA) stands out as another important factor during the observed period.

In the subsequent stage of the research, the progress towards SDG 9 among EU countries was evaluated and compared using the VIKOR and MAIRCA methods. The outcomes obtained through the VIKOR method are presented in Table 3.

Based on the results, Sweden exhibited the best performance, followed by the Netherlands and Finland. On the other hand, Germany experienced a sharp ascent and secured a position among the top three starting from 2019, while Greece, Ireland, Croatia were the lowest performing ones. Considering the acceptable advantage and stability conditions, with the exception of the year 2021, these conditions were met for all the years. In 2021, all the top-three ranked countries were identified as the best performer, since the first condition was not satisfied.

Based on the outcomes derived from the SA, the top three countries remained largely consistent with the VIKOR application, comprising Sweden, Finland, and the Netherlands. Additionally, Greece and Croatia maintained their positions as the lowest-performing countries. The rankings obtained by the second MCDM application, namely MAIRCA are given in Table 4.

Upon reviewing Table 4, it can be observed that Sweden and Germany consistently secured top rankings throughout the analyzed period. Notably, Denmark held a top-three position between 2015 and 2018, while the Netherlands took over this position in 2019. Croatia and Greece exhibited the poorest performances and were ranked at the bottom two positions.

According to the results obtained from the second SA conducted for the MAIRCA results, the rankings of the countries remained relatively similar throughout the analyzed period, including Sweden, Germany, Denmark, and the Netherlands in top performing level, while Greece and Croatia consistently occupying the lowest positions in the rankings.

Table 3. Country rankings based on the VIKOR method between 2013-2022

Countries	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*$^{\alpha}$
Austria	16	14	16	17	17	17	18	4	5	9
Belgium	18	21	21	22	22	23	5	6	6	6
Bulgaria	17	15	14	15	14	18	14	11	16	18
Croatia	23	24	24	23	23	22	20	19	20	21
Czechia	13	17	15	14	12	10	16	16	14	10
Denmark	8	7	5	4	7	5	9	15	18	11
Estonia	5	5	6	5	5	6	8	8	8	7
Finland	**2***	**2***	**2***	**3***	**3***	4	4	5	4	4
France	9	10	7	8	8	7	12	17	13	13
Germany	10	12	11	11	16	16	**3***	**3***	**1***	**3***
Greece	25	25	25	25	25	25	25	25	25	25
Hungary	12	11	12	12	13	11	13	10	10	14
Ireland	22	22	23	24	24	24	24	24	24	24
Italy	24	23	22	21	21	19	23	22	22	22
Latvia	4	4	4	6	4	**3***	6	7	7	5
Lithuania	11	6	9	9	10	13	19	20	12	17
Luxembourg	6	9	10	10	9	8	11	12	15	15
Netherlands	**3***	**3***	**3***	**2***	**2***	**2***	**2***	**2***	**3***	**2***
Poland	21	20	20	19	18	12	7	13	11	12
Portugal	15	16	17	16	15	15	17	18	19	19
Romania	20	19	19	20	20	21	21	21	21	20
Slovakia	14	13	13	13	11	14	15	14	17	16
Slovenia	7	8	8	7	6	9	10	9	9	8
Spain	19	18	18	18	19	20	22	23	23	23
Sweden	**1***	**1***	**1***	**1***	**1***	**1***	**1***	**1***	**2***	**1***

* Indicating top three countries, $^{\alpha}$ Projection based on estimated values

Table 4. Country rankings based on the MAIRCA method between 2013-2022

Countries	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*$^{\alpha}$
Austria	13	12	12	12	12	13	15	9	8	12
Belgium	11	13	13	13	13	12	5	4	4	9
Bulgaria	23	21	21	21	21	22	19	19	22	23
Croatia	25	25	25	25	25	24	24	24	24	24
Czechia	16	15	15	17	16	16	18	21	21	17
Denmark	5	4	**2***	**2***	**2***	**3***	4	5	6	4
Estonia	6	7	8	8	8	7	10	11	12	8
Finland	4	5	7	6	7	9	9	6	7	7
France	8	8	6	7	6	5	8	7	5	6
Germany	**2***	**3***	**3***	**3***	**3***	**2***	**3***	**2***	**1***	**2***
Greece	24	24	24	24	24	25	25	25	25	25
Hungary	14	16	18	18	17	17	17	15	16	16
Ireland	17	18	22	22	22	23	22	16	17	21
Italy	22	23	23	23	23	21	23	23	20	22
Latvia	**3***	**2***	4	4	5	4	6	10	11	5
Lithuania	12	10	10	11	10	10	14	13	14	13
Luxembourg	9	9	9	9	9	8	7	8	9	10
Netherlands	7	6	5	5	4	6	**2***	**3***	**3***	**3***
Poland	20	20	19	19	18	18	13	18	18	20
Portugal	18	17	17	15	15	15	16	12	10	14
Romania	19	19	16	16	19	20	21	20	19	18
Slovakia	21	22	20	20	20	19	20	22	23	19
Slovenia	10	11	11	10	11	11	11	14	13	11
Spain	15	14	14	14	14	14	12	17	15	15
Sweden	**1***	**1***	**1***	**1***	**1***	**1***	**1***	**1***	**2***	**1***

* Indicating top three countries, $^{\alpha}$ Projection based on estimated values

After reviewing the relevant literature to compare the outcomes of the Analysis 1, it's clear that the findings of the initial analysis are consistent with those of several previous studies, including the research by Szopik-Depczyńska et al. (2018), Hametner and Kostetckaia (2020), Stanujkic et al. (2020), Brodny and Tutak (2023), and Kuc-Czarnecka et al. (2023). In the second analysis, Türkiye was added to the country list, and the number of indicators was reduced to 5 due to data constraints. The criteria weighting values obtained by the Entropy method for Analysis 2 are given in Table 5.

Table 5. Weights of the selected SDG 9 criteria during 2013-2022

Criteria	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022$^{\alpha}$*
GDE	0.205	0.205	0.205	0.205	0.205	0.205	0.205	0.205	0.205	0.204
PA	0.168	0.169	0.170	0.170	0.170	0.170	0.170	0.171	0.172	0.173
RDP	0.207	0.206	0.206	0.206	0.206	0.207	0.207	0.207	0.206	0.206
SBT	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.207	0.207	0.207
TEA	0.209*	0.209*	0.208*	0.209*	0.208*	0.208*	0.208*	0.208*	0.208*	0.208*

***** The highest value, **$^{\alpha}$** Projection based on estimated values

According to the results presented in Table 5, the analysis revealed that the majority of criteria in the set exhibit close values, with the exception of the Patent applications to the European Patent Office (PA) criterion. However, TEA stands out as the most noteworthy criterion among all other. In the subsequent stage, the evaluation and comparison of progress towards SDG 9 among both EU countries and Türkiye were conducted utilizing the VIKOR and MAIRCA methods. The results derived from the VIKOR method are presented in Table 6.

Table 6. Country rankings based on the VIKOR method between 2013-2022

Countries	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022$^{\alpha}$*
Austria	15	4	4	4	4	5	4	6	5	6
Belgium	6	6	5	5	5	6	6	4	4	5
Bulgaria	22	21	19	19	23	22	22	23	24	22
Croatia	21	22	22	20	20	19	20	20	21	20
Czechia	12	11	11	13	11	11	11	11	13	13
Denmark	**2***	**2***	**2***	**2***	**3***	**3***	5	5	6	4
Estonia	14	15	16	15	15	17	15	18	18	16
Finland	5	5	6	6	8	7	7	7	8	7
France	4	**3***	**3***	**3***	**2***	**2***	**2***	**2***	**1***	**3***
Germany	**3***	10	7	7	7	4	**3***	**3***	**3***	**2***
Greece	16	16	15	16	16	16	17	13	15	15
Hungary	13	14	14	14	17	14	16	15	14	14
Ireland	8	9	9	10	10	10	10	10	10	9
Italy	20	23	24	23	21	21	21	21	19	19
Latvia	19	20	21	24	25	23	24	24	23	23
Lithuania	23	18	20	22	24	25	25	25	25	25
Luxembourg	7	7	8	9	9	9	9	9	9	10
Netherlands	9	8	10	8	6	8	8	8	7	8
Poland	17	17	17	17	14	15	14	16	17	17
Portugal	24	25	25	25	22	24	23	22	16	24
Romania	26	26	26	26	26	26	26	26	26	26
Slovakia	18	19	18	18	18	18	18	19	20	18
Slovenia	10	12	13	11	12	13	13	14	11	12
Spain	11	13	12	12	13	12	12	12	12	11
Sweden	**1***	**1***	**1***	**1***	**1***	**1***	**1***	**1***	**2***	**1***
Türkiye	25	24	23	21	19	20	19	17	22	21

***** Indicating top three countries, **$^{\alpha}$** Projection based on estimated values

It can be observed that Sweden and France are the best performing countries, and Denmark also exhibited a high performance. In line with the VIKOR outcomes from Analysis 1, Germany demonstrated an increase and attained a position among the top three countries in 2019. Romania, Portugal, Bulgaria and Latvia were the countries with the weakest performances. On the other hand, Türkiye, which exhibited poor performance in the first three years, showed improvement and climbed to the 17th position by the year 2020. However, in the last two years, a decline was observed.

Taking into account the accepatable advantage and stability conditions, except for the years 2017 and 2021, these were met throughout the analyzed period. In those years, both top two ranked countries (Sweden and France) were selected as the best performer, as the first condition was not fulfilled. Drawing insights from SA applied in Analysis 2, which encompasses Türkiye, the rankings of the countries exhibited similarity to the VIKOR results, with France, Germany, and Sweden consistently occupying leading positions; Türkiye in positions between 15th and 19th, and Romania and Bulgaria retainiing their positions as the countries with the lowest performance. The rankings obtained from the MAIRCA application are presented in Table 7.

Table 7. Country rankings based on the MAIRCA method between 2013-2022

Countries	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022$^{\alpha}$*
Austria	10	5	4	4	4	4	**3***	4	4	4
Belgium	6	8	7	7	5	5	5	**3***	**2***	5
Bulgaria	24	24	24	24	25	25	25	25	25	25
Croatia	25	25	25	25	24	24	24	23	24	24
Czechia	12	12	12	12	11	11	11	12	12	12
Denmark	**1***	**1***	**1***	**2***	**2***	**3***	4	5	5	**3***
Estonia	15	16	18	15	15	15	15	20	19	15
Finland	**3***	**3***	5	5	7	8	7	6	8	8
France	5	6	6	6	6	6	6	7	6	6
Germany	4	4	**3***	**3***	**3***	**2***	**2***	**2***	**3***	**2***
Greece	18	18	16	17	16	16	17	14	16	16
Hungary	13	13	13	13	13	13	13	13	13	13
Ireland	8	9	10	10	10	10	10	10	10	10
Italy	20	19	21	20	20	19	20	16	14	17
Latvia	19	20	22	22	23	23	23	24	23	23
Lithuania	17	14	17	18	21	21	21	21	21	21
Luxembourg	7	7	9	8	9	9	9	9	9	9
Netherlands	9	10	8	9	8	7	8	8	7	7
Poland	16	17	15	16	14	14	14	18	18	18
Portugal	23	23	23	23	22	22	22	19	17	22
Romania	26	26	26	26	26	26	26	26	26	26
Slovakia	22	22	19	21	18	20	19	22	22	20
Slovenia	11	11	11	11	12	12	12	11	11	11
Spain	14	15	14	14	17	17	16	17	15	14
Sweden	**2***	**2***	**2***	**1***	**1***	**1***	**1***	**1***	**1***	**1***
Türkiye	21	21	20	19	19	18	18	15	20	19

* Indicating top three countries, $^{\alpha}$ Projection based on estimated values

It is evident that Sweden consistently achieved the top position after 2016. Remarkably, Denmark secured top-three positions between 2013 and 2018, and Germany from 2015 to 2022. Austria ranked 3rd in 2019, and Belgium obtained the 3rd and 2nd positions in 2020 and 2021, respectively.

Conversely, Türkiye consistently ranked around the 20th position for the entire analyzed period, with the exception of 2020. According to the the SA, Germany, Sweden, and Denmark maintained top positions, while Türkiye appeared between 15th and 21st, Romania and Bulgaria occupied the lowest positions. It can also be stated that obtained results align with the findings of Ozkaya et al. (2021) and Aytekin et al. (2022), which identified Sweden, Germany, and the Netherlands as the leading countries and Türkiye as a weak performer.

The outlook of Türkiye, based on country rankings derived from the VIKOR analysis, in comparison to the top and bottom ranked countries, is presented below in Figure 2.

According to the given statistics and findings, it can be stated that between 2013 and 2020 Türkiye exhibited a significant improvement in performance based on gross domestic expenditure on R&D (GDE), PA, number of R&D personnel (RDP), share of buses and trains in inland passenger transport (SBT), and TEA compared to worst performing countries.

However, in between 2020 and 2021, there was a notable decline in performance, and its position regressed to the levels observed in 2016. The status of Türkiye, as determined by the country rankings obtained from the MAIRCA analysis, in relation to the top and bottom ranked countries, is depicted in Figure 3.

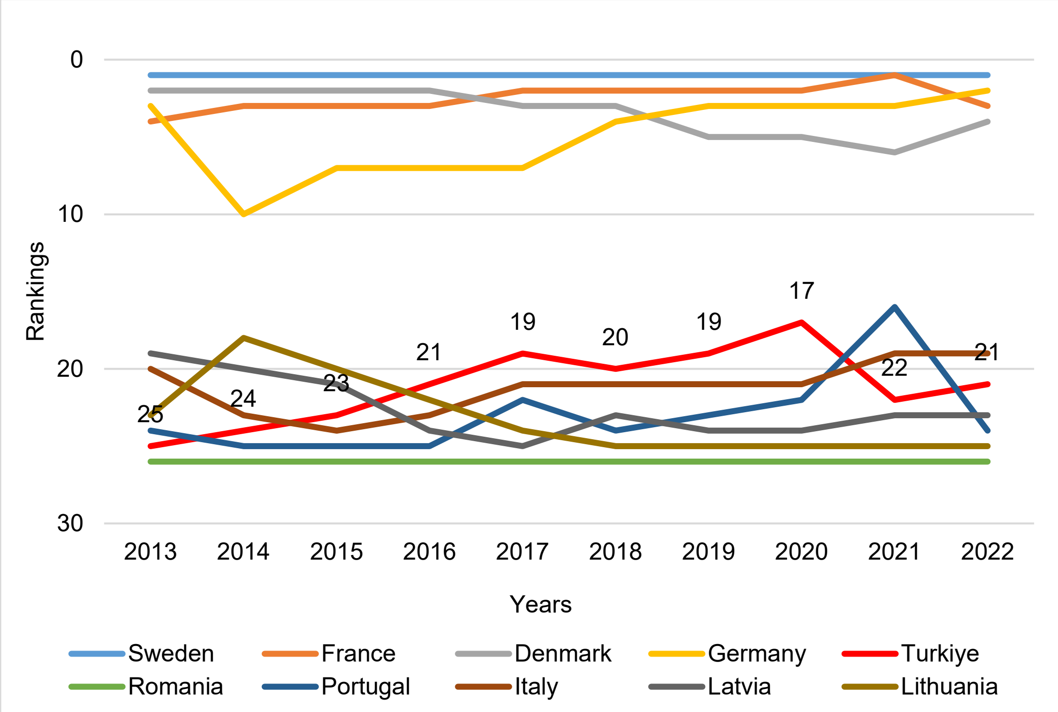

Figure 2. Performance comparisons based on VIKOR

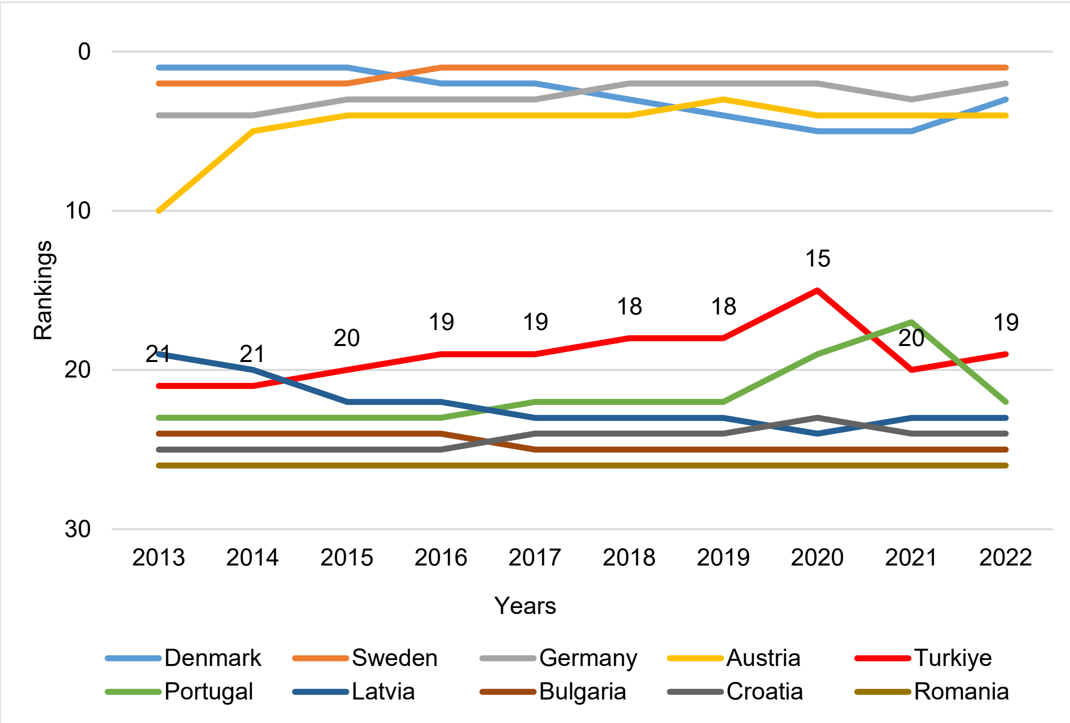

Figure 3. Performance comparisons based on MAIRCA

In line with the VIKOR results, it is evident that Türkiye demonstrated substantial performance improvement between 2013 and 2020 concerning the given criteria, as compared to lowest performers. However, during the period between 2020 and 2021, a significant decline in performance was observed, causing its position to regress to the levels observed in 2016.

5. DISCUSSION and CONCLUSION

Since the initial introduction of the concept of sustainable development (SD) in the Brundtland Report of 1987, it has gained widespread recognition as a crucial objective. In line with the United Nations (UN)'s 2030 Agenda and the establishment of 17 sustainable development goals (SDGs), the European Union

(EU) has also identified its SDG indicators.These primary indicators encompass a wide range of subjects, spanning from climate action to poverty, inequality, innovation, etc. Considering that SD is inherently intertwined with innovation, creativity, and productivity, it is evident that industrialization and infrastructure play a vital role in promoting development due to their ability to stimulate and attract investments. In this respect, among 17 indicators, SDG 9 (Industry, innovation and infrastructure) targets advancing the establishment of resilient and sustainable infrastructure, acknowledging the pivotal role of research and innovation, and encouraging inclusive and environmentally-aware industrial growth (EU, 2023a). In an EU context, the monitoring of SDG 9 encompasses various elements, including high-speed internet coverage, research and development (R&D) intensity and personnel, air emissions intensity of industry, patent applications, and modal splits in passenger and freight transport and as presented in the first chapter, it is stated that the EU has made significant advancements in SDG indicators over the years. By considering the SDG 9, the EU has also achieved noteworthy progress, such as the implementation of the Trans-European Transport Network (TEN-T) policy to establish an efficient EU-wide multimodal network of roads, railway lines, inland waterways, substantial climate action-related expenditures of approximately EUR 9.9 billion in 2021/22, and the development of IRIS2 (Infrastructure for Resilience, Interconnectivity, and Security by Satellite) to enhance communication capacities for governmental and business users (EU, 2023b). Concerning Türkiye's SDG 9 progress, it is evident that there has been an increase in gross domestic expenditure on R&D, the number of R&D personnel, and tertiary educational attainment. However, there are significant decreases in both the share of buses and trains in inland passenger transport compared to previous years and the number of patent applications to the European Patent Office in 2022 compared to 2021, as reported by the EU statistics office (Eurostat, 2023).

In this respect, the study utilized an objective criteria weighting and Multi-Criteria Decision Making (MCDM) approach to evaluate countries based on various SDG 9 criteria, by including two separate analyses aimed at assessing and comparing the progress towards SDG 9. One analysis focused solely on EU countries, while the other included both EU countries and Türkiye. The evaluation covered the period from 2013 to 2022 and it is important to note that the presence of missing values in the dataset necessitated considering the calculations for criteria weighting and country rankings for the year 2022 as projections as they are predominantly relying on estimated average values derived from the given time period. Based on the findings from the first analysis, the CRITIC method identified high-speed internet coverage (HSI) and the share of rail and inland waterways in inland freight transport (SRI) criteria as the most influential factors among others. According to the results of VIKOR and MAIRCA applications in the first analysis, Sweden demonstrated the most outstanding performance among the countries in relation to SDG 9. The Netherlands, Germany, Denmark, and Finland also attained notable rankings. Conversely, Greece and Croatia can be identified as the countries with the lowest performances. In light of the second analysis which includes Türkiye, the Entropy method indicated that most of the criteria in the set demonstrated similar values, except for the patent applications to the European Patent Office (PA) criterion. Nonetheless, tertiary educational attainment (TEA) consistently emerged as the most significant criterion, drawing notable attention among all other. Regarding the MCDM applications, Sweden remained the top performer in both applications, with Denmark and Germany also demonstrating a high level of performance. In contrast to the results of the first analysis, France exhibited effective performance during the handled period. Türkiye, after initially showing poor performance in the early years of the dataset, demonstrated improvement and managed to reach a mid-level position among 26 countries by the year 2020. However, a significant decline in performance was observed in the last two years. Taking into account the diverse sets of criteria in both Analysis 1 and 2, it can be concluded that, upon comparison, objective weighting mostly produced similar results. Additionally, the MCDM applications yielded close outcomes in both separate analyses, which can be seen as mutual validation. When comparing both analyses, it becomes evident that Sweden and Germany consistently held top rankings throughout the entire study period. Thereby, taking the approaches and applications of SDG-9 in these countries as exemplary models can be recommended, especially for nations that consistently ranked at the bottom in both analyses, such as Greece, Croatia, Bulgaria, and also Türkiye.

Upon examining the relevant literature to compare the outcomes of our initial analysis, it is evident that the findings of this paper align with those of several previous studies. Notably, Szopik-Depczyńska et al. (2018) and Stanujkic et al. (2020) also observed Sweden as the best performer. Similarly, the works of Hametner and Kostetckaia (2020), Brodny and Tutak (2023), and Kuc-Czarnecka et al. (2023) supported the notion that Sweden and Denmark, along with the Netherlands, Germany, and Finland, held the top positions in terms of performance. When related studies in the literature is revisited to compare obtained results in the second analysis, it becomes apparent that this study corroborates the work of Ozkaya et al. (2021). Similar to their findings, Northern European countries emerged as the leading performers in the rankings concerning SDG 9 criteria, with the Netherlands and Germany also maintaining top positions. In contrast, Türkiye demonstrated comparatively lower values. Furthermore, the results in this paper are also consistent with those of Aytekin et al. (2022), who found that the Netherlands, Germany, and Sweden were standouts as top-performing countries, while Türkiye exhibited weaker performance.

The study's contribution lies in its incorporation of the most recent data and adoption of an MCDM approach, thus enriching the existing literature on SDGs, particularly SDG 9, which has been explored by various previous studies utilizing similar methodologies. Furthermore, this study contributes to the academic literature by conducting two separate evaluations of EU countries and Türkiye using empirically validated indicators, two different objective criteria weighting approaches and well-known decision-making methods, while also providing significant insights into the comparison of Türkiye with EU countries in the context of SDG 9, contributing to the understanding of the re-generated Türkiye-EU relations of 2023’s. On the other hand, this study has certain notable limitations. Firstly, it focuses solely on one aspect of the SDGs, namely SDG 9, which are known to be interconnected according to the related literature. Additionally, the presence of missing values in the dataset necessitated data preprocessing, potentially influencing the final results. Moreover, the methodology employed in this study utilized only two MCDM methods, overlooking other methods available in the literature. Furthermore, the second analysis had to reduce the number of indicators to 5 due to data availability constraints, leading to an incomplete assessment of the EU-Türkiye comparison concerning SDG 9. Regarding the policy implications of this research, which validates the suitability of the adopted methodology for evaluating countries' performance with respect to SDGs, the proposed assessment model holds relevance for decision-makers, policymakers, academics, experts, and officials involved in related domains. On the other hand, the proposed model and methodology can prove valuable to policymakers and government officials aligning with the objectives of the 11th development plan aimed at achieving SDGs, especially those related to industry, innovation, and infrastructure. Particularly concerning the criteria included in the second analysis, new policies and incentives can be developed for the share of buses and trains in inland passenger transport and the number of patent applications, which experienced a decline in Türkiye during the period under study. Ultimately, the findings of this study may contribute to cross-country evaluations, especially in the context of the current reinvigorated Türkiye-EU relations. For the future researches, it is recommended to incorporate a comprehensive set of SDG indicators and/or other relevant variables pertaining to industry, innovation, and infrastructure, which have been validated by existing literature, thereby more extensive datasets for conducting similar performance analyses. Additionally, expanding the scope of this study can be achieved by exploring alternative and integrated approaches such as data mining, multi-criteria decision-making (MCDM), and even machine learning methodologies.

Conflict of Interest
No potential conflict of interest was declared by the author.

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Compliance with Ethical Standards
It was declared by the author that the tools and methods used in the study do not require the permission of the Ethics Committee.

Ethical Statement
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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VERİMLİLİK DERGİSİ
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Innovation for Economic Growth: G7 vs E7

Gökçe Sinem Erbuğa[1], Ayşegül Gürsoy[1]

ABSTRACT
Purpose: The main objective of this research is to examine the impact of R&D expenditures and Global Innovation Index ranking on per capita income in E7 and G7 country groups.
Methodology: Logistic regression model was used as the research method in the study. Stata 18 Data Analysis and Statistical Software Program was used in the analysis of the data. At the hand of Stata 18 Data Analysis and Statistical Software Program, regression analysis was used to estimate the possible and unknown effects of independent variables on the dependent variable. During the collection of the data used in the study, the archive scanning method, which is one of the qualitative research methods, was used. Archival reports and official records were also used in the study.
Findings: According to the research results, 83.56% of the model is explained by explanatory variables. With all other explanatory variables constant, a 1% increase in R&D expenditure will result in an increase of 0.5243% on GDP per capita. At the same time, this coefficient gives the flexibility of GDP per capita relative to R&D expenditure (%GDP). It is also found out that there is a positive relationship between GDP per capita and R&D expenditure and also, there is a negative relationship between GDP per capita-GII ranking. In this study, which deals with the innovation efficiency of the G7 countries and the E7 countries, and the effect of this performance on the GDP per capita, it is seen that the G7 countries spend more on innovation.
Originality: It contributes to the literature as there is no other study in the literature that deals with per capita income, Global Innovation Index ranking and R&D expenditures comparatively between the G7 and E7.
Keywords*:* Innovation, Global Innovation Index, G7, E7.
JEL Codes: O19, 032, Q55.

Ekonomik Büyüme için İnovasyon: G7, E7'ye Karşı

ÖZET
Amaç: Bu çalışmanın amacı E7 ve G7 ülke gruplarında Ar-Ge harcamaları ve Küresel İnovasyon Endeksi sıralamasının kişi başına düşen gelir üzerindeki etkisinin incelenmesidir.
Yöntem: Araştırmada araştırma yöntemi olarak lojistik regresyon modeli; verilerin analizinde Stata 18 Veri Analizi ve İstatistik Yazılım Programı kullanılmıştır. Stata 18 Programında bağımsız değişkenlerin bağımlı değişken üzerindeki olası ve bilinmeyen etkilerini tahmin etmek için regresyon analizi kullanılmıştır. Ayrıca araştırmada kullanılan verilerin toplanması sırasında nitel araştırma yöntemlerinden biri olan arşiv tarama yöntemi kullanılmıştır. Araştırmada arşiv raporlarından ve resmi kayıtlardan yararlanılmıştır.
Bulgular: Araştırma sonuçlarına göre model, %83,56 oranında belirlenen değişkenler tarafından açıklanmaktadır. Diğer tüm açıklayıcı değişkenler sabitken, Ar-Ge harcamalarındaki %1'lik bir artış, kişi başına düşen GSYİH'de %0,5243'lük bir artışla sonuçlanacaktır. Bu katsayı aynı zamanda kişi başına düşen GSYH'nin Ar-Ge harcamalarına (%GSYH) göre esnekliğini de vermektedir. Kişi başına düşen GSYİH ile Ar-Ge harcamaları arasında pozitif bir ilişkinin olduğu, kişi başına GSYH-GII sıralaması arasında ise negatif bir ilişkinin olduğu tespit edilmiştir. Firmaların inovasyon performansının ölçülmesini sağlayan global inovasyon endeksinde (GII), Ar-Ge harcaması yapan işletmelerin üst sıralarda ve zirveye yakın olduğu, kişi başına düşen GSYİH'nın daha yüksek olduğu belirlendi. G7 ülkeleri ile E7 ülkelerinin inovasyon performansının ve bu performansın kişi başına düşen GSYİH'ye etkisinin ele alındığı bu çalışmada, G7 ülkelerinin inovasyona daha fazla harcama yaptığı görülmektedir.
Özgünlük: Literatürde kişi başına düşen gelir, Küresel İnovasyon Endeksi sıralaması ve Ar-Ge harcamalarının G7 ve E7 açısından karşılaştırmalı olarak ele alan bir başka çalışma olmadığından literatüre katkı sağlamaktadır.
Anahtar Kelimeler*:* İnovasyon, Küresel İnovasyon Endeksi, G7, E7.
JEL Kodları: O19, 032, Q55.

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1. INTRODUCTION

Throughout the history, countries have done their best so as to maintain the competitive advantage they have. For sustainable economic development and increased GDP, innovation is the key driving force nowadays.

With the industrialization, there has been a recognizable escalate in the global population. The rise in the global population has followed by the reduction of natural resources and degradation of environment. In today's fast paced and dynamic environment, the importance of innovation is inevitable. The increased awareness of innovation leads individuals, companies, and countries rational and efficient use of the limited resources.

Under these circumstances, companies face the necessity to generate new ideas and create innovation. Due to its role in increasing both productivity and competitiveness, innovation has a very crucial function in the growth of national economies. Innovation triggers the growth of an economy measured in terms of GDP.

There are various innovation measurement techniques such as the European Innovation Scoreboard, the World Economic Forum (WEF), and the Global Innovation Index (GII). The World Intellectual Property Organization (WIPO) is a leader organization in supporting the intellectual property ecosystem for a sustainability-driven future. For this reason, by creating and calculating the Global Innovation Index (GII), it provides a roadmap for nations to see their current innovation performance and develop their capacities (Brás, 2023).

For the econometric analysis Global Innovation Index (GII) is considered. Published annually by Cornell University, INSEAD (European Institute of Business Management) and WIPO (World Intellectual Property Organization), this index ranks countries according to indicators using many variables that affect innovation. Besides, innovation performance is measured based on sub-input and sub-output indices.

This research's main aspiration is to find and figure out the differences between G7 group of developed countries (USA, Germany, UK, Japan, Canada, France, Italy) and the group of developing E7 countries' (Brazil, China, India, Indonesia, Mexico, Russia, and Türkiye) R&D expenditures to their GDP, GII rankings and GDP per capita during 2013-2022. GDP per capita is considered as the dependent variable in this research whereas the ratio of countries' R&D expenditures to their GDP and their GII rankings are considered as independent variables. The contribution of this paper is twofold. First, it gives the chance to emphasize the advantages and superiority of developed countries (G7). Secondly, it gives an insight to developing countries (E7) to reach the developed countries from innovation perspective.

The rest of the study is organized along these lines. Section 2 defines the innovation whereas Section 3 gives information regarding Global Innovation Index and Sub-indices. Section 4 emphasizes Research& Development and the connection between R&D and Innovation. In Section 5, the relationship between dependent and independent variables and econometrically analzed and finally Section 6 concludes.

2. INNOVATION CONTEXT

In today's world, markets have perfectly competitive structure, and there are fierce competitions between companies in these markets. In this competitive environment, companies try to maximize their profits, while contributing to and serving social welfare. In a competitive market environment, free competition-based economic relations between businesses are the most basic requirement of an efficient and healthy financial system. As a result of the dynamic structure of perfectly competitive markets, people trying to maximize their individual benefits also try to ensure the effectiveness of both themselves and the whole market. In order to ensure both individual and social welfare, companies need to carry out their activities effectively and efficiently and create innovation in pusuance of gaining desire to surpass other peers in the perfect competition market. The ability of businesses to keep up with the highly dynamic and exceedingly competitive market conditions under all circumstances depends on their ability to innovate (Rekabet Kurumu, 2023).

Moreover, the extremely rapid expansion in the global population causes the voracious depletion of natural resources and production factors, which are already limited and scarce, faster. Therefore, both individuals, companies and governments should be extremely careful and rational in the benefit of these limited resources and ensure the usage and distribution of these resources in the most optimal way. The existence of this aforementioned problem causes companies to put into practice new methods and practices in order to utilize limited resources more efficiently. And thus, companies face the necessity to generate new ideas and create innovation. Due to its role in increasing both productivity and competitiveness, innovation has a far-reaching function in the growth of national economies. For this reason, it is possible to say that innovation is an essential element that has an active function in the management of economic activities on a global scale (Şahinli and Kılınç, 2013).

Although there are many interpretations in the literature about what the concept of innovation is, it would not be correct to talk about the existence of only one definition on which a consensus has been reached. Innovation can be interpreted as "alteration" or "a new method, idea, product, etc." in its most basic and simple form.

Innovation is clarified as "the first introduction or major renewal of a good, service or process; in the form of a new or unused or non-existent marketing method, or the introduction of a first or renewed organizational method" by the OECD (2018). Considering another definition, Twiss (1989) emphasizes that innovation is a process and states that it is a field that combines science, economics, and many other disciplines. Innovation is also stated as the process of commercialization from the birth of an idea to its production and even consumption (Twiss, 1989).

While Rowley et al. (2011) agree with the idea that innovation is a process, they argue that this process is a comprehensive, multi-layered, and gradual process. At the heart of this process lies the idea of companies converting their ideas into products or services and processes with various motivations. In addition, the motivations underlying the innovation of enterprises can be various factors such as having a strong position in the markets in which they operate, gaining competitive power or standing out from their competitors by being different.

According to another definition, innovation is the sine qua non of corporate life for companies and is expressed as the key to their survival. To put it more clearly, innovation is the lifeblood of companies and the only way to grow. Innovation also enables companies to both create value and gain competitive advantage in order to stand out from their competitors or peers (Zahra and Covin, 1994).

From another point of view, the notion of innovation, which expresses both a process and a result of this process, has become an important determinant in addressing innovation competitive advantage today (Özbey ve Başdaş, 2018).

According to the definition of innovation in another source, the phenomenon of innovation is shaped by two main components: the release or definition of something completely new to the market, or a brand-new idea, method, or tool/device (Merriam-Webster, 2017).

On the other hand, innovation represents a new knowledge according to Afuah (1998). This new information is included in every step of production and consumption from products to processes and services.

Schumpeter (1982), who is considered and seen as the founding father of innovation theory in the field of economics, states that innovation is the most basic and fundamental source of technological development and growth. According to Schumpeter (1934),

- Launching a new product or a new and higher quality version of an existing product to the market, which they are not familiar with or close to,
- Introducing and implementing a new mode of production that did not exist before,
- Entering a market or a market that has never operated or existed before,
- Discovery of a new raw material or semi-product that did not exist before,
- The establishment of a new monopolistic position in the market or the deterioration of an existing monopolistic position,
- The execution of a new commercial activity or form of financial organization in any sector ensures the emergence of innovation.

The phenomenon of innovation, which expresses both a procedure (renewal) and an outcome (innovation), is not actually an invention. It fundamentally means adding new effective features to add value to an existing product & service and presenting it to the service of humanity again. In terms of the innovation phenomenon, the important thing at this stage is that the changing new feature is effective and that it adds a unique feature to the existing or new product or service as a result of the creation of innovation (Baş, 2020).

Although there are many definitions of innovation, the inability to talk about a single correct definition that has been agreed upon, and the fact that there are discussions on the accuracy and deficiencies of each definition, brought along the evaluation of innovation on concrete measures. For this reason, the approach of evaluating innovation with concrete measures and measuring it over its sub-components is adopted and used intensively.

The global innovation index (GII) is determined as one of the most widely used criteria that serves this purpose and is used to measure innovation in a healthy way. For this reason, first of all, it was deemed necessary to deal with the global innovation index (GII) and it's subfactors that make up this index in detail with the aim of understanding the comprehensive construction of innovation more clearly in this study.

3. GLOBAL INNOVATION INDEX

The fact that different countries have different innovation capacities causes the development of a common measurement system in order to compare these capacities. And thus, it is ensured that the innovative capacity assessment, which will be a standard measurement on a global scale, can be carried out more accurately and healthily. Although many institutions and organizations try to develop and measure different indices for this purpose, there are some main indices that are most frequently preferred in the literature. The European Innovation Scoreboard, the World Economic Forum (WEF), and the Global Innovation Index (GII) are the ultimate cases of such considerable world-wide measurement mechanisms. Among these indices, the most comprehensive and frequently preferred index on a global scale in practice is the KIE. While the index ranks (from the largest to the smallest) the innovation performance of the countries whose data are available every year, it also highlights certain gaps in innovation criteria (Baykul, 2022).

Published annually by Cornell University, INSEAD (European Institute of Business Management) and WIPO (World Intellectual Property Organization), this index also ranks countries according to indicators using many variables that affect innovation. Through this index, researchers can also analyze many variables (by sub-indexes) can be expressed numerically (Gürtuna and Polat, 2020).

The GII is an analysis based on an increasing number of countries every year, providing a comprehensive evaluation opportunity for the evolution of innovative competency in addition to the systematic examination of the scores. The Global Innovation Index (GII) also assesses the innovation progress of nations by benefiiting from a vast number of signals that influence innovation (Baykul, 2022).

The World Intellectual Property Organization (WIPO) is a leader organization in supporting the intellectual property ecosystem for a sustainability-driven future. For this reason, by creating and calculating the Global Innovation Index (GII), it provides a roadmap for countries to see their current innovation performance and develop their capacities. GII consists of 81 indicators in 2022 that are grouped as innovation input & output sub-index (Brás, 2023).

The Global Innovation Index consists of the Innovation Input Sub-Index and the Innovation Output Sub-Index sub-indexes, and the resulting overall GII is computed by calculating the average of the two key indices and rankings in this context. Briefly GII is the average of the Innovation Input and Output Sub-Indices, and the innovation performance rankings of countries are calculated through the GII (WIPO, 2020; GII, 2022). The Global Innovation Index report, which was presented in 2022 and symbolized 94.3% of the global population and 99.0% of the global GDP, covers 132 countries and the innovation performances of these countries are compared (Dutta et al., 2022).

Innovation Input Sub-Index: The Innovation Input Sub-Index, which consists of five main headings, includes elements that enable innovative activities of the economy. These headings are: institutions, human capital and research, infrastructure, market sophistication, and business sophistication. These five main indicators given and listed above have been determined and used to express developments that include innovation, which is one of the most fundamental values in terms of national economies (Sıcakyüz, 2023).

Innovation Output Sub-Index: It is calculated as the result of innovative activities in the economy and is equally weighted with the Innovation Input Sub-Index in calculating the Global Innovation Index scores, although it consists of only two basic components. These components are: knowledge and technology output and creative outputs.

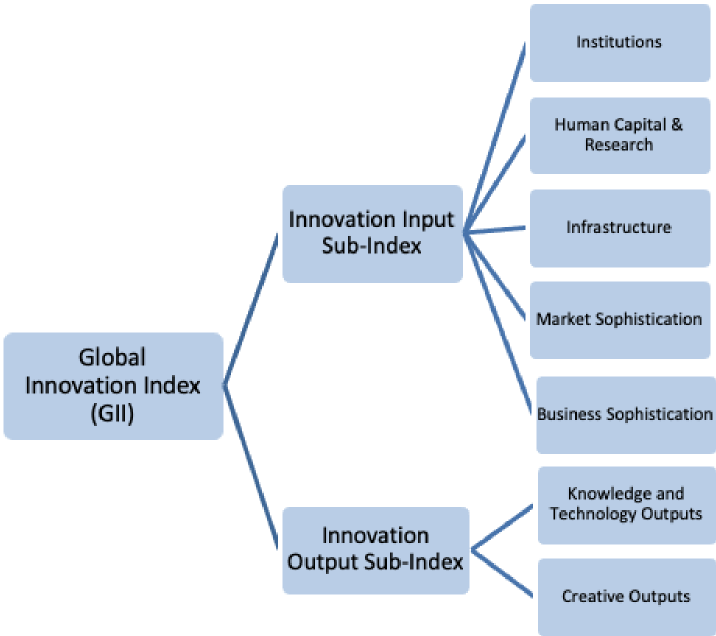


Figure 1. Global Innovation Index (GII) structure (WIPO, 2020).

Each main topic is divided into three main subheadings, and innovative performance is determined with reference to a total of 81 indicators. As seen in Figure 2,

- the political environment, regulatory environment and business environment constitute the "Institutions" main component,
- education, tertiary education and research and development (R&D) "Human Capital and Research" component,
- information and communication technologies (ICTs), general infrastructure and ecological sustainability "Infrastructure" component,
- credit, investment, trade, diversification, and market scale constitute the "Market Sophistication" component,
- knowledge workers, innovation linkages and knowledge absorption constitute the "Business Sophistication" component.

On the other hand, "Knowledge and Technology Outputs" heading consists of knowledge creation, knowledge impact and knowledge diffusion while "Creative Outputs" heading includes intangible assets, creative goods and services, and online creativity. These two main headings constitute the innovation output sub-index.

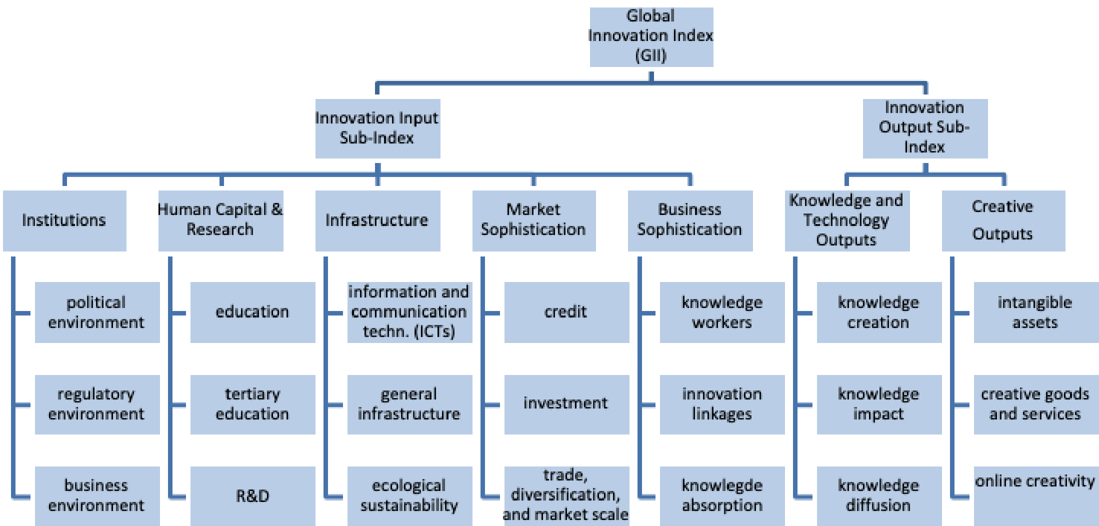


Figure 2. Global Innovation Index components (WIPO, 2020)

With an emphasis on the innovation capacities and potentials of the countries, it is necessary to determine and know the current position and standard of the education and research activities carried out by the said countries. The measurement in question means the measurement of the human capital owned by the countries, and this measurement is carried out under the title of human capital and research, which is the sub-component of the global innovation index.

In the first of the sub-factors that make up the human capital and research pillar, there are several indicators determined in order to fulfill the aim of being successful at the primary and secondary education level. In this direction, education expenditures and education (school) life expectancy serve as an important and appropriate sub-pillar for the aforementioned related factors, and its ability to represent the pillars is quite strong. On the other hand, the level of education expenditure that the states have made for each student at the secondary education level provides vital information about the importance and priority level that the nations give to secondary education. In addition, to measure the quality of education, the outcome of the OECD Program for International Student Assessment (PISA) and the performances of 15-year-old students in both reading and also mathematics and science classes are used as data (Dutta et al., 2015).

Another component of the human capital and research factor is tertiary (higher) education. Tertiary (higher) education is an integral part of national economies and is extremely important in terms of going beyond the basic and simple production processes and outputs of the value chains of countries. While the tertiary (higher) education sub-pillar evaluates participation in tertiary education, priority is given to the main fields that can be directly associated with innovation in various traditional senses, such as engineering, basic sciences, manufacturing, or construction. Beyond that, the sharing and exchange of ideas and skills that occur during the mobility of students studying in higher education institutions within the scope of the tertiary education sub-factor is quite necessary to create innovation (Dutta et al., 2015).

The R&D sub-indicator, which is the third and last sub-component of the human capital and research factor, uses the indicators of full-time researchers, gross expenditure and the characteristics of science and research institutions in order to measure the volume and current quality of the R&D activities conducted. The basis of this sub-indicator is to determine the existence of minimum 3 higher education organizations in the top 700 in the global ranking and scale within each economy. However, determining the mediocre degree of all existing institutions and organizations for a given economy is not among the main tasks of this sub-determiner (Dutta et al., 2015).

In short, human capital and research benefit from education and research activities in determining the innovation ability and potential of nations. In this direction, the current level of both education and research activities of nations and the standards they are involved in are the most basic factors used in determining the level of innovation. The human capital and research sub-component are considered as vital indicators to measure the personnel resources of the nations. The human capital and research sub-component aims to sustain and even increase the achievements of nations in secondary education. In addition, it is very important in terms of increasing the value chain of higher education and should be handled carefully.

4. LITERATURE REVIEW

Innovation enables countries to increase their production by providing improvements both in the products and services they produce and, in the methods, used in production, thus increasing the export and welfare of the countries. Therefore, today, companies trying to maximize both their profits and welfare give particular attention to research and development (R&D) activities (Akcalı ve Şişmanoğlu, 2015:768). In line with this aim, it is very important for countries to take meaningful steps towards science and technology in a stable and regular manner and to make targeted investments in this direction. Aside from the private sector, the public sector should always support the private sector in relation to the issue by acting consistently in R&D investments (Soumitra et al., 2020).

Amongst most crucial determinants of the economic power of countries is their innovative abilities and capacities. The innovative power of the countries is an important supporter of the institutional structures and support systems that carry out innovative activities. The innovative power of countries, in other words, their innovative capacities also shape their investments and policies in the public and private sectors at the same time, which will encourage their R&D activities and make them more efficient. At the same time, innovative capacity affects the long-term efforts of countries on innovation and the success of these efforts.

Improving the innovation capacity and performance is one of the most important and fundamental ways for countries to get ahead in today's tough global competitive races. Countries with a strong competitive advantage both show a breakthrough in economic growth and increase exports and therefore international trade activities as a result of economic growth. However, on the other hand, production is not the only way for enterprises to increase their export volumes and international trade. It is also very important for countries to benefit from new technologies by conducting R&D in gaining competitive advantage. The fact that countries produce new goods and services because of conducting R&D activities and even have the opportunity to be the first exporter of new goods and services allows them to grow faster (Aktaş, 2022). For this reason, the third and last sub-component of the human capital and research factor is the R&D sub-indicator.

The lack of human capital to encourage and increase R&D effort is considered as the topmost handicap in the creation and execution of innovation and is considered as the most important bottleneck which prevents innovation. Considering the countries in the middle-upper class income group, it is possible to say that both the human capital, which is very important for the execution of R&D activities, and the innovation linkage are equally effective, but on the other side, innovation is one of the most fundamental difficulties even for these countries. (Bate et al., 2023).

Spendings expressed as research and development (R&D) expenses in the literature refer to the expenses incurred directly in the research and development of the goods or services that will be produced by the enterprises producing goods or services, or any intellectual property rights arising within the production process. To put it more clearly, R&D expenses can be defined as all direct expenses incurred by companies during the production technologies, design, production, and all other processes, efforts to develop and innovate during the production of products or services (Frankenfield, 2022). It is in question that businesses often incur R&D expenses in the process of creating, finding or revealing a brand-new product or service. Boosting the volume of R&D expenditures, which is a very important expense item in terms of companies, is one of the main targets that both companies and countries set in achieving sustainable economic growth.

The total of R&D expenditures is of great importance in fulfilling the 9th objective (SDG-9), one of the sustainable development goals, of the United Nations, as well as being a data that states should follow on the path of economic growth. UN SDG-9 requires the endorsement of a sustainable development approach, stating the goal of "*building resilient infrastructure, promoting inclusive and sustainable industrialization and fostering innovation*". In this context, SDG-9 emphasizes the necessity of promoting innovation. In addition, for this purpose, it is emphasized that the sum of individuals working on R&D per 1 million people and the R&D expenditures made by both the public and private sectors should be greatly increased in the process until 2030 (UIS, 2023). As SDG Target 9.5 mentions developing scientific research and studies in all countries, especially in developing countries, and increasing the technological capacity of industries directly linked to industry are another important point (UNECE, 2023).

Although there are many studies in the jurisprudence delving into the relationship between R&D and innovation, most of these studies try to determine and evaluate the impact of R&D expenditures on innovation. Many studies reveal that the R&D expenditures of organizations precisely impact their ability to innovate, and it is even considered as the most effective factor determining these capabilities (Dosi, 1988; Freeman and Soete, 1997; Shefer and Frenkel, 2005). R&D investments of companies enable them to gain a competitive advantage by gaining a strong position against rival companies (or peers) even at the very beginning of the innovation diffusion process (Shefer and Frenkel, 2005).

In the study of Aghion and Howitt (1992), which selected companies operating in the USA as a sample, economic growth was handled in an R&D-based way. In the aforementioned study, the relationship between R&D expenditure and economic growth was examined and it was identifed that this relationship was not a strong one. Although the relationship is not strong, it has been emphasized that it has an effect and can be utilized in a valid endogenous growth model that can be used for the USA.

In the study carried out by Wakelin (1998), it was tried to determine the function of innovation on the possibility of exporting and export tendency behavior of enterprises. According to the findings obtained because of the research, businesses that carry out and do not carry out innovation activities in England differ in terms of export behavior. Large-scale enterprises tend to export more, and they are more likely to enroll in export markets.

In the study carried out by Crosby (2000), the place and importance of savings, invesment, human capital and innovation in the economic growth of nations were stated and the findings of the study supported the new growth theories. According to the study, in line with the new growth theory, it is emphasized by considering the companies operating in Australia that innovation has a very important function in economic growth. It is also stated in the study that the increase in the number of patents obtained as an outcome of innovation is extremely important not only in terms of economic growth but also productivity of labor.

Wakelin (2001) investigated whether there is any relationship between the R&D expenditures of the companies and the efficiency they provide in production. In this direction, in the aforementioned study, 170 companies operating in the UK were examined and the intensity of R&D activities and efforts associated to these enterprises were evaluated. As findings of this study shows, it’s been found that there is a positive and also significant relationship between the R&D expenditures and companies' production growth, and the success of innovative enterprises in R&D has been determined as more remarkable.

In another study, Ülkü (2004) investigated the relationship between GDP per capita, R&D expenditure and innovation within the scope of two groups of countries, both OECD members and non-OECD members, in the period between 1981-1997. According to the findings obtained as a result of the said study, it was found out that there is a strong positive relationship between GDP and innovation for both country groups; emphasized that R&D investments have a positive and supportive effect on innovations.

Vogiatzoglou (2009) examined 28 different countries within the scope of the study, and as a result of the regression analysis he conducted, he revealed that R&D and human capital are statistically extremely important for national economies, especially regarding information and communication technologies.

Bogliacino and Pianta (2013), who consider R&D efforts as the most fundamental component of innovative activities, did not limit technology indicators only to R&D and patents in their studies, but also tried to measure innovation in all its dimensions by making use of pioneering researches (Archibugi and Pianta, 1996; Smith, 2005) in the field in a comprehensive and detailed way.

Gökçe et al. (2012) conducted a panel causality analysis by collecting data from 27 different countries between 1997 and 2007. As a result of the research conducted, the existence of the existing relationship between high-tech exports and R&D has been proven. It was also stated that there is a correlation between high R&D expenditures and large exports of highly technological products.

In another research, Akcali and Sismanoğlu (2015) tried to reveal the relationship of innovation with growth of national economies in terms of developing countries and developed countries. According to the results of this study, in which Swamy's random cooficient model was used, it was determined that there is a positive relationship between R&D investments and economic growth.

Rodil et al. (2016) explored the relationship between innovation and export behavior at the micro (company) level and as a result, they concluded that there is a positive relationship between innovation and export.

In another study examining the relationship between R&D expenditures and economic growth in the literature, E28 countries were chosen as a sample and the effect of R&D expenditures in these countries on real GDP was monitored between 2002 and 2012. According to the results of this study, in which the multiple regression model was used, 1 unit surplus in R&D expenditures creates a more than 2 times increase in real GDP (Sokolov-Mladenović et al., 2016).

Muñoz-Bullón et al. (2020), in their study, examined the R&D loci regarding the innovation performance of family firms (FF) and other non-family firms (NFF) operating in Spain between 1990 and 2016. In line with the findings obtained by means of this study, it has been concluded that FF have more effort and success in turning their combined R&D activities into innovation performance compared to companies that are not FF. In this direction, in the conclusion part of the study, the success and innovation performance of family businesses in this regard has been evaluated.

In another study, it was investigated whether the effect of R&D expenditures and the government had an effect on the growth of states. In the study, to measure innovation, R&D expenses were considered as a measurement factor. In the same way, GDP was determined as the basic (fundamental) indicator in order to measure growth. In this study, which tries to determine whether innovation has an effect in the development of African countries, a linear regression model was applied to the data obtained from 4 African countries determined between the years 2000-2016. The findings got from the research show that R&D has a critical importance for the realization of economic growth in Africa (Olaoye et al., 2021).

According to the study conducted by Benetyte et al. (2021), innovation is the basis of a "sustainable economy" approach. Within the framework of this understanding, it has been emphasized that innovation is one of the most basic and critical resources that companies can benefit from in order to contribute to their national economies. For this reason, the contribution of R&D to the sustainable economy approach has been evaluated within the scope of the study. In line with this view, it is extremely important for the company and the country's economy to adopt and manage the risks related to R&D in a healthy way by companies (Benetyte et al., 2021).

In both studies by Adıyaman and Hayaloğlu (2020) and Eygü and Coşkun (2020), the relationship between innovation and economic development was evaluated between 1995 and 2018 and it was shown that R&D expenditures and innovation had a positive effect on economic development both. While Adıyaman and Hayaloğlu (2020) used panel data analysis while examining 30 developing countries within the scope of their study, Eygü and Coşkun (2020) benefited from time series analysis in their study conducted in Türkiye. Reaching the same conclusion, Elverdi and Atik (2021), on the other hand, analyzed the data of 127 countries within the scope of the 2017 GII report, using the structural equation model, and again concluded that there is a positive and strong relationship between development and innovation economically.

Hammar and Belarbi (2021) analyzed the impact of R&D expenditures on innovation at 36 countries covering the period 2002–2014. Secondly, the impact of innovation on productivity, and thirdly the impact of innovation on medium-high technology exports are investigated.

Pelikánová (2019) analyzed the relationship between R&D expenditure and innovation in the EU countries with an emphasis on sustainable development. Dritsaki and Dritsaki (2023) examined the relationship between R&D expenditures and the GII in the scope of EU countries. The findings indicate the higher investment on R&d results with higher innovative performance.

Chen et al. (2022) investigated the output by examining patents of listed companies with and without R&D expenditure disclosures by using Chinese listed firms. The study emphasizes the impact of voluntary R&D disclosure on innovation performance prediction.

Kučera, J. and Fiľa (2022) quantified the possible impact of R&D expenditure on innovation performance and possible impact of the innovation performance on economic development of the EU countries.

When the existing literature is examined in detail, it is seen that there are studies that evaluate the development levels of countries and innovation performance together. However, on the other hand, no study has been found that aims to mutually evaluate the innovation performance between G7 countries, which represent developed countries, and E7 countries, which define developing countries. Therefore, in this study, these countries with different development levels were compared in order to fill this existing gap in the literature. This study thst is conducted, contributes to the literature as there is no other study in the literature that deals with per capita income, Global Innovation Index ranking and R&D expenditures comparatively between the G7 and E7.

5. IMPLICATION

In this section, the G7 group of developed countries (USA, Germany, UK, Japan, Canada, France, Italy) and the group of developing E7 countries (Brazil, China, India, Indonesia, Mexico, Russia, and Türkiye) have carried out R&D activities between 2013-2022. These country groups are chosen because the factors that affect the high innovation performance of G7 is emphasised. With an emphasis on G7, E7 can focus on factors that trigger being a developed country. GII is calculated since 2013, for this reason the mentioned time interval is used for the empirical analysis.

The possible effects of expenditures and their ranking in the global innovation index on economic growth have been analyzed. A comparative analysis was carried out between the G7 and E7 countries. As independent variables, the ratio of countries' R&D expenditures to their GDP and their GII rankings were determined.

As seen in the literature, there is a close relationship between the innovation status of countries and their economic development (Wang, 2013; Inekwe, 2015; Sohn et al., 2016; Franco and Oliveira, 2017 etc.). Among the most concrete determinants of innovation efforts is human capital and research. In other words, the budget allocated by countries for R&D investment directly affects their innovation efforts. A concrete output of the innovation efforts of countries is their ranking in the global innovation index. Therefore, in this research, the effect of R&D expenditure and innovation ranking on the economic situation of the countries was tried to be determined. For this purpose, firstly, data on R&D expenditures of both E7 and G7 countries were collected.

Table 1. GDP per capita for E7 and G7 countries

Countries	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*
Brazil	12358	12175	8846	8857	9978	9194	8914	6970	7754	8995
China	7039	7645	8034	8063	8760	9848	10170	10525	12572	12813
India	1438	1559	1590	1714	1957	1974	2050	1913	2234	2379
Indonesia	3684	3533	3367	3605	3885	3947	4194	3932	4362	4798
Mexico	10578	10967	9857	8788	9342	9753	10025	8533	9869	10867
Russian Federation	15928	14007	9257	8723	10723	11261	11555	10180	12617	15444
Türkiye	12488	12079	10973	10891	10628	9507	9132	8612	9654	10618
Germany	46299	48035	41107	42124	44636	47961	46798	46735	51237	48636
US	53245	55083	56729	57839	59878	62787	65077	63577	70159	76348
UK	43492	47476	45085	41275	40666	43377	42797	40347	46421	45294
France	44144	44616	37937	38348	40134	43060	41924	40385	45185	42409
Italy	35534	35836	30463	31190	32648	34917	33628	31784	35842	34113
Japan	40934	38522	35005	39411	38903	39850	40547	40117	39882	33821
Canada	52708	51020	43626	42382	45191	46625	46449	43383	52387	55085

Source: Created by the author using data from www.worldbank.org

According to Table 1, as of 2013, the US has the highest income level with a GDP per capita of $53245. Among the G7 countries, the USA was followed by Canada ($52708) and France ($44144). In 2013, Italy ($35534), Japan ($40934) and UK ($43492) had the lowest GDP per capita level among the G7 countries, respectively. When E7 countries are evaluated in 2013, the countries with the topmost GDP per capita levels in this group were determined as Russian Federation ($15928), Türkiye ($12488), and Brazil ($12358). Among the E7 countries, the countries with the lowest GDP per capita levels as of 2013 are India ($1438), Indonesia ($368), and China ($7039) respectively. By 2022, Germany took the place of France in the ranking. Italy, Japan and France were the G7 countries with the lowest GDP per capita levels as of 2022. Speaking in terms of E7 countries, while Brazil's GDP per capita value decreased, China made a big attack and became one of the three largest E7 countries. In Table 2, where the ratio of countries' R&D expenditures to GDP per capita is shown, the R&D expenditures of E7 and G7 countries between 2013 and 2022 are indicated as a percentage, both on the basis of scores and ranking.

Table 2. R&D expenditures % of GDP

		2013	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*
Brazil	Score	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.2	1.2
	Ranking	31	31	30	29	32	27	28	30	34	34
China	Score	1.8	2.1	2	2	2.1	2.1	2.1	2.1	2.2	2.4
	Ranking	21	19	17	15	17	14	15	13	13	13
India	Score	0.8	0.8	0.8	0.8	0.8	0.6	0.6	0.6	0.7	0.7
	Ranking	43	41	42	40	43	52	50	57	52	53
Indonesia	Score	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.2	0.3
	Ranking	98	105	109	105	105	107	109	85	89	80
Mexico	Score	0.4	0.4	0.5	0.5	0.6	0.5	0.5	0.3	0.3	0.3
	Ranking	21	66	62	59	59	61	65	79	81	78
Russian	Score	1.1	1.1	1.1	1.2	1.1	1.1	1.1	1	1	1.1
Federation	Ranking	33	32	33	31	34	33	33	37	38	38
Türkiye	Score	0.8	0.9	0.9	1	1	0.9	1	1	1.1	1.1
	Ranking	38	38	37	35	37	38	37	39	36	39
Germany	Score	2.8	2.9	3	2.8	2.9	2.9	3	3.1	3.2	3.1
	Ranking	8	7	8	9	9	7	8	7	6	9
US	Score	2.8	2.8	2.8	2.7	2.8	2.7	2.8	2.8	3.1	3.5
	Ranking	10	11	10	10	10	10	9	9	8	5
UK	Score	1.8	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.8	1.7
	Ranking	20	21	21	21	21	20	22	21	21	22
France	Score	2.2	2.3	2.3	2.3	2.2	2.2	2.2	2.2	2.2	2.3
	Ranking	15	14	14	13	12	12	12	12	14	14
Italy	Score	1.3	1.3	1.3	1.3	1.3	1.4	1.4	14	1.4	1.5
	Ranking	29	30	27	26	26	24	24	26	25	26
Japan	Score	3.3	3.3	3.5	3.6	3.5	3.1	3.2	3.3	3.2	3.3
	Ranking	5	5	3	3	3	5	5	5	4	6
Canada	Score	1.7	1.7	1.6	1.6	1.6	1.6	1.7	1.5	1.5	1.7
	Ranking	23	23	24	22	22	22	21	23	23	23

Source: Created by the author using data from www.worldbank.org

Table 3. GII Ranking for E7 and G7 countries

Year	*Factor*	*Brazil*	*China*	*India*	*Indonesia*	*Mexico*	*Russian Federation*	*Türkiye*	*Germany*	*US*	*UK*	*France*	*Italy*	*Japan*	*Canada*
2013	Global Innovation Index	64	35	66	85	63	62	68	15	5	3	20	29	22	11
	Innovation Input	67	46	87	115	68	52	81	20	3	4	23	28	14	9
	Innovation Output	68	25	42	62	60	73	53	10	12	4	17	29	33	13
2014	Global Innovation Index	61	29	76	87	66	49	54	13	6	2	22	31	21	12
	Innovation Input Sub-Index	63	45	93	117	62	56	78	19	4	3	20	32	15	8
	Innovation Output Sub-Index	64	16	65	60	70	45	39	8	7	4	26	33	27	20
2015	Global Innovation Index	70	29	81	97	57	48	58	12	5	2	21	31	19	16
	Innovation Input Sub-Index	65	41	100	114	58	52	71	18	5	6	17	29	12	9
	Innovation Output Sub-Index	74	21	69	54	49	49	46	8	9	5	23	32	26	22
2016	Global Innovation Index	69	25	66	88	61	43	42	10	4	3	18	29	16	15
	Innovation Input Sub-index	58	29	72	99	60	44	59	18	3	7	15	28	9	10
	Innovation Output Sub-index	79	15	59	76	62	47	37	8	7	4	19	31	24	23
2017	Global Innovation Index	69	22	60	87	58	45	43	9	4	5	15	29	14	18
	Innovation Input Sub-index	60	31	66	99	54	43	68	17	5	7	15	29	11	10
	Innovation Output Sub-index	80	11	58	73	60	51	36	7	5	6	18	29	20	23
2018	Global Innovation Index	64	17	57	85	56	46	50	9	6	4	16	31	13	18
	Innovation Input Sub-index	58	27	63	90	54	43	62	17	6	4	16	29	12	10
	Innovation Output Sub-index	70	10	57	73	61	56	43	5	7	6	16	32	18	26
2019	Global Innovation Index	66	14	52	85	56	46	49	9	3	5	16	30	15	17
	Innovation Input Sub-index	60	26	61	87	59	41	56	12	3	6	16	30	14	9
	Innovation Output Sub-index	67	5	51	78	55	59	49	9	6	4	14	29	17	22
2020	Global Innovation Index	62	14	48	85	55	47	51	9	3	4	12	18	16	17
	Innovation Input Sub-index	59	26	57	91	61	42	52	14	4	6	16	33	12	9
	Innovation Output Sub-index	64	6	45	76	57	58	53	7	5	3	12	24	18	22
2021	Global Innovation Index	57	12	46	87	55	45	41	10	3	4	11	29	13	16
	Innovation Input Sub-index	56	25	57	87	62	43	45	14	3	7	17	33	11	8
	Innovation Output Sub-index	59	7	45	84	51	52	41	8	4	6	10	25	14	23
2022	Global Innovation Index	54	11	40	75	58	47	37	8	2	4	12	28	13	15
	Innovation Input Sub-index	58	21	42	72	70	46	49	12	2	7	13	31	11	9
	Innovation Output Sub-index	53	8	39	74	55	50	33	7	5	3	11	15	12	23

Table 3 shows the innovation index ranking of G7 and E7 countries. As reported by the table, the general GII performances of the countries are seen, as well as the country ranking based on innovation input and innovation output sub-indicies, which are GII sub-pillars.

5.1. Dataset and Methodology

Stata 18 analysis program was implied to examine the data within the scope of the study. With the help of Stata 18 Data Analysis and Statistical Software Program, regression analysis was employed to estimate the possible and unknown effects of independent variables on the dependent variable. During the collection of the data used in the study, the archive scanning method, one of the qualitative research methods, was used. Archival reports and official records were used in the study. To find out how much Y changes when X changes one unit the linear regression model was used to when conducting the research process. Data on innovation, R&D expenditure and GDP of countries were collected for the period between 2013-2022. Since the main objective of this study is to reveal whether there is any effect on the innovation ranking based on the innovation sub-pillar R&D expenditure and the global innovation index, GDP per capita is considered as the dependent variable in the study. The innovation factors of G7 and E7 countries constitute the independent variables in the study. The dependent and independent variables used in the study can be expressed as in the table below.

Table 4. Dependent and Independent Variables Used in the Study

Variable Labels	*Definition of the Variable*
Dependent Variable	
GDPpc	GDP per capita
Independent Variables	
GIIranking	Global Innovation Index (GII) ranking
RD	R&D Expenditure % of GDP
G7	E7=0; G7=1

It is observed whether the variables have any effect on GDP per capita represented by the dependent variable (GDP) in the study, if there is an effect, to what extent and in which direction, whether there is a significant relationship between the listed independent variables and GDP. The regression model established for this purpose is expressed in Equation 1.

$$GDP_{it} = \beta_{oi} + \beta_{1i}RD_{it} + \beta_{2i}GIIranking_{it} + \beta_{3i}\, G7 + e_{it} \quad (1)$$

The hypotheses created within the scope of the model can be expressed as follows:

H_1: There is a statistically significant relationship between R&D and innovation.

H_2: There is a statistically significant relationship between the rankings of countries in the global innovation index (GII) and economic growth.

6. FINDINGS

Before performing the logistic regression analysis, it is very important to determine the variables or factors that will be included in the established regression model. For this reason, before moving on to the findings obtained as a result of the regression analysis, the descriptive statistics regarding the variables used in the model are given below.

Table 5. Descriptive statistics

Variable	*Mean*	*Standard Deviation*
RD	1.63	0.95
lnRD	0.23	0.85
GDP	26506.42	19694.84
lnGDP	9.76	1.05
GIIranking	34.28	25.78
G7	0.5	0.50

The regression coefficients obtained in the logistic regression analysis explain the size and direction of the relationship between the predictive variables and the response variable. The coefficients are the numbers in which the values of the terms in the regression model are multiplied. Regression coefficients are used to determine whether a change in a prediction variable (independent variable) makes the observed event more likely or less likely. The estimated regression coefficient for an independent variable shows the change in the link function as a result of each unit change that will occur in this independent variable, while all other independent variables are constant.

The relationship between coefficient and probability is determined by many dimensions of the analysis, such as reference values for categorical variables and reference event. Mostly positive coefficients make the predicted event more probable; on the contrary, negative coefficients make the event less likely. As the estimated regression coefficient approaches 0, it shows that the predictive power of the independent variable is small (Minitab, 2019).

In this part of the study, it is determined whether the independent variables in the research model have an effect on the dependent variable of GDP per capita. The expected values of the dependent variable are expressed as probabilities.

Table 6. Regression analysis results

InGDP	*Coefficient*	*Std.Error*	*T*	*P*	*t*	*95% Confidence Interval*
InRD	0.12	0.82	1.51	0.13	-0.38	0.29
GIIranking	-0.01	0.00	-3.00	0.00	-0.18	-0.00
G7	1.28	0.12	10.28	0.00	1.03	1.52
_cons	9.46	0.18	51.80	0.00	9.10	9.82

In this part, the findings obtained as a result of logistic regression analysis are reported and interpreted. Parameter estimates, standard deviations, z-score, p-value, odds ratio, and odds ratio (confidence interval) lower and upper limits for the regression model selection methods information is shown in Table 6. The equation of the model can be restated as in Equation 2.

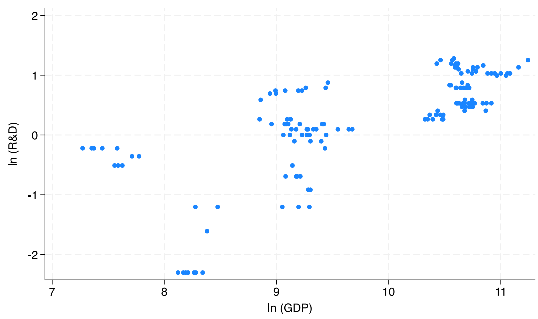
$$GDP_{it} = 9.461971 + .1241591\,RD_{it} - .0105565\,GIIranking_{it} + 1.276084\,G7 + e_{it} \quad (2)$$

The F statistic, which was used to evaluate whether the model was significant as a whole, was F (3, 136) = 230.43, and the F table value was F0.05(3, 136) = 2.60. Since F (3, 136) = 230.43 > F0.05(3, 136) = 2.60, the H0 hypothesis is rejected. In other words, all explanatory variables in the model can explain the dependent variable with a margin of error of 0.05.

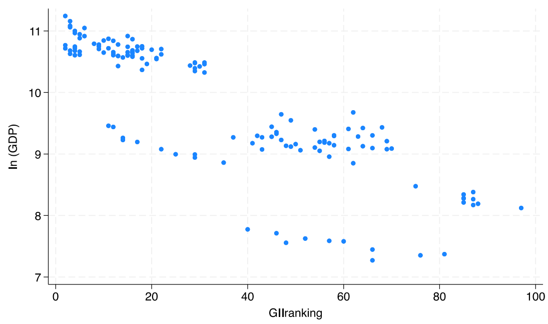
The probability value for the F statistic was found to be p = 0.0000. If this probability value is less than 0.05, the H_0 hypothesis that all coefficients in the model is equal to zero is rejected. Since 0.05 > p = 0.0000, the H_0 hypothesis is rejected. Again, we can say that all of the explanatory variables in the model can explain the dependent variable. It can be seen that R^2 is equal to 0.8356. This means that 83.56% of the model is explained by explanatory variables.

The constant term of the model is 9.461971. GDP per capita takes the value 9.461971 while all other explanatory variables are equal to zero. The coefficient of the lnrRD variable, which is one of the slope coefficients, was found to be 0.1241591. With all other explanatory variables constant, a 1% increase in R&D expenditure will result in an increase of 0.5243% on GDP per capita. At the same time, this coefficient gives the flexibility of GDP per capita relative to R&D expenditure (%GDP). The other slope coefficient, GIIranking, is -0.0105565. All other explanatory variables held constant, a 1% increase in the GII ranking will result in a 0.0105565% decrease in GDP per capita. This coefficient gives the elasticity of GDP per capita according to the global innovation index ranking.

The positive relationship between GDP per capita and R&D expenditure and the negative relationship between gdp per capita-GII ranking can be seen with the help of the graphs below.



GDP per capita – R&D Expenditure (%GDP)



GDP per capita – GII Ranking

Figure 1. GDP per capita- R&D expenditure (%GDP) & GII ranking correlation

7. CONCLUSION

Today, intense competition wars between companies and countries reveal that increasing productivity in production is a very important factor in gaining competitive advantage. Responsible, conscious, and innovative production methods have been preferred at every stage, especially after the rational and optimal use of limited natural resources in production was placed first on the agenda of countries. The possibility of using natural resources, which is decreasing gradually, directs the enterprises to newer and more technological production methods in production. For this reason, it is a common situation for businesses and countries to turn to innovation today. Innovation has become evident in every field with the existence of the understanding of sustainable development, which has become increasingly important in recent years.

Innovation covers the process rather than a result, and it can serve the purpose of creating a solution to a need that has not yet been resolved or to an unsolved problem. In addition, as a result of innovation's R&D efforts, a brand-new raw material, material, product, technology, or idea is at the stage of finding a solution to existing problems. It can also be revealed in the form of more effective use.

At this stage, the importance of R&D in terms of innovation is undoubtedly very great. R&D is an integral part of innovation and it is clear that the more importance is given to R&D, the more successful companies and countries will be in innovation. In this study, findings parallel to the opinions in the literature were obtained. Both innovation and R&D are of great importance in terms of ensuring the growth and sustainability of the national economies of the countries. R&D activities and efforts were measured by the ratio of R&D expenditures to GDP in the study, and it was ensured that each country's R&D expenditures could be expressed proportionally. According to this, while countries' R&D expenditures are transformed into economy as growth, it is seen that countries with higher GDP per capita allocate larger budgets to R&D expenditures and spend more R&D. On the other hand, in the GII, which provides the measurement of the innovation performance of the companies, it has been determined that the enterprises that make R&D expenditures are in higher ranks and close to the peak, and their GDP per capita is higher. In this study, which deals with the innovation performance of the G7 countries representing the developed countries and the E7 countries representing the developing countries, and the effect of this performance on the GDP per capita, it is seen that the G7 countries spend more on innovation. For this reason, E7 countries should increase the part they allocate from the national budget to innovation, especially R&D, like the G7 countries, in order to rise to the top in the innovation ranking. The findings of the study are in line with one of the most recent studies conducted by Dritsaki and Dritsaki (2023). Findings of the paper reveal that highly developed and innovative European countries are those with high rate of investment in R&D.

A number of limitations were encountered during the conduct of the study. First of all, the last 10 years were chosen as the time window, and this may cause different results in the innovation evaluations of countries over a longer period of time. In addition, there are many factors affecting the GDP volume, and the complex and comprehensive structure of GDP, consisting of many components, was not evaluated within the study. Ignoring some other factors that have the power to affect the economic growth of countries constitutes another limitation of the study. Within the scope of this study, a comparison was made between the current situations of 7 developing countries (E7) and 7 developed countries (G7) for the last 10 years. Although it is possible to reach a conclusion based on the findings obtained within the scope of the study, further research should be carried out to talk about an absolute result. This study, which was conducted in terms of studies with different scopes and covering different time periods, can be considered as a guiding pioneer study. Despite the fact that the paper focuses only on the GII rankings, which can be referred as a limitation of the study, our study contributes to the literature in terms of guiding other studies to be conducted in the literature. This study can be seen as an exemplary study specifically for G7 and E7 countries, and a more comprehensive research can be conducted in future studies by including more developed and developing countries within the study and extend the scope of the research. If the study is replicated over a longer period of time, it will be possible to obtain results that can be interpreted more broadly. Finally, it is recommended that different innovation rankings be used for further studies or country comparisons can be made on a sub-pillar basis. So, as to make a more general evaluation, the study needs to consider countries in a broader context.

Author Contributions

Gökçe Sinem Erbuğa: Literature Review, Conceptualization, Methodology, Data Curation, Analysis, Writing-original draft *Ayşegül Gürsoy*: Modelling, Writing-review and editing

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VERİMLİLİK DERGİSİ
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R&D and Innovation Activities in Leading Export-Based Industries in Türkiye: An Analysis for Future Insights

Melisa Özbiltekin-Pala[1], Yeşim Deniz Özkan-Özen[1]

ABSTRACT

Purpose: Research and Development (R&D) and innovation activities critically impact an organization's development and competitive advantage. Although all industries have R&D and innovation activities, sectoral applications vary depending on readiness, investment opportunities, and organizational strategies. This study focuses on the automotive, textile, and main metal industries, with the highest export rates in Türkiye. This study aims to analyze R&D and innovation activities for the selected industries and provide practitioners with future insights.

Methodology: Six different R&D and innovation indicators, i.e., current expenditure, personnel expenditures, trade investments, number of patent applications and number of R&D personnel, are considered for this study, and the GM (1,1) forecasting model is used to predict 2022-2030.

Findings: As a result, although an increase in R&D and innovation activities in the automotive industry is expected, especially for each indicator, these values are limited for textile and main metal. It is realized that especially these two industries need more support.

Originality: Within the scope of this study, future insights and suggestions are given under digitalization and technology adoption, encouraging postgraduate studies of employees and higher education - industry collaborations, adopting R&D and innovation as a part of corporate culture, extending R&D and innovation incentives, supporting SMEs in R&D and innovation activities according to sectoral comparisons.

Keywords: Research and Development, Innovation Management, Forecasting.

JEL Codes: M11, O32, C53.

Türkiye'nin İhracata Dayalı Öncü Endüstrilerinde Ar-Ge ve İnovasyon Faaliyetleri: Gelecek Görüşleri İçin Bir Analiz

ÖZET

Amaç: Araştırma ve Geliştirme (Ar-Ge) ve inovasyon faaliyetleri, organizasyonun gelişimi ve rekabet avantajı üzerinde kritik etkilere sahiptir. Tüm sektörlerin Ar-Ge ve inovasyon faaliyetleri olmasına rağmen, sektörel uygulamalar; hazırlık düzeyi, yatırım fırsatları ve organizasyonel stratejilere göre farklılık göstermektedir. Bu çalışma, Türkiye'nin en yüksek ihracat oranlarına sahip otomotiv, tekstil ve ana metal sektörlerine odaklanmaktadır. Bu çalışma, seçilen endüstriler için Ar-Ge ve yenilik faaliyetlerini analiz etmeyi ve uygulayıcılara geleceğe yönelik öngörüler sağlamayı amaçlamaktadır.

Yöntem: Bu çalışma için cari harcamalar, personel harcamaları, ticari yatırımlar, patent başvuru sayısı ve Ar-Ge personeli sayısı olmak üzere altı farklı Ar-Ge ve yenilik göstergesi dikkate alınmış ve 2022-2030 tahmininde GM (1, 1) tahmin modeli kullanılmıştır.

Bulgular: Sonuç olarak, özellikle her gösterge için otomotiv sanayinde Ar-Ge ve inovasyon faaliyetlerinde artış beklenmesine rağmen, tekstil ve ana metal için bu değerler sınırlıdır. Özellikle bu iki sektörün daha fazla desteğe ihtiyacı olduğu anlaşılmaktadır.

Özgünlük: Bu çalışma kapsamında, sektörel farklılıklar göz önüne alınarak dijitalleşme ve teknolojinin benimsenmesi, çalışanların lisansüstü eğitimlerinin ve yükseköğretim-sanayi işbirliklerinin teşvik edilmesi, Ar-Ge ve inovasyonun kurum kültürünün bir parçası olarak benimsenmesi, Ar-Ge ve inovasyon teşviklerinin yaygınlaştırılması, Ar-Ge ve yenilik faaliyetlerinde KOBİ'lerin desteklenmesi gibi başlıkları altında geleceğe yönelik öngörü ve öneriler verilerek sektörel açıdan katkı sağlamak amaçlanmaktadır.

Anahtar Kelimeler: Araştırma ve Geliştirme, İnovasyon Yönetimi, Tahminleme.

JEL Kodları: M11, O32, C53.

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1. INTRODUCTION

Research and Development (R&D) and innovation activities are vital in discovering new ideas, ensuring technological progress and productivity and gaining a competitive advantage globally (Ahmad and Zheng, 2023). Successful innovation practices increase profit and market share and reduce costs (Yanmaz Arpacı and Gülel, 2023). Businesses, universities, research institutions and governments invest heavily in R&D and innovation activities (Zhou and Wang, 2023). Many countries follow strategic plans to lead R&D and innovation activities and compete globally. These plans aim to encourage innovative ideas, support R&D activities, encourage scientific studies and commercialize new technologies (Yontar and Ersoy Duran, 2023). Innovation and R&D studies have an impact on many different industries (Cipek et al., 2023). For example, significant progress has been made in areas such as developing new products in the technology industry and discovering renewable energy sources in the energy industry. In addition, in recent years, there has been a significant focus on innovation and R&D studies in areas such as artificial intelligence, big data analytics, and the Internet of Things (Murrieta-Oquendo ve De la Vega, 2023). These technologies have transformed many industries and created new business opportunities.

The development of R&D and innovation activities in a country provides excellent benefits to that country (Temel et al., 2023). Similarly, R&D and innovation activities in Türkiye are essential for economic growth, competitiveness and sustainable development (Yontar and Ersoy Duran, 2023). To be competitive in the global economy, offering innovative products and services is necessary. R&D and innovation activities enable companies to develop products and services based on new technologies by increasing their competitiveness (Dhar et al., 2023). In addition, innovative products and technologies increase export potential (Dong et al., 2022). Thanks to R&D and innovation activities, Türkiye can become more competitive in exports by producing high-value-added products (Çalık, 2021). Besides R&D and innovation activities, it encourages technological development and increases the country's knowledge, which enables Türkiye to become a country with advanced technologies (Ahmad and Zheng, 2023).

In addition to being a country with a high export rate, when the last three reports of the Türkiye Exporters Assembly published until 2023 are examined, based on export rates, the leading industries are automotive, textile, main metal, chemicals, electricity and electronics. However, considering the increase in exports between years, the three industries with the highest rates are the automotive, textile and main metal (Türkiye Exporters Assembly, 2022, Türkiye Exporters Assembly, 2023). In these industries, carrying out R&D and innovation activities and planning the proper expenditures have become crucial. Being environmentally friendly, sustainable and circular in globalizing conditions in these leading industries has become a critical competitive advantage and productivity issue. Hence, it is necessary to make predictions situation of Türkiye in terms of R&D and innovation activities to make future-oriented approaches in these industries. Therefore, the following research question needs to be answered;

- What are future insights for R&D and innovation activities in leading export-based industries in Türkiye?

To answer the research question, firstly, based on Turkish Statistical Institute (TurkStat) data, industrial R&D and innovation indicators in Türkiye are chosen as the most affordable and most suitable inclusiveness. Then, the data set belonging to these indicators between 2018-2021 is determined and predicted until 2030 by the GM (1,1) forecasting model. Forecasting R&D and innovation activities in Türkiye's leading export-oriented industries is vital in strengthening the country's economic success. First, these activities enable companies to gain a competitive advantage in the international market. Innovative products and processes offer the ability to compete with other countries and quickly adapt to global demands.

Moreover, anticipating technological developments enables sectors to maintain their leading positions and adapt to changes in the world economy, which is a critical factor for long-term sustainable growth. Additionally, when environmental factors are becoming increasingly important, R&D and innovation support sustainability by focusing on developing environmentally friendly products and processes. This provides a strategic advantage in terms of adapting to the demands of consumers and the global market and fulfilling environmental responsibilities. As a result, forecasting R&D and innovation activities in Türkiye's leading export-oriented industries plays an important key role in economic growth, competitiveness, environmental sustainability and long-term success. Accurate forecasts made in this context contribute to the country's ability to effectively respond to future challenges and achieve a strong position in the international area. Therefore, this study aims to forecast industrial R&D and innovation indicators in Türkiye until 2030. By doing this, future insights for R&D and innovation activities in leading export-based industries in Türkiye are presented in this study.

The structure of this study as follows; firstly, R&D and innovation activities in Türkiye will be explained and industrial R&D and innovation indicators in Türkiye will be determined. Ten, materials and methods will be explained and results will be presented. In the following section, a theoretical background of R&D and innovation activities in Türkiye is explained in detail.

2. LITERATURE REVIEW

2.1. R&D and Innovation Activites in Türkiye

As an emerging economy, Türkiye's economy is based on exports, which are essential for the country's growth and development. Türkiye exports various products to many countries around the world. In recent years, Türkiye's export performance has been gradually increasing. Export is vital in the country's economy and constitutes a large part of the national income.

Among Türkiye's most important export items are automotive and sub-industry products, textile and ready-made clothing, chemicals, steel, electronics and agricultural products. The biggest markets for Türkiye's exports are generally the European Union countries, the Middle East, North America and Asian countries. Türkiye's most significant export partner countries include Germany, England, Italy, France and the United States. According to Turkish Statistical Institute data, in the January-December period of 2022, exports increased by 12.9% compared to the same period of the previous year. They reached 254 billion 172 million dollars, while imports increased by 34.0% and reached 363 billion 711 million dollars. In addition, since the increase in exports and R&D activities support each other, an increase is observed in the investments made in R&D in Türkiye to gain a competitive advantage and increase productivity.

Moreover, as R&D and innovation activities increase the demand for a highly qualified workforce, they support employment opportunities and human resources development in Türkiye (Belgin and Balkan, 2019). In addition, R&D and innovation activities contribute to developing environmentally friendly and sustainable solutions, which supports Türkiye's achievement of environmental sustainability and green economy goals (Costantiello and Leogrande, 2023). Considering these benefits, the contribution of R&D and innovation activities in Türkiye to the country's development is revealed again. R&D and innovation activities and a country's export status can be associated with each other (Jiyamuratov, 2023). The relationship between the export rate in Türkiye and R&D and innovation activities enables Türkiye to increase its export revenues by increasing its competitive power. Therefore, the Turkish government encourages R&D and innovation activities with policies such as R&D incentives and support programs and contributes to increased exports and productivity in operations. Consequently, it is essential to detail the leading industries for the country in terms of exports to examine the R&D and innovation activities in Türkiye.

As mentioned before, it has been determined that the most critical three industries are the automotive, textile and main metal industries based on their increase in export rates between years, respectively (Türkiye Exporters Assembly, 2023). The automotive industry is generally defined as an industry branch that manufactures road vehicles (passenger cars, buses, minibusses, tow trucks, trucks, tractors, etc.) and the parts used to produce these vehicles (Barazza, 2023). The automotive industry is considered the locomotive of the economy in all industrialized countries (Cipek et al., 2023). This is because it is very closely related to other branches of industry and other industries of the economy. Changes in this industry have a significant impact on the economy. The automotive industry's share in the total production of the manufacturing industry in Türkiye is above the average of the manufacturing industries (Yontar and Ersoy Duran, 2023). Although the export rate of the automotive industry has fluctuated between years, it has increased every year and reached 251 billion dollars in 2021 (Ministry of Industry and Technology, 2021a). In addition, the employment increase in the industry in 2021 is 73% (Ministry of Industry and Technology, 2021a).

Although the automotive industry has the highest export rate in Türkiye, it has become the export base of foreign automotive companies due to the world's leading automotive companies establishing facilities with Turkish partners (Ministry of Industry and Technology, 2021a). Since there has been great competition in the Turkish automotive industry in recent years due to the increase in R&D and the high investment requirement for the use of new technology, there has been an increase in power alliances through mergers between companies (Akçomak and Bürken, 2021). R&D and innovation activities in the industry have become even more critical in Türkiye than in the rest of the world, with the ability to meet the financial burden of excess capacity in the automotive industry, the competitive environment in the industry, the limited growth in the market, and the more selective customers (Alpkan and Gemici, 2023).

The textile industry has a wide range of production, also under the supply chain of the ready-to-wear industry in Türkiye. The textile industry ranks first in Türkiye regarding product quality and high technology (Kantur and Türkekul, 2023). In 2021, the textile industry's export was approximately 17 billion dollars and employs around 1 million people (Ministry of Industry and Technology, 2021b). In this industry, where the competition level is increasing daily, R&D and innovation activities also increase. In the textile industry, which is applicable in R&D and innovation activities, improvements and innovations made at each stage of production significantly contribute to the value chain of products and product groups (Kose and Atasever, 2023). Especially with digital and green transformation, developments and innovations in sustainable, ecological and technical textile products bring serious value to businesses (Xu et al., 2023).

Moreover, the main metal industry in Türkiye includes many sub-branches, especially iron-steel and aluminum industries (Ministry of Industry and Technology, 2021c). It provides primary inputs and raw materials to the main metal industry, machinery, automotive, electronics, chemistry, defense, aviation, mining and transportation industries throughout the country. In 2021, the industry that increased its exports the most in terms of value was the iron and steel industry, which is considered within the main metal industry with 52% (TurkStat, 2022). When the developments in recent years are examined, effects are seen in terms of R&D and innovation activities in this industry.

When the three industries with the highest export rates in Türkiye are examined, it is seen that there is a general increase in export rates, although there have been fluctuations over the years. In addition, the importance given to R&D care and innovation activities is increasing in all three industries with the competition conditions around the world, the increase in environmental awareness and the variability in customer demands. However, this increase has not yet reached a sufficient level throughout the country (Ministry of Industry and Technology, 2021a).

As mentioned before, for Türkiye, R&D and innovation activities have become more important. Therefore, it has become highly critical for the country to identify industrial R&D and innovation indicators in Türkiye and find solutions to improve them. Hence, in the following section, industrial R&D and innovation indicators in Türkiye are explained in detail.

2.2. Industrial R&D and Innovation Indicators in Türkiye

Industrial R&D and innovation indicators in Türkiye are the data used to evaluate the country's technological capacity and innovation performance. These indicators are of great importance in terms of economic growth, competitiveness and sustainable development of the country.

Previous studies mostly approached the subject by only considering R&D and innovation investments while making country-wised assessments, and most of these studies investigated the relationship between these investments and the economic growth of Türkiye (i.e., Demir and Geyik, 2014; Bozkurt, 2015; Sungur et al., 2016; Börü and Çelik, 2019).

For instance, Demir and Geyik (2014) considered R&D and innovation investments as patent applications and the number of patents and made a comparison between East Asian countries with Türkiye. In addition, Bozkurt (2015) investigated the long-term relationship between R&D and innovation expenditures and economic growth and concluded that there is a unidirectional causal relationship between them. Moreover, Sungur et al. (2016) analyzed the number of R&D researchers, R&D expenditures, patents and innovation activities on export and economic growth for Türkiye between 1990 to 2013, and they provide outcomes related to the relationship between these indicators. On the other hand, Börü and Çelik (2019) investigated the impacts of R&D and innovation investments on economic growth with a focus on the innovative investment movement in Türkiye.

Furthermore, in a recent study, Çubuk (2023) proposed an R&D and innovation map for Türkiye by using a hybrid methodology. In this study, 81 cities in Türkiye were evaluated according to their R&D and innovation performance by considering twelve different criteria. On the other hand, it is revealed that the current literature related to Türkiye lacks in providing sectoral analysis in terms of R&D and Innovation activities. From this point of view, this study specifically focuses on the automotive, textile, and main metal industries, which are leading industries based on export rates.

Different indicators are detected when examining the "R&D Investments" data set in the Turkish Statistical Institute's database. Among them, six indicators with high data availability and coverage are selected for analysis in this study. These indicators can be summarized as follows;

- *Current Expenditure:* Current expenditures refer to the direct costs of resources used for R&D and innovation projects, such as personnel salaries, materials, equipment, laboratory costs, consultancy services, travel expenses, and software licenses (Pelikánová, 2019).
- *Personnel Expenditure:* Personnel expenditures in R&D and innovation investments represent the costs for employees to carry out research and development activities of companies such as salaries, fringe benefits, insurance premiums, training and development expenses of researchers, engineers, scientists, technicians and other personnel working in the R&D and innovation department (Afriana and Khoirunurrofik, 2023).

- *Trade Investment:* Trade investments aim to use financial resources related to R&D and innovation projects, and these projects produce results that increase the company's revenues or reduce its costs (Belgin and Balkan, 2019). Transforming R&D and innovation investments into commercial investments provides introducing new products to the market, obtaining patents, commercial evaluation of technological innovations or gaining competitive advantage (Madaleno and Nogueira, 2023).
- *Foreign Investment:* Foreign investment refers to investments made by a foreign company or investor in a country's R&D activities (Cao et al., 2023).
- *Number of Patent Applications:* The number of patent applications in investments refers to the number of applications filed by companies to claim patent protection for new inventions or technological innovations (Aydin et al., 2023).
- *Number of R&D Personnel:* It refers to the number of R&D employees companies employ to conduct research and development activities (Çelik, 2020). R&D personnel include researchers, engineers, scientists, technicians and other experts.

Being aware of the indicators for the country and making sectoral analyses provide essential information for policymakers and decision-makers while simultaneously revealing the technological capacity of Türkiye, innovation capabilities and sectoral competitiveness. Evaluation of competitiveness is vital to identify the country's strengths and improve its weaknesses. In addition, these indicators enable the identification of potential business opportunities and investment areas.

Moreover, analyzing the indicators and predicting the future makes it easier to obtain information about Türkiye and its current situation in the world, as it will enable international comparisons. Therefore, it is critical to predict these indicators until 2030 so that future investments can be planned, the workforce can be designed, and priority areas can be identified in leading export-based industries in Türkiye. By comparing the previous studies, GM (1,1) methods are used for forecasting about environmental issues such as energy consumption (Khan et al., 2023), greenhouse gas emissions (Kazancoglu et al., 2021), solid waste generation (Pudcha et al., 2023), and also production and consumption topics (Wang et al., 2023), hydropower generation capacities (Zeng et al., 2023) etc. Therefore, this method is practical and appropriate to forecast R&D and innovation activities in Türkiye.

3. MATERIALS and METHOD

In this study, a 4-stage methodology is followed. According to the flowchart presented in Figure 1, firstly, R&D and innovation activities in Türkiye and industrial R&D and innovation indicators in Türkiye are examined to know the current situation of Türkiye. Then, based on defined indicators, the time series data between 2018-2021 are determined separately for the automotive, textile and main metal industries. These data are gathered from TIS and Turkish Patent and Trademark Office databases. According to these data sets, a total of 18 calculations are made using the GM (1,1) model to forecast these data until 2030 for each industry and each indicator separately. Lastly, it is aimed to present future insights for R&D and innovation activities in leading export-based industries in Türkiye.

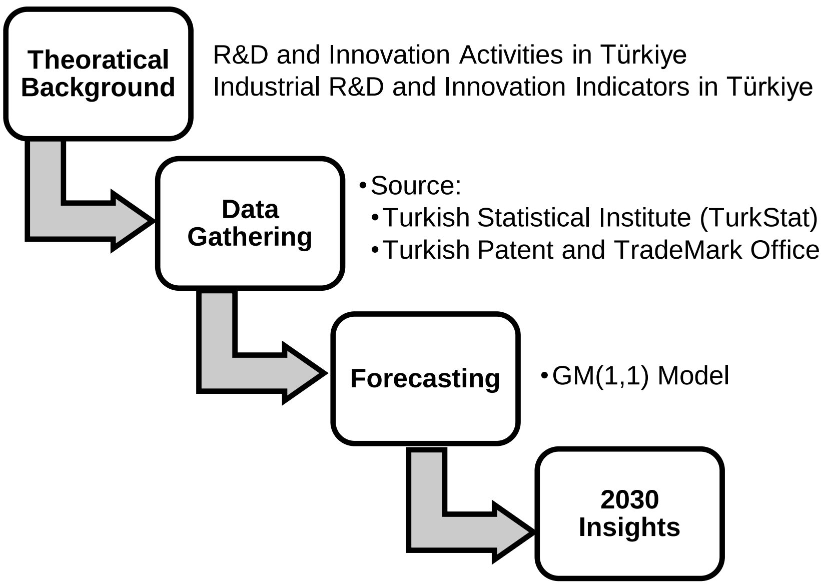


Figure 1. Flow chart of the research

In the following sections, each stage of the methodology is explained respectively. From this view, the next section presents the data set.

3.1. Data Set

As mentioned in the previous section, data related to R&D and innovation indicators were derived from the Turkish Statistical Institute (TurkStat) and the Turkish Patent and Trademark Office. Due to the nature of the methodology, data from the previous four years are required. Except for the number of patent applications, the recent data belongs to 2021; therefore, forecasting is made from 2022 to 2030.

The data set, presented in Table 1, includes data related to current expenditures (₺), personnel expenditures (₺), trade investments ($), number of patent applications and number of R&D personnel for textile, main metal and automotive industries. The last four years' data clearly shows that the automotive industry comes to the fore in the R&D and innovation activities.

Table 1. Data set

	Period			
Indicators/Industries	*2018*	*2019*	*2020*	*2021*
Current Expenditures (₺)				
Textile Industry	250,554,864	355,831,879	389,106,887	442,606,840
Main Metal Industry	153,621,198	186,489,935	265,859,690	374,558,864
Automotive Industry	2,215,673,056	2,823,580,559	3,552,349,701	5,464,924,027
Personnel Expenditures (₺)				
Textile Industry	148,289,387	203,182,656	237,410,401	259,386,926
Main Metal Industry	88,345,115	110,107,895	143,450,313	177,025,681
Automotive Industry	907,931,895	1,074,556,307	1,205,051,721	1,845,851,592
Trade Investments (₺)				
Textile Industry	268,343,068	348,948,876	396,342,855	449,211,019
Main Metal Industry	209,557,367	267,032,832	277,125,548	415,423,995
Automotive Industry	2,261,507,064	2,768,658,210	3,021,010,444	5,265,387,350
Foreign Investments ($)				
Textile Industry	839,999	149,089	2,121,224	1,168,239
Main Metal Industry	444,181	1,009,971	2,777,913	5,511,576
Automotive Industry	131,385,059	275,796,542	342,223,793	516,493,500
Number of Patent Applications				
Textile Industry	144	159	114	111
Main Metal Industry	342	363	357	337
Automotive Industry	950	1,048	882	1,009
Number of R&D Personnel				
Textile Industry	2,561	2,719	2,708	2,639
Main Metal Industry	1,200	1,407	1,440	1,398
Automotive Industry	8,328	8,641	9,034	10,085

The methodology used for forecasting R&D and innovation activities in textile, main metal and automotive industries is explained in detail in the following section.

3.2. GM (1,1) Model

The GM (1,1) model is a prediction model known as the Grey System Theory. This model analyses time series with limited data and predicts future trends. The GM (1,1) model reveals the hidden dynamics within the system and makes predictions. The basic principle of the GM (1,1) model is to use first-order differential equations and arithmetic mean data. This model works to separate the systematic and random components of the data series.

The GM (1,1) forecasting method, based on grey system theory, is notable for its simplicity and ability to deal with limited or irregular data sets. Especially effective when historical information is limited or uncertain, GM (1,1) requires less data and does not assume linearity compared to traditional techniques such as ARIMA or exponential smoothing (Khan and Osinska, 2023). Additionally, compared to more complex predictive tools such as machine learning models and neural networks, GM (1,1) is less complicated but valuable in situations where a basic model is sufficient (Wei et al., 2023). Machine learning models are effective at capturing complex relationships. Still, they may require larger data sets and complex parameter tuning and neural networks, on the other hand, are known for their capacity to recognize intricate patterns but require larger data and computational resources (Su and Huang, 2023). Fundamentally, the choice between GM (1,1) and other forecasting techniques focuses on the characteristics of the data and the complexity requirements of the prediction task encountered (Li et al., 2023). In the study, GM (1,1) model implementation was preferred as the method because the data was limited and required a more practical implementation.

The steps of the GM (1,1) model are as follows:

GM (1, 1) model includes actual data of series (x_1^0 , x_2^0..) and aims to predict future data as $x_3^0, \ldots, x_n^1$,. In this study, a total of 18 GM (1, 1) models are applied. According to the actual data set (x0), the Accumulating Generation Operation (AGO) is calculated. The formula is as shown in Equation 1.

$$x_k^1 = \sum_{i=1}^{k} x^0 i \quad (1)$$

After finding the AGO formula, x_1 series are expressed as Equation 2.

$$x_k^1 = x_1^1, x_2^1, \ldots, x_n^1 \quad (2)$$

Then, z_k^1 is calculated after finding x_k^1 series. The generated mean sequence z_k^1 of x_k^1 is expressed as in Equation 3.

$$z_k^1 = 0.5x_k^1 + 0.5\, x_{(k-1)}^1 \quad (3)$$

k = 1, 2,….., n

By using the formula, z_k^1 is obtained as in Equation 4.

$$z_k^1 = (z_1^1, z_2^1, \ldots . z_n^1) \quad (4)$$

Moreover, a and b parameters are found by using Equation 5 and 6. These parameters are used for the prediction of data.

3.3. Least Square Method

To use Equation 5, all values are substituted as in the Equation 6.

$$b = x_{(k)}^0 + az_k^1 \quad (5)$$

$$x_{(2)}^0 = az_2^1 + b$$

$$x_{(3)}^0 = az_3^1 + b$$

……………………

$$x_{(n)}^0 = az_n^1 + b \quad (6)$$

Equation 7 is used to find a and b values, which are x and z series, shown as "B" and "Y" in the matrix representation.

$$Y = \begin{matrix} x_2^0 \\ x_3^0 \\ x_n^0 \end{matrix} \qquad B = \begin{matrix} -z_2^1 & 1 \\ -z_3^1 & 1 \\ -z_n^1 & 1 \end{matrix} \quad (7)$$

Then, the matrix method is applied by using Equation 8.

$$\alpha = [a, b]^T = (B^T B)^{-1}(B^T . Y) \quad (8)$$

Furthermore, the Grey differential equation should be calculated to get the estimated value of the initial data at a time (k + 1) in Equation 9.

$$x_{(k+1)}^1 = \left[x_1^0 - \frac{b}{a}\right] e^{-ak} + \frac{b}{a} \quad (9)$$

After that, the Inverse Accumulating Generation Operation is calculated by using Equation 10.

$$x_{(k+1)}^0 = x_{(k+1)}^1 - x_k^1 \quad (10)$$

$k = 1,2,3, \ldots, n$

At the end of the implementation, the error rate is calculated by using Equation 11.

Prediction can be made when k <n. to find the error average of the model; equation 11 is used when $k = 1, 1+1, \ldots, n-1$. (Podrecca and Sartor, 2023).

x_k^0 = true (initial) value

$\hat{x}_k^0$ = predicted value of the dataset

$$e(k+1) = \left|\frac{x^0_{(k+1)} - \hat{x}^0_{(k+1)}}{x^0_{(k+1)}}\right| x\ 100\% \qquad (11)$$

The accuracy of the GM (1, 1) model is $p\circ$, as shown in Equation 12.

$$p\circ = (1 - \varepsilon) \times 100\% \qquad (12)$$

The general requirement is $p\circ$ > 80%.

The GM (1,1) model is considered a helpful prediction model when it has limited data. This model, which is practical in implementation and needs very little data, can also be evaluated by calculating the error rate and how close the model's predictions are to the actual data. In the following section, the implementation and results of this study are explained in detail.

4. IMPLEMENTATION AND RESULTS

Implementation of the study was conducted using the GM (1,1) for prediction values of current expenditure, personnel expenditures, trade investments, number of patent applications, number of R&D personnel and foreign investments for the textile, main metal and automotive industries between 2022 to 2030. These models are applied separately for each industry and indicator, in total 18 times, and equations were formulated by using Microsoft Excel.

As mentioned earlier, implementations have been made for the textile, main metal, and automotive industries. For the textile industry, the first prediction model was established based on data obtained from the TurkStat for the years 2018-2021 to forecast the “current expenditure situation” in the textile industry. The second prediction model, again for the textile industry, was built based on "personnel expenditure" data from the TurkStat for the years 2018-2021, and predictions were made for the years 2022-2030. The third prediction model for the textile industry was established based on "trade investment" data from the TurkStat for the years 2018-2021, and predictions were made for the years 2022-2030. The fourth prediction model for the textile industry was built based on the "number of patent applications" data from the Turkish Patent and Trademark Office for the years 2019-2022, and predictions were made for the years 2022-2030. The fifth prediction model for the textile industry was established based on the "number of R&D personnel" data from the TurkStat for the years 2018-2021, and predictions were made for the years 2022-2030. The sixth prediction model for the textile industry was built based on "foreign investment" data from the TurkStat for the years 2018-2021, and predictions were made for the years 2022-2030.

Similarly, similar calculations have been conducted for the main metal industry. For the main metal industry, the first prediction model was established based on data obtained from the TurkStat for the years 2018-2021 to forecast the “current expenditure” situation in the main metal industry. The second prediction model, for the main metal industry, was built based on "personnel expenditure" data from the TurkStat for the years 2018-2021, and predictions were made for the years 2022-2030. The third prediction model, for the main metal industry, was established based on "trade investment" data from the TurkStat for the years 2018-2021, and predictions were made for the years 2022-2030. The fourth prediction model, for the main metal industry, was built based on the "number of patent applications" data from the Turkish Patent and Trademark Office for the years 2019-2022, and predictions were made for the years 2022-2030. The fifth prediction model, for the main metal industry, was established based on the "number of R&D personnel" data from the TurkStat for the years 2018-2021, and predictions were made for the years 2022-2030. The sixth prediction model for the main metal industry was built based on "foreign investment" data from the TurkStat for the years 2018-2021, and predictions were made for the years 2022-2030.

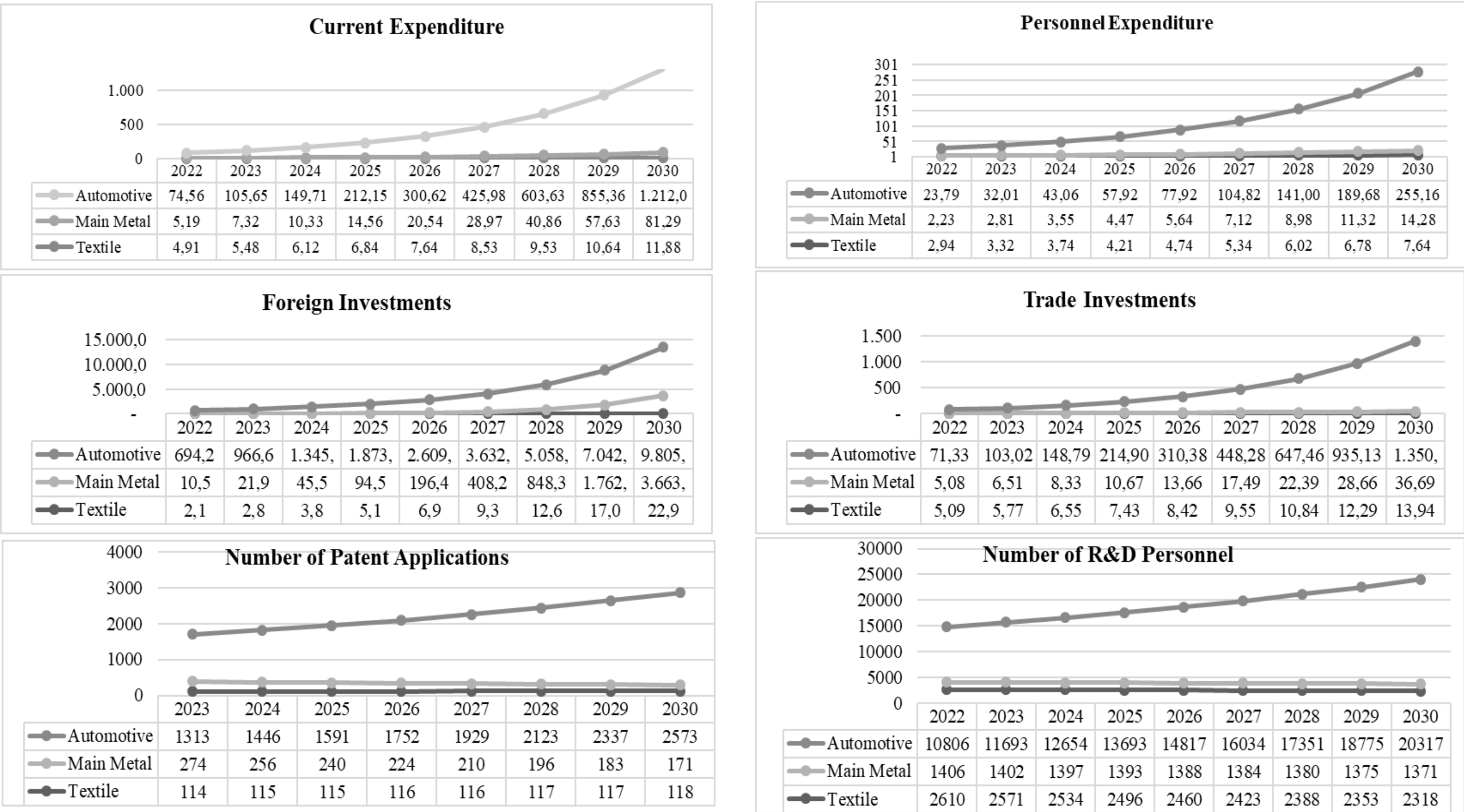
Finally, similar calculations have been applied to the automotive industry. For the automotive industry, the first prediction model was established based on data obtained from the TurkStat for the years 2018-2021 to forecast the “current expenditure” situation in the automotive industry. The second prediction model, for the automotive industry, was built based on "personnel expenditure" data from the TurkStat for the years 2018-2021, and predictions were made for the years 2022-2030. The third prediction model, for the automotive industry, was established based on "trade investment" data from the TurkStat for the years 2018-2021, and predictions were made for the years 2022-2030. The fourth prediction model, for the automotive industry, was built based on the "number of patent applications" data from the Turkish Patent and Trademark Office for the years 2019-2022, and predictions were made for the years 2022-2030. The fifth prediction model, for the automotive industry, was established based on the "number of R&D personnel" data from the TurkStat for the years 2018-2021, and predictions were made for the years 2022-2030. The sixth prediction model for the automotive industry was built based on "foreign investment" data from the TurkStat for 2018-2021, and predictions were made for 2022-2030.

Moreover, as mentioned before, calculating the error rate in a GM (1,1) model is an essential tool for understanding how well the model performs with real-world data, assessing the reliability of the model and conducting a statistical significance of parameters. These calculations are used to understand the model's effectiveness in practice and quantify the model's accuracy. For this reason, the error rate was calculated separately for each prediction made. A summary of the forecast results is presented in Table 2.

Table 2. Summary of the forecast results

Indicators	*Years*	*Textile Industry*	*Main Metal Industry*	*Automotive Industry*	*Indicators*	*Years*	*Textile Industry*	*Main Metal Industry*	*Automotive Industry*
Current Expenditure (Divided by 100M)	2022	4.91	5.19	74.56	Foreign Investments (Divided by 1M)	2022	2.1	10.5	694.2
	2023	5.48	7.32	105.65		2023	2.8	21.9	966.6
	2024	6.12	10.33	149.71		2024	3.8	45.5	1,345.8
	2025	6.84	14.56	212.15		2025	5.1	94.5	1,873.9
	2026	7.64	20.54	300.62		2026	6.9	196.4	2,609.1
	2027	8.53	28.97	425.98		2027	9.3	408.2	3,632.7
	2028	9.53	40.86	603.63		2028	12.6	848.3	5,058.0
	2029	10.64	57.63	855.36		2029	17.0	1,762.9	7,042.4
	2030	11.88	81.29	1,212.06		2030	22.9	3,663.6	9,805.5
Personnel Expenditure (Divided by 100M)	2022	2.94	2.23	23.79	Number of Patent Applications	2022	-	-	-
	2023	3.32	2.81	32.01		2023	114	274	1313
	2024	3.74	3.55	43.06		2024	115	256	1446
	2025	4.21	4.47	57.92		2025	115	240	1591
	2026	4.74	5.64	77.92		2026	116	224	1752
	2027	5.34	7.12	104.82		2027	116	210	1929
	2028	6.02	8.98	141.00		2028	117	196	2123
	2029	6.78	11.32	189.68		2029	117	183	2337
	2030	7.64	14.28	255.16		2030	118	171	2573
Trade Investments (Divided by 100M)	2022	5.09	5.08	71.33	Number of R&D Personnel	2022	2610	1406	10806
	2023	5.77	6.51	103.02		2023	2571	1402	11693
	2024	6.55	8.33	148.79		2024	2534	1397	12654
	2025	7.43	10.67	214.90		2025	2496	1393	13693
	2026	8.42	13.66	310.38		2026	2460	1388	14817
	2027	9.55	17.49	448.28		2027	2423	1384	16034
	2028	10.84	22.39	647.46		2028	2388	1380	17351
	2029	12.29	28.66	935.13		2029	2353	1375	18775
	2030	13.94	36.69	1,350.61		2030	2318	1371	20317

When these results are examined with an integrated perspective, it can be said that R&D and innovation activities in the automotive industry become prominent in every indicator, and forecast results show a continuous increase in the given time. On the other hand, although the textile and main metal industries are very different regarding market area and processing, their current condition and forecast results are similar for the selected indicators. In addition to this, based on error rates, it can be seen that all error rates of these calculations are under the error limit, which is 20%. That means this model gave results below the error rate required by the model for the implementation of the study. A graphical representation of the forecast results is presented in Figure 2.



Current Expenditure

	2022	2023	2024	2025	2026	2027	2028	2029	2030
Automotive	74,56	105,65	149,71	212,15	300,62	425,98	603,63	855,36	1.212,0
Main Metal	5,19	7,32	10,33	14,56	20,54	28,97	40,86	57,63	81,29
Textile	4,91	5,48	6,12	6,84	7,64	8,53	9,53	10,64	11,88

Personnel Expenditure

	2022	2023	2024	2025	2026	2027	2028	2029	2030
Automotive	23,79	32,01	43,06	57,92	77,92	104,82	141,00	189,68	255,16
Main Metal	2,23	2,81	3,55	4,47	5,64	7,12	8,98	11,32	14,28
Textile	2,94	3,32	3,74	4,21	4,74	5,34	6,02	6,78	7,64

Foreign Investments

	2022	2023	2024	2025	2026	2027	2028	2029	2030
Automotive	694,2	966,6	1.345,	1.873,	2.609,	3.632,	5.058,	7.042,	9.805,
Main Metal	10,5	21,9	45,5	94,5	196,4	408,2	848,3	1.762,	3.663,
Textile	2,1	2,8	3,8	5,1	6,9	9,3	12,6	17,0	22,9

Trade Investments

	2022	2023	2024	2025	2026	2027	2028	2029	2030
Automotive	71,33	103,02	148,79	214,90	310,38	448,28	647,46	935,13	1.350,
Main Metal	5,08	6,51	8,33	10,67	13,66	17,49	22,39	28,66	36,69
Textile	5,09	5,77	6,55	7,43	8,42	9,55	10,84	12,29	13,94

Number of Patent Applications

	2023	2024	2025	2026	2027	2028	2029	2030
Automotive	1313	1446	1591	1752	1929	2123	2337	2573
Main Metal	274	256	240	224	210	196	183	171
Textile	114	115	115	116	116	117	117	118

Number of R&D Personnel

	2022	2023	2024	2025	2026	2027	2028	2029	2030
Automotive	10806	11693	12654	13693	14817	16034	17351	18775	20317
Main Metal	1406	1402	1397	1393	1388	1384	1380	1375	1371
Textile	2610	2571	2534	2496	2460	2423	2388	2353	2318

Figure 2. Graphical representation of the forecast results

To start with the forecast results related to current expenditure, a significant difference is revealed between industries. While the automotive industry is expected to have a sharp increase in current expenditure related to R&D activities and reach around 121,200M ₺ in 2030, forecast results for main metal industry are revealed around 8100M ₺ and for textile only 1100M ₺. Furthermore, the main metal and textile industry is expected only slightly to increase for the given time.

Results related to personnel investments are similar to the current expenditure. The difference between industries is very high. While personnel expenditure is expected to be 25500M ₺ for the automotive industry in 2030, predictions for main metal and textile are only around 1100M ₺ and 600M ₺.

For trade investments and foreign investments, forecast results follow a similar pattern. For both indicators, the automotive industry comes forefront with approximate values of 135000M ₺ and 9805M $ in 2030. On the other hand, the difference between the main metal and textile industries is higher for these indicators. Significantly, foreign investments for the main metal industry are predicted as 3663M $; conversely, only 22M $ for the textile industry.

The number of patent applications is another critical R&D and innovation indicator that reflects the general approaches. An exciting outcome is revealed related to these indicators. Although a continuous increase is expected in the number of patent applications in the automotive industry, and it is predicted that applications will reach 2573 in 2030, a slight decreasing pattern is revealed for the main metal and textile industry.

Finally, forecast results related to the number of R&D personnel indicator show that future employment for the automotive industry is expected to increase to 20317 by 2030. On the other hand, main metal and textile have a slight decrease similar to the previous indicator. This result is because the number of patent applications and R&D personnel are interrelated indicators. When industries are compared for indicators, the textile industry precedes the main metal industry for only the number of R&D personnel.

Furthermore, cross-validation has been conducted to enhance the robustness of the analysis and evaluate the generalization ability of the GM (1,1) model. Cross-validation is a well-known data resampling method to forecast the true prediction error of models (Berrar, 2018). For the cross-validation of the GM (1,1) model, a forecast was made for 2018 to 2022 using the testing set as data between 2014 and 2017. For the given time, estimation has been conducted for current expenditures, personnel expenditures, trade investments, patent applications, and R&D personnel for the textile, main metal and automotive industries. Results of the forecasts are compared with the actual data between 2018 to 2022, the training set, and it is revealed that the GM (1,1) model is suitable method for the estimation of R&D and innovation indicators for the selected industries.

4.1. Analysing Performance of GM (1,1) Model Implementation

Performance analyses in forecasting methods include various factors when evaluating how effective a model is (Davis et al., 2019). First, performance analysis evaluates the model's ability to match real data. This is a critical way to determine how accurately the model makes predictions and how consistent it is with real-world data (Xie et al., 2023). In addition, performance analyses enable the comparison of different models and the determination of the strengths and weaknesses of each model (Xie et al., 2023). This makes it easy to choose the model that provides the best performance in the context of an application. There are other variants of the GM (1,1) model such as Fourier error corrections (EGM) or the Gray Verhulst model (GVM) (Anisah et al., 2023). Conducting a detailed performance analysis with different GM variants is critical for several important reasons. First, it helps determine how well each model fits certain data features and patterns (Zhang et al., 2023). By comparing their accuracy in predictions, it is possible to determine which variant best fits the unique features of the data set (Davis et al., 2019). Context fit is also a critical aspect; Understanding the strengths and weaknesses of each GM variant specific to its application context ensures whether the chosen model is suitable for a particular sector or industry. Additionally, comparative analysis provides the basis for informed decision making; This allows selecting a model that not only adapts to the available data set but also meets the specific requirements and objectives of the prediction task.

Deciding between the GM (1,1) model and alternatives depends on specific considerations tailored to prediction needs (Comert et al., 2021). The GM (1,1) model is known for its simplicity and effectiveness in scenarios with limited or irregular data. It is a practical choice when a clear understanding of the prediction process is essential (Nguyen et al., 2019). Conversely, models like EGM, incorporating Fourier error corrections, provide enhanced accuracy for datasets with pronounced cyclic patterns. The GVM introduces nonlinear growth modelling, offering flexibility for capturing more intricate data behaviours (Liu et al., 2023). Nevertheless, the GM (1,1) model excels in resource efficiency and a parsimonious approach, especially in cases with smaller datasets (Zhang et al., 2023). Its ability to provide reliable forecasts with minimal computational complexity makes it an appealing choice in contexts prioritizing simplicity, interpretability, and efficiency.

In addition to this, the importance of calculating the error rate in the GM (1,1) model is critical to conducting a statistical test to determine the statistical significance of the parameters of the GM (1,1) model. Error rates help to understand how accurate and reliable predictions the model makes (Wei et al., 2023). Error measures used when evaluating how compatible the model is with real data are essential tools that quantitatively measure the success of the model (Zhang et al., 2023). Error rates commonly used in the GM (1,1) model include metrics such as mean absolute error (MAE), mean square error (MSE), root mean square error (RMSE), mean absolute percentage error (MAPE) (Wei et al., 2023). These metrics evaluate the closeness of the model's predictions to the actual values from different perspectives. Calculating the error rate allows us to objectively assess the model's performance, developing a more robust understanding of the model's reliability and predictive ability (Li and Zhang, 2023). This is important for improving the model or comparing it with alternative models. In summary, calculating the error rate separately for each calculation as a result of the application proves the applicability of the method.

Performance analysis with other GM variants, particularly models such as the EGM or GVM, requires assessing the important factors driving model selection. In addition to the reasons for choosing the GM (1,1) model, there are several reasons that strengthen the logic behind this choice (Comert et al., 2021). Additionally, the fact that the GM (1,1) model has been used successfully in various fields in the past may support the reliability and applicability of the model behaviours (Liu et al., 2023). Computational efficiency can make GM (1,1) run faster than other more complex models, especially when working with large data sets or limited computational resources. Data fit determines how well the model can be fitted to specific characteristics in the data set; The GM (1,1) model may provide an advantage at this point thanks to its simplicity (Wei et al., 2023). Robustness and prediction accuracy should also be considered because these factors are important in determining how effective a model is under different conditions (Li and Zhang, 2023). In conclusion, opting for the GM (1,1) model may be a choice supported by both its simplicity and past success, but in all cases, the analysis, data set characteristics, and specific requirements must be considered.

However, in this study, a comparison was made between GM (1,1) and GVM for performance analysis to justify the applicability of GM (1,1) model. First of all, similar with GM (1,1) model implementation, GVM model is applied separately for each industry and indicator, in total 18 times, and equations were formulated by using Microsoft Excel. After that, error calculations are made. In this context, it is aimed to evaluate the prediction accuracy of both models by making error analysis according to the model results. Comparisons were made between simulated values and real values with MAPE, precision rate and relative error rate calculations. This is an important stage to understand how well the models fit the trends and variations in the data set. Therefore, the error comparison between the values, which are MAPE, Precision Rate and Relative Error Rates of the results of GM (1,1) and GVM models as shown in Table 3.

As shown in Table 3, in forecasting methods; if the MAPE is under 5, it means that highly accurate predictability. A 5-10 range is still good, but once you go beyond 20, it's like the model decided to take a scenic route through inaccuracies (Wei et al., 2023). Furthermore, the "Precision Rate (P)" serves to gauge how closely the forecasted values align with the actual ones (Li and Zhang, 2023). Moreover, when relative error rates and other metrics are considered, it is seen that GM (1,1) model is more suitable to implement for forecasting than GVM model. The following section includes suggestions and future insights for Türkiye by considering these forecast results.

Table 3. Comparison of performance metrics for GM (1,1) and GVM Models

		GM (1,1)	*GVM*	*GM (1,1)*	*GVM*	*GM (1,1)*	*GVM*
	Index	*Textile Industry*		*Main Metal Industry*		*Automotive Industry*	
Current Expenditure (Divided by 100M)	MAPE (%)	9%	24%	10%	20%	8%	30%
	Precision Rate (%)	91%	76%	90%	80%	92%	70%
	Relative Error Rate (%)	0.69%	9%	1%	50%	4%	60%
Personnel Expenditure (Divided by 100M)	MAPE (%)	6%	20%	7%	21%	6%	32%
	Precision Rate (%)	94%	80%	93%	79%	94%	68%
	Relative Error Rate (%)	0.36%	9%	0.88%	28%	1%	47%
Trade Investments (Divided by 100M)	MAPE (%)	10%	25%	11%	21%	9%	35%
	Precision Rate (%)	90%	75%	89%	79%	91%	65%
	Relative Error Rate (%)	0.12%	11%	6%	36%	8%	74%
Foreign Investments (Divided by 1M)	MAPE (%)	10%	45%	11%	22%	10%	18%
	Relative Error Rate (%)	90%	55%	89%	78%	90%	82%
	Error Rate (%)	13%	35%	9%	19%	4%	56%
Number of Patent Applications	MAPE (%)	4%	56%	2%	26%	3%	32%
	Precision Rate (%)	96%	44%	98%	74%	97%	68%
	Relative Error Rate (%)	1%	15%	0.32%	15%	1%	1%
Number of R&D Personnel	MAPE (%)	1%	19%	3%	11%	3%	26%
	Precision Rate (%)	99%	81%	97%	89%	97%	74%
	Relative Error Rate (%)	1%	9%	0.84%	7%	5%	9%

5. FUTURE INSIGHT for TÜRKİYE

As mentioned before, R&D and innovation activities are essential worldwide. In addition to providing countries and companies with a competitive advantage, innovative products and technologies create new job opportunities, increase employment, improve productivity, and support economic growth. Although R&D and innovation activities have become a critical issue in Türkiye, a developing country, sectoral differences have emerged. When the Automotive, textile and main metal industries are examined, it is seen that the values considered in terms of R&D and innovation activities differ. According to the forecasted results, the automotive industry in Türkiye emerges as an industry where R&D and innovation activities are given more importance in every parameter. Some future suggestions and insights are presented to expand R&D and innovation activities in the industry and throughout the country of Türkiye as in line with the established model and addressed forecast problem (Figure. 3).

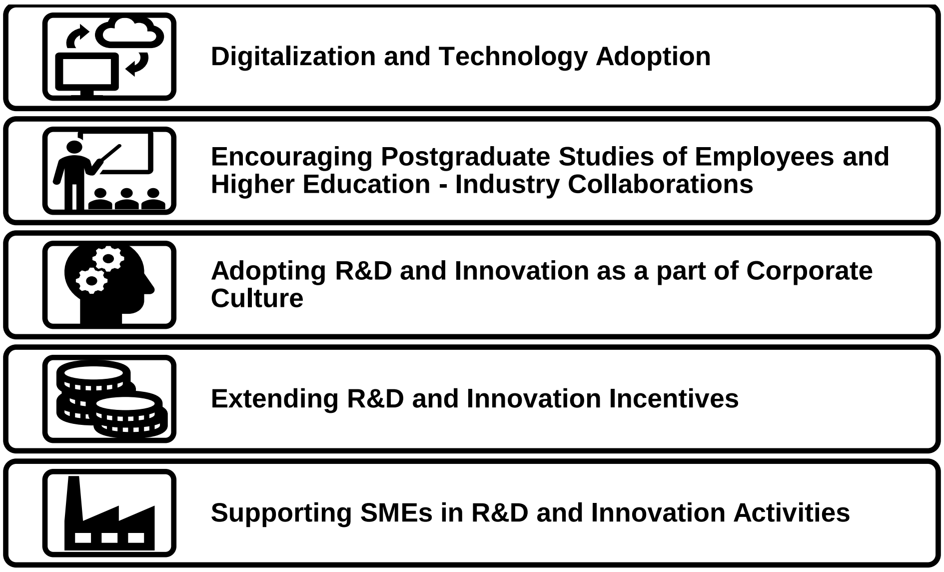


Figure 3. Suggestions and Future Insights for Türkiye

Digitization and adaptation to technology have become a priority worldwide. Digitalization must become the center for both factory-level and innovation activities. Therefore, expanding R&D investments in these areas is of great importance. In particular, R&D investments play a significant role in the digital transformation process of companies. By digitizing their business processes, companies can increase efficiency, improve the customer experience, and create new revenue models. It is essential to focus on R&D activities in digital technologies, cloud computing, big data analytics, artificial intelligence, and the Internet of Things. In addition, to remain competitive in the rapidly changing technological environment, companies must follow new technologies and adapt to these technologies. R&D investments should be used to monitor technology trends, provide early adaptation to new technologies and gain technology-oriented competitive advantages. In Türkiye, the Authority of Information and Communication Technology (BTK) presented the digital transformation targets for 2023 as increasing the number of SMEs that use cloud platforms, increasing the number of competence and digital transformation centers, and increasing the number of digitalization projects to develop new products and services (BTK, 2022). As it can be understood from these targets, digitalization and innovation activities are integrated into Türkiye while defining strategic goals.

Furthermore, numerical results showed that the automotive industry has the highest R&D investments among the industries covered. Due to its structure, this industry is very prone to digitalization and technology adaptation. Still, the low R&D investments in the main metal industry are due to the limited possibility of digitalization. The textile industry offers significant opportunities in digitalization and automation and has sufficient infrastructure. However, the textile industry is generally concentrated in developing countries based on cheap labor. In this case, the problem of not giving crucial importance and resources to R&D arises. As can be seen from the results, the reason for not experiencing high increases in R&D investments is cheap labor in the press.

As can be seen from the results, the automotive industry is superior in terms of all parameters. Especially in the projections made until 2030, a decrease is expected in the number of patent applications and personnel expenditures in the textile and main metal industries. The textile industry is affected by changing consumer preferences and increasing demand for more sustainable and innovative materials. In addition, the main metal industry is subject to fluctuations, often due to the demands of the construction, automotive and other manufacturing industries. The decrease in patent applications and personnel expenditures may be due to the reduction in the demand in the industry in a certain period or the decline in investments made in innovation activities. Therefore, a decrease is expected in new patent applications and expenditures on R&D activities. Postgraduate studies of employees need to be encouraged, mainly to prevent the reduction of patent applications and R&D personnel. In line with this, according to Türkiye Informatics Association's digital transformation index report of 2022, changes in curriculums of university education according to sectoral needs, increasing digital and innovative capabilities through higher education, and better integration between industries and educational institutions are essential to increase the performance of R&D and innovation activities (TÜBİSAD, 2022).

Furthermore, companies can enable their employees to develop their R&D skills by providing graduate education opportunities and supporting them with in-house training programs and may provide scholarships or financial aid. This helps employees achieve higher levels of education while reducing training costs. In addition, companies can provide flexible working arrangements such as flexible working hours or remote working so that employees can carry out their graduate studies. This helps employees to balance work life and education. With postgraduate training to motivate employees in this regard, it can be made a priority for employees to be promoted to higher positions or assigned to more strategic tasks.

Making R&D and innovation a part of corporate culture is vital for companies to achieve sustainable success. However, innovation culture in Türkiye is seen as very low according to TÜSİAD's High Technology Action Plan, published in 2023, and the reason behind that is presented as not being able to transform the digitally supported innovation knowledge into a skilled workforce (TÜSİAD, 2023). From this point of view, the corporate culture of R&D and innovation should be planned at different levels in terms of factory level. For example, the process of changing the corporate culture and adopting R&D and innovation should start with the commitment of the top management. Top management should set R&D and innovation as a strategic priority, direct resources toward this and inspire employees. In addition, effective communication and information sharing are essential for developing an R&D and innovation culture within the organization. It is necessary to share innovative ideas and encourage the flow of information within the company. Communication channels and platforms should provide an environment where employees can easily share their thoughts and experiences. In addition, a supportive infrastructure and adequate resources must be provided for adopting R&D and innovation. This includes technological infrastructure, budget, training programs, laboratories, and prototype production. Employees must be able to turn their innovative ideas into reality by accessing the necessary tools and resources.

Especially for the textile and main metal industries, R&D and innovation incentives should be created to increase current and personnel expenditures and provide indicators such as increasing patent applications. Supporting these industries in R&D and innovation activities is extremely important in delivering competitive advantage. Although these industries have high export rates and are suitable for technology infrastructure, their development becomes difficult if adequate support is not provided. The automotive industry is where technological innovations occur rapidly, and competition is intense. Therefore, as mentioned before, automotive companies must focus on R&D and innovation activities and develop innovative solutions.

When the numerical results of the study are examined, it is revealed that there is a lot of work in the automotive industry, but a need to develop them in terms of incentives.

Supporting SMEs in R&D and innovation activities is essential for increasing competitiveness, revealing innovation potential and sustainable growth. For this purpose, various support programs and policies for SMEs are implemented in many countries and regions. In Türkiye, the TUBITAK SME R&D start-up support program can be shown as an example, where SMEs are encouraged to be more competitive by improving their innovation capabilities (TÜBİTAK, 2023). However, these supports should be extended in terms of reaching more organizations and should be created as financial support, tax incentives, consultancy, cooperation, patent and utility model support. Financial support can be applied through state institutions, development agencies, and European Union funds. In addition, incentives such as tax deductions, tax exemptions or tax credits should be offered for R&D expenditures. To increase R&D and innovation activities at the SME scale, training on technical information transfer, patent application process, market research, and business plan creation should be established. Cooperation with universities, research centers, other SMEs or large-scale companies should be established.

6. CONCLUSIONS

R&D and innovation activities have recently become an issue that has affected countries' future. This issue needs to be addressed more, especially in emerging economies. Therefore, in this study, in terms of exports, three crucial industries, automotive, textile and main metal, were determined for Türkiye to examine the R&D and innovation activities in Türkiye. To analyze their R&D and innovation activities for Türkiye, or these industries, different indicators are determined by considering "R&D Investments" in the Turkish Statistical Institute's database. A total of six indicators, which are current expenditure, personnel expenditure, trade investment, foreign investment, number of patent applications and number of R&D personnel, are selected to analyze this study. To have a future-oriented idea based on the industry, each indicator for each industry has been forecasted until 2030 by using the GM (1,1) model. As a result, although an increase in R&D and innovation activities in the automotive industry is expected, especially for each indicator, these values are limited for textile and main metal. It is realized that especially these two industries need more support. Within the framework of these results, five main suggestions for the future are given as Digitalization and Technology Adoption, Encouraging Postgraduate Studies of Employees and Higher Education - Industry Collaborations, Adopting R&D and Innovation as a part of Corporate Culture, Extending R&D and Innovation Incentives, Supporting SMEs in R&D and Innovation Activities. For future research, comparison industries and indicators can be increased.

By comparing similar studies in the literature, it can be seen that Although no study on this subject has been found in terms of Türkiye, Ralphs and Mustapha (2023) discussed R&D innovation indicators in terms of South Africa. Similar with our study, they analysed the number of R&D personnel and R&D expenditures in their indicators. Moreover, Bate et al. (2023) focused on measures of innovation such as patent applications, human capital as in our study. Furthermore, for Türkiye's side, Çubuk focused on R&D and innovation capabilities for provisions of Türkiye contrast with our study. To sum up, different studies were examined in general and specific to this study, important indicators were determined and it was aimed to obtain a meaningful and guiding result for Türkiye. Furthermore, as previously mentioned, the GM (1,1) model has several variants, such as EGM or GVM. Therefore, these methods can be implemented if more datasets can be obtained. As a limitation of this study, collecting data on a country basis and being unable to find the appropriate data from the databases has forced the study.

Author Contributions
Melisa Özbiltekin-Pala: Literature Review, Conceptualization, Data Curation, Writing-original draft *Yeşim Deniz Özkan-Özen*: Conceptualization, Methodology, Analysis, Modelling, Writing-review and editing

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It was declared by the authors that the tools and methods used in the study do not require the permission of the Ethics Committee.

Ethical Statement

It was declared by the authors that scientific and ethical principles have been followed in this study and all the sources used have been properly cited.

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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

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

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

$$u_r, v_i \geq 0, \ \forall r, i \quad (3)$$

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.

$$e_j = Max \sum_r u_r y_{rj} \quad (4)$$

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

$$\sum_i v_i x_{ij} = 1, \ \forall j \quad (6)$$

$$u_r, v_i \geq 0, \ \forall r, i \quad (7)$$

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.

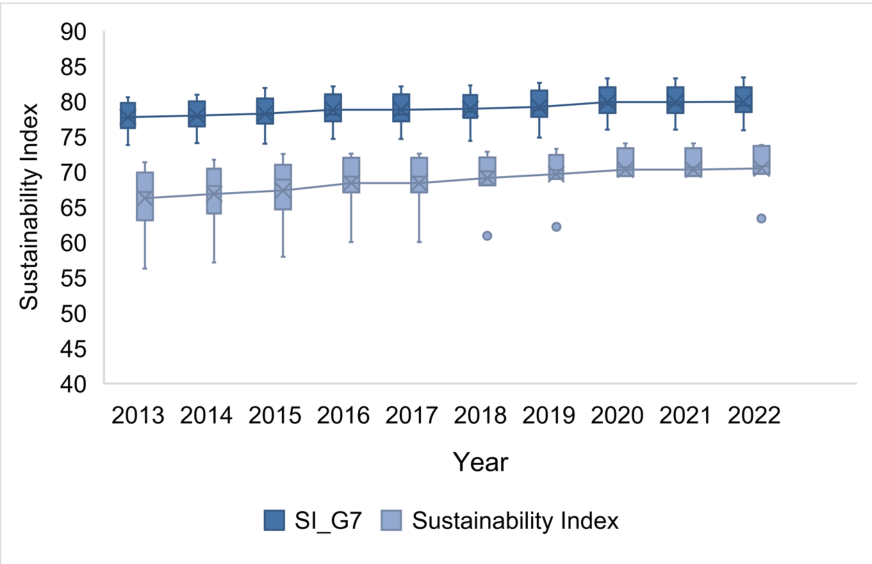

Figure 1. Sustainability index of G7 and E7 countries over years

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.

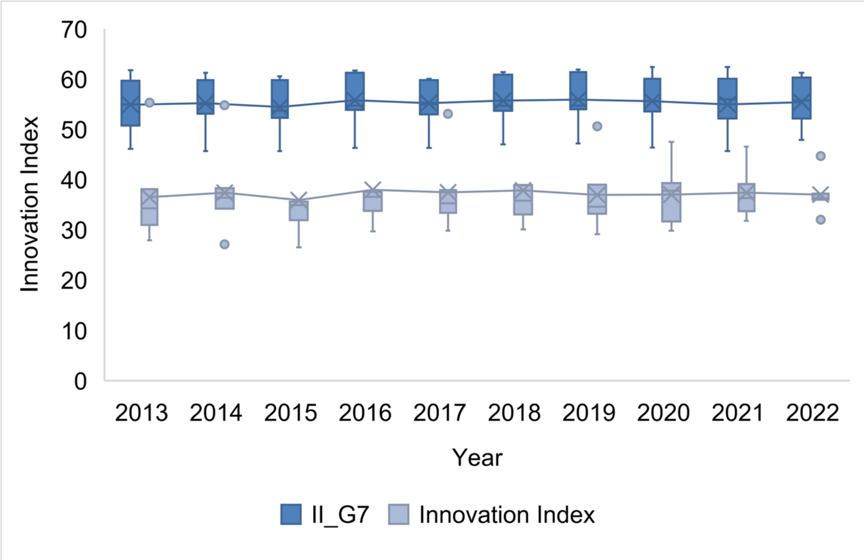

Figure 2. Innovation Index of G7 and E7 countries over years

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.

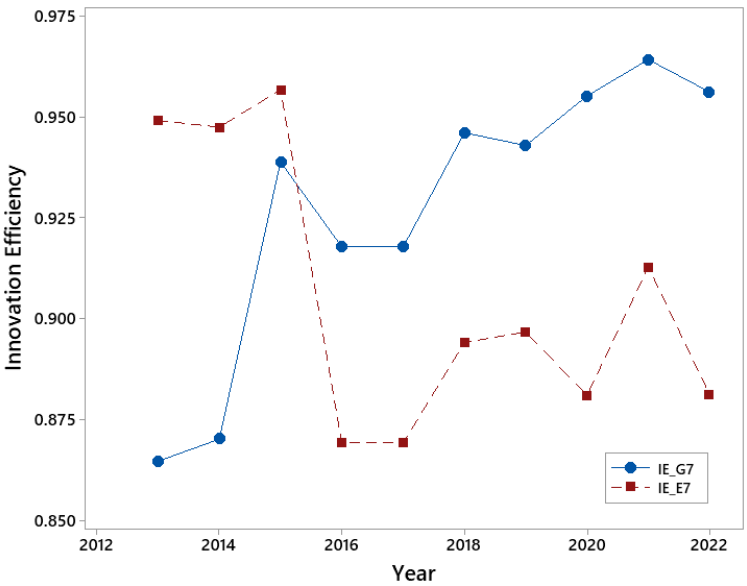

Figure 3. Mean of innovation efficiency over years

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.

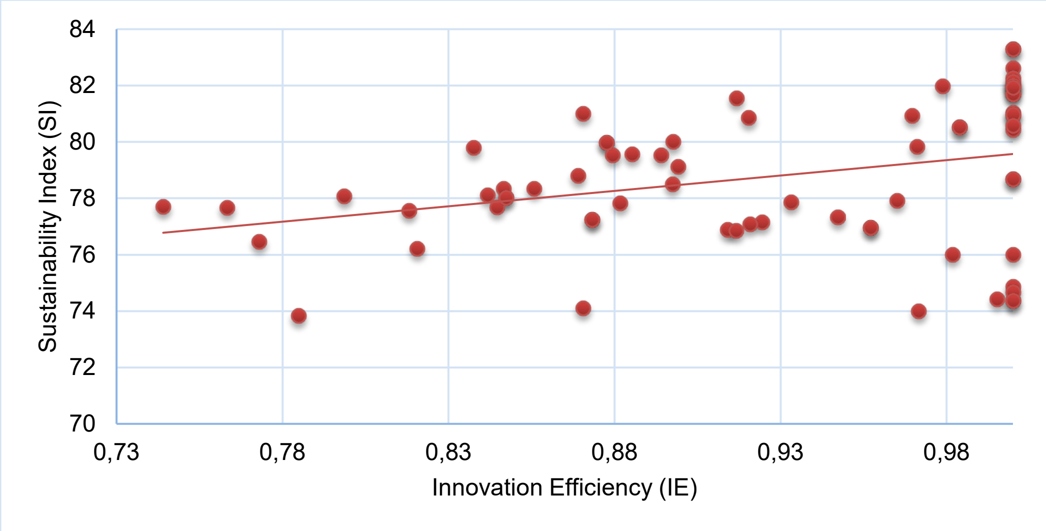

Figure 4. Scatter plot of SI vs II for G7 countries (2013-2022)

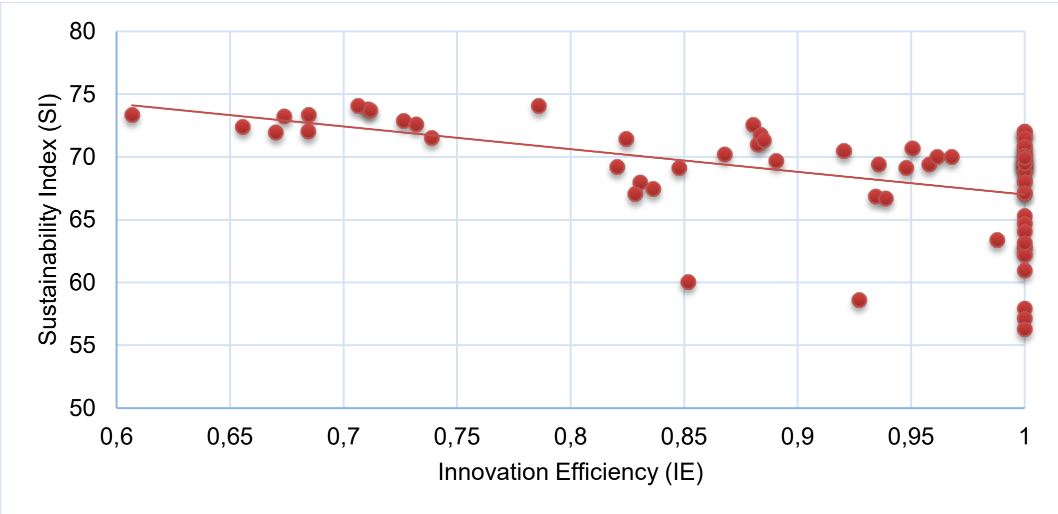

Figure 5. Scatter plot of SI vs II for E7 countries (2013-2022)

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.

Conflict of Interest

No potential conflict of interest was declared by the author.

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Any specific grant has not been received from funding agencies in the public, commercial, or not-for-profit sectors.

Compliance with Ethical Standards

It was declared by the author that the tools and methods used in the study do not require the permission of the Ethics Committee.

Ethical Statement

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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VERİMLİLİK DERGİSİ
JOURNAL OF PRODUCTIVITY

Evaluation of Factors Affecting Innovation Productivity by Pythagorean Fuzzy AHP Method

Miraç Tuba Çelik[1], Aytaç Yıldız[1]

ABSTRACT
Purpose: In this study, it is aimed to rank the factors affecting the innovation productivity of enterprises.
Methodology: The Pythagorean Fuzzy Analytical Hierarchy Process (AHP) method, which gives successful results in modelling uncertainty and uses Pythagorean fuzzy sets, is used to rank the factors affecting innovation productivity according to their importance.
Findings: In the application part of study firstly, the factors affecting the innovation productivity were determined and as a result of expert evaluations, the steps of the method were applied and the factors were ranked according to their importance. Finally, the most important factors were determined by performing a sensitivity analysis. When the results obtained from the study are examined, it has been determined that the factor of preparing the technology roadmap affects the innovation productivity the most, while the sector and market structure affect the innovation productivity the least among the determined factors.
Originality: It is the first study in the literature in which the factors affecting innovation productivity are determined and ranked according to their importance.
Keywords: Innovation, Productivity, Innovation Productivity, Pythagorean Fuzzy AHP.
JEL Codes: D24, D81, O32, O47.

İnovasyon Üretkenliğine Etki Eden Faktörlerin Pisagor Bulanık AHP Yöntemi İle Değerlendirilmesi

ÖZET
Amaç: Bu çalışmada, işletmelerin inovasyon verimliliğini etkileyen faktörlerin sıralanması amaçlanmaktadır.
Yöntem: Belirsizliğin modellenmesinde başarılı sonuçlar veren ve Pisagor bulanık kümelerini kullanan Pisagor Bulanık Analitik Hiyerarşi Süreci (AHP) yöntemi yenilik üretkenliğini etkileyen faktörlerin önem derecelerine göre sıralanmasında kullanılmıştır.
Bulgular: Çalışmanın uygulama kısmında öncelikle inovasyon verimliliğini etkileyen faktörler belirlenmiş ve uzman değerlendirmeleri sonucunda yöntemin adımları uygulanmış ve faktörler önem sırasına göre sıralanmıştır. Son olarak duyarlılık analizi yapılarak en önemli faktörler belirlenmiştir. Çalışmadan elde edilen sonuçlar incelendiğinde, belirlenen faktörler arasında inovasyon verimliliğini en çok teknoloji yol haritası hazırlama faktörünün etkilediği, en az ise sektör ve pazar yapısının inovasyon verimliliğini etkilediği tespit edilmiştir.
***Özgünlük*:** İnovasyon üretkenliğine etki eden faktörlerin belirlendiği ve önem derecesine göre sıralandığı literatürdeki ilk çalışma özelliği göstermektedir.
Anahtar Kelimeler: İnovasyon, Verimlilik, İnovasyon Verimliliği, Pisagor Bulanık AHP.
***JEL Kodları*:** D24, D81, O32, O47.

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1. INTRODUCTION

Due to the high competition experienced today, companies want to make a difference in the fierce competition environment by gaining new customers and increasing their market share. The best way to do this is to generate innovative ideas (Sivam et al., 2019). In this context, the concept of innovation emerges. According to the definition in the Oslo Manual published jointly by the European Commission and the OECD, innovation is “a new or significantly improved product (good or service), or process, a new marketing method or a new approach in business practices, workplace organization or external relations. It is defined as the realization of the organizational method” (Oslo Manual, 2005: 46). Innovation is also expressed as a complex system embedded in complex systems (Tainter, 1988). Innovation is often confused with the concepts of R&D and invention. However, invention and R&D can only be considered as an element of innovation. R&D can be defined as creating new approaches through scientific and applied research. The fact that R&D studies take place in most steps of innovation activities shows how important R&D contributes to innovation (Mairesse and Mohnen, 2004; Tiwari, 2007). Innovation is the general name of the transformation of all kinds of transactions into benefits and returns in order to meet the expectations and demands in the production of services and products in the maximum way. In short, anything that benefits and brings success is innovation (Çetin, 2019: 61). Innovation emerges as innovations that benefit companies by playing a key role in achieving long-term plans that companies make in order to gain an advantage over their competitors, and increasing the satisfaction of their customers and employees (Akgemci et al., 2005). Today, since the growth and profitability of businesses depends on innovation, companies need to ensure continuity of innovation to a large extent (Gupta, 2007: 2).

Innovation is an important factor both in the development of the country's economy and in bringing the country to a better position. For this reason, underdeveloped and developing countries should develop their innovation capabilities by creating global policies (Çetin, 2019: 74). However, innovation can be affected by external variables such as the technical capacity of the enterprise, capital infrastructure, and research infrastructure. This shows that innovation deals with applied and fundamental innovation together (Rao et al., 2001: 7).

Innovation is a process that increases the efficiency of an enterprise and develops as a result of important studies in the struggle for survival and long-term profitability. In this respect, innovation has a great importance in the growth of enterprises. If businesses that can effectively carry out the innovation process can achieve commercialization, they can quickly identify and analyse the possibilities in innovation processes, develop innovations in the best way and offer strategic solutions with high efficiency (Aktaş, 2018: 29).

In this study, it is aimed to rank the factors affecting the innovation productivity of enterprises according to the degree of importance. Thus, it is aimed to raise awareness about which factors should be prioritized if businesses want to increase their innovation productivity. In the second part of the study, the relationship between innovation and productivity is explained and the factors affecting innovation productivity are stated, the method used in the study is mentioned in the third part, the findings obtained from the study are included in the fourth part, and the results and evaluation are made in the last part.

2. INNOVATION AND PRODUCTIVITY

Only with sustainable growth can developing countries become more competitive globally and achieve the same level of prosperity as wealthy countries. This growth is made possible by increasing productivity (Doğan, 2017: 1). The concept of productivity is defined in different ways in the literature. The term productivity was coined by Quesnay in the Journal de l'Agriculture over two centuries ago (Asan, 2006: 28). Starr (1978: 43) defines it as the relationship between the amount of goods or services produced and the amount of resources used in the production of goods and services; Mendel (1983) defined productivity as the ratio of outputs to the resources used in the product in general, productivity is a term used to describe the measure of how well inputs are used to create meaningful outputs. The productivity approach and the measurement of productivity are two key concepts for the concept of productivity. The productivity approach is one way of looking at productivity. The productivity measure is the actual count of input and output (Asan, 2006: 28).

The biggest difficulty in measuring productivity is that the inputs and outputs are very diverse and cannot be gathered under a single common measure because of this diversity. To overcome this great difficulty in measuring inputs, the partial productivity measure is used. This measure computes the ratio of the output quantity corresponding to one unit of an input. For example, there are problems when collecting different labor-hour inputs under a single unit, since there is not a single feature when calculating the labor input (Top, 2002). When measuring productivity, no single measurement technique is used. As institutions and sectors change, the measurement technique is determined according to the target of the study and the characteristics of the organization. Productivity measures are used to monitor the performance of businesses over time, to evaluate the performance of an industry or the productivity of a country (Asan, 2006: 33).

It is seen that economic competitiveness increases in societies with a high standard of living, and innovation productivity increases with this increasing competitiveness. Innovation is the key to increasing productivity in countries (Elçi, 2007: 32). It is seen that economic competitiveness increases in societies with a high standard of living, and productivity in production also increases with this increasing competitiveness. Innovation, which is an important key to increasing productivity in countries, is considered as the main element of competitiveness spread over a wide area as organizational structures, processes, products and services in a business. Entrepreneur uses technology as a competitive tool through innovation, and technological competition also manifests itself as the driving force of growth. Innovation is considered as one of the basic elements of growth strategies in order to enter new markets, increase the existing market share and provide a competitive advantage to the business. Therefore, innovation is an indispensable element of corporate strategies for various purposes such as implementing more efficient production processes and performing better. Innovation serves as a strategic guide for businesses as they try to achieve a sustainable competitive advantage to overcome the problems they face (Fagerberg, 2003: 16).

In addition to increasing productivity, innovation is the key factor in increasing production volume, employment and quality of life. As countries invest in innovation, products and services obtained from scarce resources turn into added value and provide social benefits (Elçi, 2007: 48).

It can be said that innovation increases productivity performance and leads to higher income per employee. Different types of innovation, such as product, process, organizational and marketing, can contribute to improving productivity performance. Product innovations can lead to revenue increases with the introduction of new and improved products. Process innovations can reduce costs and increase productivity by increasing the efficiency of production processes. Organizational innovations can make business processes more effective through the improvement of ways and structures of doing business. Marketing innovations, on the other hand, can increase revenues by improving the marketing strategies of products and services (Hall, 2011: 7).

In the literature, the link between innovation and productivity is specifically explored. The bond between the two is as complex as it is strong and clear (Rao et al., 2001: 7). In the relationship between innovation and productivity, economic conditions such as the size of the financial structure, financing risk and demand are taken into account. In the researches, it has been concluded that economic conditions affect innovation and productivity. Innovation productivity affects the business decisions, investment decisions, strategic plans of enterprises, and the supply and demand in the market in which they operate, thus also affecting the competitiveness of enterprises. It is known that increasing innovation productivity increases national competitiveness. Since every place is a market for every business in today's global competition, innovation productivity plays a determining role in the overall performance of companies (Ciocanel and Pavelescu, 2015).

Harris' (1999) review of the literature highlights three key productivity factors in an overarching framework where innovation generates development prospects: investment in machinery and equipment, human capital, and trade openness for an investment. Hall (2011: 16) argues that the effort for innovation will turn into productivity gains in favor of companies, and thus, companies will improve and their productivity will increase, and thus, production costs will decrease due to increased demand. Innovation has a long-term and lasting impact on productivity. This suggests innovation as a “growth engine” (Rao et al., 2001: 7). Academics, industry representatives and policy makers are paying close attention to innovation and productivity development as they are considered to be particularly important factors in economic growth. These people work hard to create policies that will promote innovation performance and productivity (Saunila et al., 2020). Innovation and R&D are an important driving force in the development of countries and in ensuring economic growth (Bourgeois and Leblanc, 2002: 46). It is important to include these factors in the production processes so that R&D investments and knowledge sharing can contribute to innovation and productivity. R&D investments facilitate knowledge exchange and affect labor productivity, both directly and indirectly, by collaborating with external partners and investing in the knowledge of other firms in the industry. Additionally, the potential impact of R&D investments on innovation is also important. The complementarity between R&D capital and knowledge spillover explains the potential to increase labor productivity. These factors can also encourage different innovation channels and strategies by increasing the possibilities and quality of inter-firm and sectoral cooperation. As a result, various innovation approaches and strategies may emerge, such as the co-development of new products with external partners (Audretsch and Belitski, 2020).

Thanks to R&D studies, new technologies are developed, the market share, profitability and growth power of the enterprises increase according to their current level and thus contribute to the increase in productivity

(Bourgeois and Leblanc, 2002: 42). In short, besides the innovation activities, R&D studies are also important in increasing both economic growth and productivity. Another important indicator for innovation performance is patents. Because the number of patents shows both the R&D and innovation capacity of a country and the output obtained as a result of innovation activities. Patents support further innovation activities and have a positive impact on economic performance. These effects increase productivity (Doğan, 2017: 16).

When the literature is examined, the concepts of innovation and productivity are discussed separately. Only the effects of innovation on business performance and firm productivity were examined. In this context, a concept called Innovation productivity has not been found. However, in today's world, it has become very important not only to examine how innovations affect performance, but also how productive innovation should be done, that is, in what ways the productivity of innovation should be increased. Because innovations that take a lot of time and cost are not desired. Therefore, this study will focus on determining the factors affecting the productivity of innovations and ranking them according to their importance. However, since the factors affecting innovation productivity are not clearly determined in the literature, in our study, the factors affecting innovation performance obtained from the literature and discussed within the scope of the INOSUIT program organized by TİM (Turkish Exporters Assembly) and aiming to establish corporate innovation systems for companies, were taken into account. It is also seen in the evaluation reports published by TIM that the factors taken from the TIM INOSUIT program increase the productivity of innovation studies in companies (TIM Inosuit, 2019-2022: 7). These factors are discussed in detail below.

- *Innovation strategies:* Innovation strategies are directly related to the performance of the firm. It is the most important part of the overall strategy of the company (Aksoy and Demir, 2019). Thanks to the determined rules, it ensures that the best alternative is selected in the innovation decision-making phase and that the company's goals are realized in the best way. From this point of view, it provides the emergence of more innovation products as it creates a roadmap for the innovations targeted by the enterprise (Yılmaz, 2016: 52).
- *Corporate memory:* Corporate Memory is the storage of data and information that an institution has from the past to the present and its reuse when necessary (Megill, 2005: 1). Since the information accumulated in the corporate memory is reflected in all stages, it is of great importance for the continuity of innovation and therefore the continuity of the competitive power of the company. Experiences and experience gained in the innovation process enable a much more successful and faster process to be realized in the development and implementation of new innovation ideas (Gandon et al., 2002).
- *Idea suggestion/Reward system:* Businesses need to develop new ideas in order to grow in the long run and reach their goals (Dahl, 2011). One of the ways to do this is to discover and encourage innovative individuals, which is the first stage of innovation. The main thing here is to encourage new ideas to transform existing ones into innovative processes. In order to do this, an idea suggestion and reward system is used by the institutions both to encourage the employees to develop new ideas and to increase the motivation and performance of the employees (Güngör, 2011). In this way, an innovative and participatory corporate culture is created, and the probability of the enterprise developing innovative products with more innovative ideas is increased. This contributes to the company's innovation performance in the long run (Aksoy and Demir, 2019).
- *Innovation project teams:* Success in technology and innovation management is achieved not only by making strategic decisions, but also by transforming projects from the idea stage to a commercial product or an efficient new production process. Since this process includes many problem solving activities, it needs to be carried out with a team. Innovation studies carried out with a specific project team result in earlier and more successful results. Korkmaz et al., (2018) also found in their study that there is a positive and strong relationship between the innovation project team and innovation performance.
- *Innovation board:* The innovation board, where innovation activities are centrally monitored, innovative business ideas are evaluated and presented to the management, and different units participate, is a great combination of business-wide managers who manage and oversee the entire innovation journey of companies. This board plays an integral role in the creation and prioritization of an organization's innovation roadmap and makes significant contributions to the emergence of innovative products/services (Aslantaş, 2021).
- *Sector and market structure:* It means that the company offers new products for the market it is in, and that the company's tendency to expand into other markets and its activities are carried out in accordance with the strategic framework. The structure of the sector in which the enterprises are located and the structure of the market affect their innovation status. If the business is in an industry where the needs of customers are constantly changing, the tendency to innovate will increase and they

can develop innovative products and services. Also, when you are in a high-tech industry, this affects further innovation (Muhtar, 2022: 23).

- *Financial support/incentives:* Funds, grants and tax support provided by the state for innovation activities; commercially funded directly from the government for R&D; R&D expenditures at universities and research institutions; represents venture capital investments. Therefore, providing these incentives to businesses will lead these businesses to produce more innovative products/services (Satıcı, 2021; Muhtar, 2022: 21).
- *Human resources:* All human resources management functions, from the selection of the human resources that will demonstrate and implement the innovation to their training and motivation, have also gained importance. Because the realization of innovation is possible with creative and innovative employees with high problem-solving skills who understand the importance of innovation. The correct management of the human resources of the enterprises positively affects the innovation process. When innovative enterprises are examined, it is seen that these enterprises adopt a human resources management approach that chooses their employees well, encourages them, and shares their responsibilities. The adoption of innovation as a corporate culture by businesses and the innovative approach of employees to their work will positively affect their performance (Yılmaz, 2020: 29).
- *R&D investments:* R&D studies are important for innovation and are seen as a prerequisite for innovation. Thanks to the R&D studies, new ideas emerge and these ideas are commercialized and create innovation. The fact that innovation has become more vital for economic growth shows that R&D investments are an important indicator of economic development (Seçilmiş and Konu, 2019). It is necessary for companies to use R&D investments in their efforts to grow and innovate. These R&D investments involve both internalizing information obtained from external sources and exposing their own knowledge and skills. As a result, it can not only increase workforce productivity, but also increase the return from knowledge diffusion by generating a range of new innovations developed internally, created with collaborating partners, or developed by other firms. That is, R&D investments not only increase the company's internal innovation capacity, but also improve its ability to innovate by integrating outside information. This increases the company's growth and competitiveness, while also accelerating the flow of information within the industry and creating a broader innovation ecosystem (Audretsch and Belitski, 2020).
- *Technology roadmap:* The Technology Roadmap is a flexible strategic planning tool that enables companies and industries to link technology and scientific resources with business and business objectives. The purpose of a healthy roadmap is to create innovative products and services that meet customer needs, market demands and company goals in the short and long term. (Ramos et al., 2022). Therefore, it is a fact that the companies that make up the technology roadmap are more motivated to produce promising innovative technological products, thus increasing their innovation performance (Feng et al., 2023).
- *Systematic management of innovation projects:* Successful innovation projects to bring out innovative products and services have complex management processes. Long lead times, variability in the market and business environment (customer expectations, company strategies, environmental factors, technological requirements, etc.) and the change of information as the project progresses have made R&D and innovation projects extra complicated. Therefore, determining the objectives, success criteria and the team that will take part in the project in a systematic way will both accelerate the emergence of innovative products/services and contribute to the increase in the number of these projects (Kurt and Yıldız, 2020).
- *Project portfolio:* It includes the creation of prioritized and focused projects that arise depending on the determination of the critical problem pool and projects that will be based on interdepartmental cooperation by determining the needs/development areas and possible innovation issues in various departments of the enterprise. Thus, regular decisions are made about which innovation projects to invest in under rapidly changing economic conditions. Such decisions contribute to the proliferation of innovative products and services in companies (Kurt and Yıldız, 2020).
- *Open innovation processes and external stakeholder collaborations:* In open innovation, which is a structure created by using both internal and external resources to develop new products and approaches, suppliers, customers, competitors, institutions and organizations, private R&D centers, commercial laboratories, consulting companies, public and private research centers, universities and higher education organizations are included in this cooperation (Güler and Kanber, 2011). As seen in open innovation, many participants come together and create added value by sharing knowledge (Chesbrough and Appleyard, 2007). Projects may arise from internal or external technology sources and new technology may be added to the project at various stages. Therefore, with open innovation,

the innovation of companies is enriched (Chesbrough, 2006) and innovation performance is significantly affected (Muhtar, 2022).

- *Innovation training:* In the enterprises, the trainings, in which general information about the concept of innovation is given first, contribute to the formation of an innovation culture in the enterprise by creating a common language and perception. Innovative product development and problem-solving trainings given to certain employees later on trigger the emergence of more innovative products and services. When considered as a whole, it is thought that the trainings provided to the employees enable businesses to produce more innovative products/services (TİM Inosuit, 2019-2022).

3. METHODOLOGY

3.1. Identification of Factors Affecting Innovation Productivity

Innovation is a vital element for organizations looking to gain and maintain a competitive advantage. In this context, the factors affecting innovation productivity are critical factors that determine the innovation capacity and success of an organization or a country. These factors may differ between organizations and countries, but it is important to consider and manage these factors in order to increase innovation productivity. However, which factor should be given more importance or the transfer of financial resources is also very important. Because transferring these resources to a factor that is not important for the organization will negatively affect the success of the organization. Therefore, knowing which are the most important factors can create an effective innovation strategy, provide a competitive advantage and support sustainable growth.

Therefore, in this study, it is aimed to rank the factors that affect the productivity of innovation activities of companies according to their importance. In this context, first of all, the factors affecting innovation productivity were determined based on a common perspective by a technology and innovation expert, an academician with approximately four years of mentoring experience assigned by TIM for establishing corporate innovation systems in firms, and an employee who has been working at a company for 23 years, holding the position of R&D Center Manager for the last 12 years, and recently also taking on the role of Innovation Director and are given in Table 1.

Table 1. Factors affecting innovation productivity determined within the scope of the study

Factor Number	*Factors*	*References*
IP-1	Innovation strategies	Yılmaz (2016: 52)
IP-2	Corporate memory	Megill (2005: 1), Gandon et al. (2002)
IP-3	Idea suggestion/Reward system	Dahl (2011), Güngör, (2011), Aksoy and Demir, (2019)
IP-4	Innovation project teams	Korkmaz et al. (2018)
IP-5	Innovation board	Aslantaş (2021)
IP-6	Sector and market structure	Muhtar (2022: 23)
IP-7	Financial support/incentives	Satıcı (2021), Muhtar (2022: 21)
IP-8	Human resources	Yılmaz (2020: 29)
IP-9	R&D investments	Seçilmiş and Konu (2019), Audretsch and Belitski, 2020
IP-10	Technology roadmap	Ramos et al. (2022), Feng et al. (2023)
IP-11	Systematic management of innovation projects	Kurt and Yıldız, 2020
IP-12	Project portfolio	Kurt and Yıldız (2020)
IP-13	Open innovation processes and external stakeholder collaborations	Chesbrough (2006), Chesbrough and Appleyard (2007), Güler and Kanber (2011), Muhtar (2022: 12)
IP-14	Innovation training	TİM İnosuit (2019-2022)

3.1. Pythagorean Fuzzy AHP

Considering the criteria given in Table 1, it is inevitable with classical methods that the evaluations to be made to determine which factor affects innovation productivity more are subjective. Because, it is not possible to make an assessment with precise numbers for each factor, like impacting (1) or not impacting (0). Therefore, instead of classical methods, it is very useful to use methods that use fuzzy sets that take into account other values in the range (very little effect-very high effect), contrary to the 1-0 logic, in the evaluation phase. One of these methods, the Pythagorean fuzzy AHP method, is briefly explained below.

Fuzzy sets are a mathematical framework developed by Zadeh (1965) as an extension of classical set theory. While classical sets are based on clear, well-defined boundaries within which an element does or does not belong to a set, fuzzy sets introduce the concept of partial membership and allow elements to have different degrees of membership in a set. In a fuzzy set, each element is assigned a membership value between 0 and 1, which indicates the degree of belonging of that element to the set. A membership value of 1 represents full membership, while a value of 0 indicates no membership. Values between 0 and 1 represent partial membership degrees (Zimmermann, 2010; Yıldız, 2016). Fuzzy sets are particularly useful for modeling and dealing with imprecise and ambiguous information. They provide a flexible and intuitive way to represent and reason about vague concepts and fuzzy boundaries commonly encountered in many real-world scenarios (De et al., 2022; Özbek and Yildiz, 2020). In other words, the application of mathematics to the real world can be defined for fuzzy logic. An important difference of fuzzy logic from other logic systems is that it allows the use of verbal variables (Şengül et al., 2012; Yıldız and Demir, 2019). Verbal variables provide approximate characterization of concepts that cannot be expressed clearly. Thus, verbal variables become a tool that requires the use of fuzzy sets to express verbal expressions mathematically. In a sense, fuzzy set theory, which is a multi-valued set theory, is a formulation of uncertainty. His approach is not to abandon the concept of membership used in classical set theories and replace it with a completely new one, but to generalize the bivalent membership by carrying it to polyvalent (Şengül et al., 2012).

Later, Atanassov (1986) extended the fuzzy set theory to present an intuitive fuzzy set theory in order to provide an easier approach to expressing uncertainty. Unlike fuzzy sets, it defines the membership degree of the element X as well as the non-membership degree. In heuristic fuzzy set theory, membership and non-membership degrees take values in the range of [0,1]. He also defined a degree of hesitation parameter apart from these two parameters.

Developed by Yager (2013), Pythagorean fuzzy numbers were developed as a generalization to heuristic fuzzy sets, which in some cases cannot cope with uncertainty. Pythagorean fuzzy sets are an extension of traditional fuzzy sets. These clusters provide a more flexible and meaningful way to handle uncertainty in decision making and modeling complex systems. In Pythagorean fuzzy sets, each element is associated with a triple value: degree of membership, degree of non-membership, and degree of indeterminacy. Compared to traditional fuzzy sets, Pythagorean fuzzy sets offer additional information through the degree of indeterminacy. This allows decision makers to express their hesitations more clearly, which is especially useful when dealing with subjective or imprecise information (Lin et al., 2021). Among the fuzzy theories, the Pythagorean fuzzy set (PFS) has been applied to various fields as it is more prominent in expressing and handling uncertainty in uncertain environments (Xiao and Ding, 2019). In these sets, the sum of membership and non-membership degrees may be greater than 1, but the sum of their squares cannot exceed 1. As a result, PFS has better application in multi-criteria decision making (MCDM) problems due to its capacity to avoid uncertainty in decision making (Ejegwa, 2021). Some important definitions of Pythagorean fuzzy sets are given below.

Definition 1: A Pythagorean fuzzy set P is an object expressed as in Equation 1 (Zhang and Xu, 2014).

$$\tilde{P} = \{\langle x, \tilde{P}\left(\mu_{\tilde{P}}(x), v_P(x)\right);\ \rangle x \in X\} \quad (1)$$

where the membership degree $\mu_p(x)$:x $\mapsto [0,1]$ and non-membership degree $v_p(x)$:x $\mapsto$ [0,1] of element $x \in X$ to *P*. For every $x \in X$, the following holds (Equation 2):

$$0 \leq \mu_p^2(x) + v_p^2(x) \leq 1 \quad (2)$$

The degree of indeterminacy is calculated using Equation 3.

$$\mu_{\tilde{P}}(x) = \sqrt{1 - \mu_p^2(x) - v_p^2(x)} \quad (3)$$

The basic operations on Pythagorean fuzzy sets are listed below.

Definition 2: The operations are as in Equations 4-7, where β_1 = $P(\mu_{\beta_1}, v_{\beta_1,})$ *and* β_2 = $P(\mu_{\beta_2}, v_{\beta_2,})$ are two Pythagorean fuzzy numbers.

$$\beta_1 \oplus \beta_2 = P\left(\sqrt{\mu_{\beta_1}^2 + \mu_{\beta_2}^2 - \mu_{\beta_1}^2\mu_{\beta_2}^2}, v_{\beta_1,} v_{\beta_2}\right) \quad (4)$$

$$\beta_1 \otimes \beta_2 = P\left(u_{\beta_1,} u v_{\beta_2} \sqrt{v_{\beta_1}^2 + v_{\beta_2}^2 - v_{\beta_1}^2 v_{\beta_2}^2}\right) \quad (5)$$

$$\lambda\beta_1 = P\left(\sqrt{1 - \left(1 - \mu_{\beta_1}^2\right)^{\lambda}}, v_{\beta_1}^{\lambda}\right) \quad (6)$$

$$\beta_1{}^{\lambda} = P\left(\mu_{\beta_1}^{\lambda}, \sqrt{1-\left(1-v_{\beta_1}^2\right)^{\lambda}}\right) \quad (7)$$

Definition 3: The distance between two PFS is defined by Equation 8.

$$d(\beta_1, \beta_2) = \frac{1}{2}\left(\left|\mu_{\beta_1}^2 - \mu_{\beta_2}^2\right| + \left|v_{\beta_1}^2 - v_{\beta_2}^2\right| + \left|\pi_{\beta_1}^2 - \pi_{\beta_2}^2\right|\right) \quad (8)$$

Definition 4: If more than one decision maker (DM) evaluates the criteria, the interval-valued Pythagorean Fuzzy (PF) numbers are aggregated using the interval-valued PF weighted geometric operator $\beta_i = ([\mu_i^L, \mu_i^U], [v_i^L, v_i^U])$ is a PF number. Where n is the number of DM, and $w_j = (w_1, w_2, w_3, \ldots, w_n)^T$ be the weight vector of $\beta_i (i = 1,2,3, \ldots, n)$ with $\sum_{i=1}^{n} w_i = 1$, then an Interval-Valued Pythagorean Fuzzy Weighted Geometric (IVPFWG) operator is shown as in Equation 9 (Peng and Yang, 2016).

$$IVPFWG(\beta_1, \beta_2, \beta_3, \ldots, \beta_n) = \left(\left[\prod_{j=1}^{n}(\mu_{\alpha_J}^L)^{w_j}, \prod_{j=1}^{n}(\mu_{\alpha_J}^U)^{w_j}\right], \left[\prod_{j=1}^{n}(v_{\alpha_J}^L)^{w_j}, \prod_{j=1}^{n}(v_{\alpha_J}^U)^{w_j}\right]\right) \quad (9)$$

In Pythagorean fuzzy sets, the sum of the membership and non-membership degrees can be greater than 1, but not the sum of their squares. This means that for every point (x, y) with heuristic membership degree as well as Pythagorean membership degree, the heuristic membership degrees are all points below the line x + y ≤ 1, while the Pythagorean membership degrees are all points with $x^2 + y^2 \leq 1$. Therefore, the set of Pythagorean membership degrees is larger than the heuristic set of membership degrees. Thus, Pythagorean fuzzy sets give decision makers more freedom to express their views on the uncertainty of the problem (Karasan et al., 2019).

The Pythagorean Fuzzy Analytical Hierarchy Process (AHP), using these sets, is an extension of the traditional AHP method that includes the concept of Pythagorean fuzzy sets (Ayyildiz and Taskin Gumus, 2021). Decision making in the AHP method involves creating a hierarchical structure of criteria and alternatives and then evaluating pairwise comparisons between them to determine their relative importance. Pythagorean fuzzy AHP takes into account uncertainty in these pairwise comparisons by using Pythagorean fuzzy numbers instead of exact numbers (Celik and Yildiz, 2022). Pythagorean fuzzy AHP allows decision makers to express their preferences in a more flexible and realistic way by considering multiple criteria and alternatives at the same time when there is uncertainty in the evaluation process. It enables decision makers to express and handle uncertainties more effectively through Pythagorean fuzzy numbers, resulting in more realistic and nuanced decision results (Yucesan ve Kahraman, 2019).

When the literature is reviewed, recent studies using the Pythagorean fuzzy AHP method include Yucesan and Kahraman (2019) for risk assessment in hydroelectric power plants, Ayyildiz and Taskin Gumus (2021) for risk assessment in hazardous materials transportation, Karasan et al. (2019) for solving the storage area selection problem for Istanbul city in Türkiye, Başaran et al. (2023) for measuring and evaluating supplier performance, Shahzad et al. (2022) for analyzing entrepreneurial barriers related to renewable energy promotion in Pakistan, Shahzad et al. (2023) for addressing the obstacles to biomass energy production in Pakistan, Farooq and Moslem (2022) for evaluating and prioritizing critical driver behavior criteria, Deshpande et al. (2023) for ranking enablers in healthcare businesses, and Çelik and Yıldız (2022) for prioritizing green innovation criteria. Moreover, Ayyildiz et al. (2023) integrated Quality Function Deployment (QFD) with Pythagorean fuzzy AHP to investigate the impact of customer expectations and cultivation processes on the hazelnut industry in Türkiye. Lahane and Kant (2021) employed Pythagorean fuzzy AHP and Pythagorean fuzzy DEMATEL approaches to determine the relationships among obstacles in the circular supply chain and analyze their effects. Zhou and Chen (2023) utilized a hybrid approach combining Pythagorean fuzzy AHP, Pythagorean fuzzy TOPSIS, and Linear Assignment Method (LAM) for supplier evaluation. Bulut and Özcan (2023) applied Pythagorean fuzzy AHP-TOPSIS methods to evaluate performance criteria in social media campaigns. Yucesan and Gul (2020) developed a model based on TOPSIS and Pythagorean fuzzy AHP methods to assess hospital service quality. Sarkar and Biswas (2021) integrated the Pythagorean fuzzy AHP-TOPSIS approach for selecting the best transportation company. Çalık (2021) used Pythagorean fuzzy AHP and Pythagorean fuzzy TOPSIS methods to select the best green supplier. Yazıcı et al. (2023) employed Pythagorean fuzzy AHP-Pythagorean fuzzy TOPSIS methods for prioritizing industries in creating a sustainable industrial symbiosis network.

When we look at the studies examined, it has been determined that the Pythagorean fuzzy AHP method is generally used in the solution of the ranking problem in the studied problems. However, it has been observed that it is not used in solving any problem involving innovation issues. Because of these features, the Pythagorean fuzzy AHP method was used in this study. The steps of the Pythagorean Fuzzy AHP method are as follows (Karasan et al., 2019).

Step 1: According to the scale given in Table 2, the decision makers compare the criteria or alternatives in pairs and accordingly create the pairwise comparison matrix.

Table 2. Linguistic variables and pythagorean fuzzy numbers

	Pythagorean Fuzzy Numbers			
Linguistic Variables	*The lower value of the membership degree* (μ_L)	*The upper value of the membership degree* (μ_U)	*The lower value of the non-membership degree* (v_L)	*The upper value of the non-membership degree* (v_U)
Certainly Low Importance (CLI)	0	0	0.9	1
Very Low Importance (VLI)	0.1	0.2	0.8	0.9
Low Importance (LI)	0.2	0.35	0.65	0.8
Below Average Importance (BAI)	0.35	0.45	0.55	0.65
Average Importance (AI)	0.45	0.55	0.45	0.55
Above Average Importance (AAI)	0.55	0.65	0.35	0.45
High Importance (HI)	0.65	0.8	0.2	0.35
Very High Importance (VHI)	0.8	0.9	0.1	0.2
Certainly High Importance (CHI)	0.9	1	0	0
Exactly Equal (EE)	0.1965	0.1965	0.1965	0.1965

Step 2: Calculation of the difference matrix $D=(d_{ik})_{mxm}$ between the lower and upper points of the membership and non-membership functions with the help of Equations 10 and 11.

$$d_{ik_l} = \mu_{ik_l}^2 - v_{ik_u}^2 \quad (10)$$

$$d_{ik_u} = \mu_{ik_u}^2 - v_{ik_l}^2 \quad (11)$$

Step 3: Calculation of the multiplicative matrix $S=(s_{ik})_{mxm}$ using Equations 12 and 13.

$$s_{ik_l} = \sqrt{1000^{d_{ik_l}}} \quad (12)$$

$$s_{ik_u} = \sqrt{1000^{d_{ik_u}}} \quad (13)$$

Step 4: Calculation the degrees of determinacy for each criterion with the help of Equation 14.

$$\tau_{ik} = 1 - (\mu_{ik_l}^2) - (v_{ik_u}^2 - v_{ik_l}^2) \quad (14)$$

Step 5: Determining the weights before normalization using both the degrees of determinacy and the multiplication matrix with the help of Equation 15.

$$t_{ik} = \left(\frac{s_{ik_l}+s_{ik_u}}{2}\right) \tau_{ik} \quad (15)$$

Step 6: Calculation of weights of importance (w_i) is as in Eqaution 16.

$$w_i = \frac{\sum_{k=1}^{m} t_{ik}}{\sum_{i=1}^{m}\sum_{k=1}^{m} t_{ik}} \quad (16)$$

4. EMPIRICAL RESULTS

According to the steps described above, the factors affecting innovation productivity were prioritized.

Step 1: The factors given in Table 1 have been collectively assessed based on a common perspective by a previously identified academic and an innovation director. These assessments have been conducted using the scale provided in Table 2, and the results have been obtained through the pairwise comparison matrix given in Table 3.

Table 3. Pairwise comparison matrix of factors affecting innovation productivity

	IP-1	*IP-2*	*IP-3*	*IP-4*	*IP-5*	*IP-6*	*IP-7*	*IP-8*	*IP-9*	*IP-10*	*IP-11*	*IP-12*	*IP-13*	*IP-14*
IP-1	EE	HI	AAI	AAI	HI	VHI	AAI	VHI	AAI	EE	AAI	AAI	AI	HI
IP-2	LI	EE	LI	BAI	AI	AI	BAI	BAI	LI	VLI	BAI	BAI	VLI	LI
IP-3	BAI	HI	EE	AAI	AAI	HI	AAI	HI	BAI	VLI	BAI	AI	BAI	HI
IP-4	BAI	AAI	BAI	EE	BAI	AAI	AAI	HI	BAI	LI	EE	AAI	BAI	AAI
IP-5	LI	AI	BAI	AAI	EE	AAI	BAI	AAI	BAI	LI	EE	AAI	LI	HI
IP-6	VLI	AI	LI	BAI	BAI	EE	VLI	BAI	VLI	VLI	BAI	LI	BAI	LI
IP-7	BAI	AAI	BAI	BAI	AAI	VHI	EE	HI	EE	LI	EE	AAI	AI	HI
IP-8	VLI	AAI	LI	LI	BAI	AAI	LI	EE	VLI	VLI	LI	LI	BAI	BAI
IP-9	BAI	HI	AAI	AAI	AAI	VHI	EE	VHI	EE	BAI	AAI	AAI	AAI	HI
IP-10	EE	VHI	VHI	HI	HI	VHI	HI	VHI	AAI	EE	HI	AAI	HI	VHI
IP-11	BAI	AAI	AAI	EE	EE	AAI	EE	HI	BAI	LI	EE	AAI	AI	HI
IP-12	BAI	AAI	AI	BAI	BAI	HI	BAI	HI	BAI	BAI	BAI	EE	LI	AAI
IP-13	AI	VHI	AAI	AAI	HI	AAI	AI	AAI	BAI	LI	AI	HI	EE	HI
IP-14	LI	HI	LI	BAI	LI	HI	LI	AAI	LI	VLI	LI	BAI	LI	EE

Step 2: The difference matrix between the lower and upper points of the membership and non-membership functions is calculated with the help of Equations 10 and 11 and given in Table 4-5.

Table 4. The difference matrix between lower points of membership and non-membership functions

	IP-1	*IP-2*	*IP-3*	*IP-4*	*IP-5*	*IP-6*	*IP-7*	*IP-8*	*IP-9*	*IP-10*	*IP-11*	*IP-12*	*IP-13*	*IP-14*
IP-1	0.00	0.30	0.10	0.10	0.30	0.60	0.10	0.60	0.10	0.00	0.10	0.10	-0.10	0.30
IP-2	-0.60	0.00	-0.60	-0.30	-0.10	-0.10	-0.30	-0.30	-0.60	-0.80	-0.30	-0.30	-0.80	-0.60
IP-3	-0.30	0.30	0.00	0.10	0.10	0.30	0.10	0.30	-0.30	-0.80	-0.30	-0.10	-0.30	0.30
IP-4	-0.30	0.10	-0.30	0.00	-0.30	0.10	0.10	0.10	-0.30	-0.60	0.00	0.10	-0.30	0.10
IP-5	-0.60	-0.10	-0.30	0.10	0.00	0.10	-0.30	0.10	-0.30	-0.60	0.00	0.10	-0.60	0.10
IP-6	-0.80	-0.10	-0.60	-0.30	-0.30	0.00	-0.80	-0.30	-0.80	-0.80	-0.30	-0.60	-0.30	-0.60
IP-7	-0.30	0.10	-0.30	-0.30	0.10	0.60	0.00	0.10	0.00	-0.60	0.00	0.10	-0.10	0.10
IP-8	-0.80	0.10	-0.60	-0.60	-0.30	0.10	-0.60	0.00	-0.80	-0.80	-0.60	-0.60	-0.30	-0.30
IP-9	-0.30	0.10	0.10	0.10	0.10	0.60	-0.60	0.60	0.00	-0.30	0.10	0.10	0.10	0.10
IP-10	0.00	0.60	0.60	0.10	0.10	0.60	0.10	0.60	0.10	0.00	0.10	0.10	0.10	0.60
IP-11	-0.30	0.10	0.10	0.00	0.00	0.10	0.00	0.10	-0.30	-0.60	0.00	0.10	-0.10	0.10
IP-12	-0.30	0.10	-0.10	-0.30	-0.30	0.10	-0.30	0.10	-0.30	-0.30	-0.30	0.00	-0.60	0.10
IP-13	-0.10	0.60	0.10	0.10	0.10	0.10	-0.10	0.10	-0.30	-0.60	-0.10	0.10	0.00	0.10
IP-14	-0.60	0.10	-0.60	-0.30	-0.60	0.10	-0.60	0.10	-0.60	-0.80	-0.60	-0.30	0.12	0.00

Table 5. The difference matrix between upper points of membership and non-membership functions

	IP-1	*IP-2*	*IP-3*	*IP-4*	*IP-5*	*IP-6*	*IP-7*	*IP-8*	*IP-9*	*IP-10*	*IP-11*	*IP-12*	*IP-13*	*IP-14*
IP-1	0.00	0.60	0.30	0.30	0.60	0.80	0.30	0.80	0.30	0.00	0.30	0.30	0.10	0.60
IP-2	-0.30	0.00	-0.30	-0.10	0.10	0.10	-0.10	-0.10	-0.30	-0.60	-0.10	-0.10	-0.60	-0.30
IP-3	-0.10	0.60	0.00	0.30	0.30	0.60	0.30	0.60	-0.10	-0.60	-0.10	0.10	-0.10	0.60
IP-4	-0.10	0.30	-0.10	0.00	-0.10	0.30	0.30	0.30	-0.10	-0.30	0.00	0.30	-0.10	0.30
IP-5	-0.30	0.10	-0.10	0.30	0.00	0.30	-0.10	0.30	-0.10	-0.30	0.00	0.30	-0.30	0.30
IP-6	-0.60	0.10	-0.30	-0.10	-0.10	0.00	-0.60	-0.10	-0.60	-0.60	-0.10	-0.30	-0.10	-0.30
IP-7	-0.10	0.30	-0.10	-0.10	0.30	0.80	0.00	0.30	0.00	-0.30	0.00	0.30	0.10	0.30
IP-8	-0.60	0.30	-0.30	-0.30	-0.10	0.30	-0.30	0.00	-0.60	-0.60	-0.30	-0.30	-0.10	-0.10
IP-9	-0.10	0.30	0.30	0.30	0.30	0.80	-0.30	0.80	0.00	-0.10	0.30	0.30	0.30	0.30
IP-10	0.00	0.80	0.80	0.30	0.30	0.80	0.30	0.80	0.30	0.00	0.30	0.30	0.30	0.80
IP-11	-0.10	0.30	0.30	0.00	0.00	0.30	0.00	0.30	-0.10	-0.30	0.00	0.30	0.10	0.30
IP-12	-0.10	0.30	0.10	-0.10	-0.10	0.30	-0.10	0.30	-0.10	-0.10	-0.10	0.00	-0.30	0.30
IP-13	0.10	0.80	0.30	0.30	0.30	0.30	0.10	0.30	-0.10	-0.30	0.10	0.30	0.00	0.30
IP-14	-0.30	0.30	-0.30	-0.10	-0.30	0.30	-0.30	0.30	-0.30	-0.60	-0.30	-0.10	-0.22	0.00

Step 3: The multiplicative matrix was calculated using Equations 12 and 13 and given in Table 6-7.

Table 6. The multiplicative matrix of the lower points

	IP-1	*IP-2*	*IP-3*	*IP-4*	*IP-5*	*IP-6*	*IP-7*	*IP-8*	*IP-9*	*IP-10*	*IP-11*	*IP-12*	*IP-13*	*IP-14*
IP-1	1.00	2.82	1.41	1.41	2.82	7.94	1.41	7.94	1.41	1.00	1.41	1.41	0.71	2.82
IP-2	0.13	1.00	0.13	0.35	0.71	0.71	0.35	0.35	0.13	0.06	0.35	0.35	0.06	0.13
IP-3	0.35	2.82	1.00	1.41	1.41	2.82	1.41	2.82	0.35	0.06	0.35	0.71	0.35	2.82
IP-4	0.35	1.41	0.35	1.00	0.35	1.41	1.41	1.41	0.35	0.13	1.00	1.41	0.35	1.41
IP-5	0.13	0.71	0.35	1.41	1.00	1.41	0.35	1.41	0.35	0.13	1.00	1.41	0.13	1.41
IP-6	0.06	0.71	0.13	0.35	0.35	1.00	0.06	0.35	0.06	0.06	0.35	0.13	0.35	0.13
IP-7	0.35	1.41	0.35	0.35	1.41	7.94	1.00	1.41	1.00	0.13	1.00	1.41	0.71	1.41
IP-8	0.06	1.41	0.13	0.13	0.35	1.41	0.13	1.00	0.06	0.06	0.13	0.13	0.35	0.35
IP-9	0.35	1.41	1.41	1.41	1.41	7.94	0.13	7.94	1.00	0.35	1.41	1.41	1.41	1.41
IP-10	1.00	7.94	7.94	1.41	1.41	7.94	1.41	7.94	1.41	1.00	1.41	1.41	1.41	7.94
IP-11	0.35	1.41	1.41	1.00	1.00	1.41	1.00	1.41	0.35	0.13	1.00	1.41	0.71	1.41
IP-12	0.35	1.41	0.71	0.35	0.35	1.41	0.35	1.41	0.35	0.35	0.35	1.00	0.13	1.41
IP-13	0.71	7.94	1.41	1.41	1.41	1.41	0.71	1.41	0.35	0.13	0.71	1.41	1.00	1.41
IP-14	0.13	1.41	0.13	0.35	0.13	1.41	0.13	1.41	0.13	0.06	0.13	0.35	1.53	1.00

Table 7. The multiplicative matrix of upper points

	IP-1	*IP-2*	*IP-3*	*IP-4*	*IP-5*	*IP-6*	*IP-7*	*IP-8*	*IP-9*	*IP-10*	*IP-11*	*IP-12*	*IP-13*	*IP-14*
IP-1	1.00	7.94	2.82	2.82	7.94	15.85	2.82	15.85	2.82	1.00	2.82	2.82	1.41	7.94
IP-2	0.35	1.00	0.35	0.71	1.41	1.41	0.71	0.71	0.35	0.13	0.71	0.71	0.13	0.35
IP-3	0.71	7.94	1.00	2.82	2.82	7.94	2.82	7.94	0.71	0.13	0.71	1.41	0.71	7.94
IP-4	0.71	2.82	0.71	1.00	0.71	2.82	2.82	2.82	0.71	0.35	1.00	2.82	0.71	2.82
IP-5	0.35	1.41	0.71	2.82	1.00	2.82	0.71	2.82	0.71	0.35	1.00	2.82	0.35	2.82
IP-6	0.13	1.41	0.35	0.71	0.71	1.00	0.13	0.71	0.13	0.13	0.71	0.35	0.71	0.35
IP-7	0.71	2.82	0.71	0.71	2.82	15.85	1.00	2.82	1.00	0.35	1.00	2.82	1.41	2.82
IP-8	0.13	2.82	0.35	0.35	0.71	2.82	0.35	1.00	0.13	0.13	0.35	0.35	0.71	0.71
IP-9	0.71	2.82	2.82	2.82	2.82	15.85	0.35	15.85	1.00	0.71	2.82	2.82	2.82	2.82
IP-10	1.00	15.85	15.85	2.82	2.82	15.85	2.82	15.85	2.82	1.00	2.82	2.82	2.82	15.85
IP-11	0.71	2.82	2.82	1.00	1.00	2.82	1.00	2.82	0.71	0.35	1.00	2.82	1.41	2.82
IP-12	0.71	2.82	1.41	0.71	0.71	2.82	0.71	2.82	0.71	0.71	0.71	1.00	0.35	2.82
IP-13	1.41	15.85	2.82	2.82	2.82	2.82	1.41	2.82	0.71	0.35	1.41	2.82	1.00	2.82
IP-14	0.35	2.82	0.35	0.71	0.35	2.82	0.35	2.82	0.35	0.13	0.35	0.71	0.47	1.00

Step 4: In Table 8, the degrees of uncertainty are given for each factor calculated with the help of Equation 14.

Table 8. Determinacy degrees of the factors

	IP-1	*IP-2*	*IP-3*	*IP-4*	*IP-5*	*IP-6*	*IP-7*	*IP-8*	*IP-9*	*IP-10*	*IP-11*	*IP-12*	*IP-13*	*IP-14*
IP-1	1.00	0.70	0.80	0.80	0.70	0.80	0.80	0.80	0.80	1.00	0.80	0.80	0.80	0.70
IP-2	0.70	1.00	0.70	0.80	0.80	0.80	0.80	0.80	0.70	0.80	0.80	0.80	0.80	0.70
IP-3	0.80	0.70	1.00	0.80	0.80	0.70	0.80	0.70	0.80	0.80	0.80	0.80	0.80	0.70
IP-4	0.80	0.80	0.80	1.00	0.80	0.80	0.80	0.80	0.80	0.70	1.00	0.80	0.80	0.80
IP-5	0.70	0.80	0.80	0.80	1.00	0.80	0.80	0.80	0.80	0.70	1.00	0.80	0.70	0.80
IP-6	0.80	0.80	0.70	0.80	0.80	1.00	0.80	0.80	0.80	0.80	0.80	0.70	0.80	0.70
IP-7	0.80	0.80	0.80	0.80	0.80	0.80	1.00	0.80	1.00	0.70	1.00	0.80	0.80	0.80
IP-8	0.80	0.80	0.70	0.70	0.80	0.80	0.70	1.00	0.80	0.80	0.70	0.70	0.80	0.80
IP-9	0.80	0.80	0.80	0.80	0.80	0.80	0.70	0.80	1.00	0.80	0.80	0.80	0.80	0.80
IP-10	1.00	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	1.00	0.80	0.80	0.80	0.80
IP-11	0.80	0.80	0.80	1.00	1.00	0.80	1.00	0.80	0.80	0.70	1.00	0.80	0.80	0.80
IP-12	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	1.00	0.70	0.80
IP-13	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.70	0.80	0.80	1.00	0.80
IP-14	0.70	0.80	0.70	0.80	0.70	0.80	0.70	0.80	0.70	0.80	0.70	0.80	1.34	1.00

Step 5: Pre-normalized weights are calculated with the help of Equation 15 and given in Table 9.

Table 9. Matrix of weights before normalization

	IP-1	*IP-2*	*IP-3*	*IP-4*	*IP-5*	*IP-6*	*IP-7*	*IP-8*	*IP-9*	*IP-10*	*IP-11*	*IP-12*	*IP-13*	*IP-14*
IP-1	1.00	3.77	1.69	1.69	3.77	9.52	1.69	9.52	1.69	1.00	1.69	1.69	0.85	3.77
IP-2	0.17	1.00	0.17	0.43	0.85	0.85	0.43	0.43	0.17	0.08	0.43	0.43	0.08	0.17
IP-3	0.43	3.77	1.00	1.69	1.69	3.77	1.69	3.77	0.43	0.08	0.43	0.85	0.43	3.77
IP-4	0.43	1.69	0.43	1.00	0.43	1.69	1.69	1.69	0.43	0.17	1.00	1.69	0.43	1.69
IP-5	0.17	0.85	0.43	1.69	1.00	1.69	0.43	1.69	0.43	0.17	1.00	1.69	0.17	1.69
IP-6	0.08	0.85	0.17	0.43	0.43	1.00	0.08	0.43	0.08	0.08	0.43	0.17	0.43	0.17
IP-7	0.43	1.69	0.43	0.43	1.69	9.52	1.00	1.69	1.00	0.17	1.00	1.69	0.85	1.69
IP-8	0.08	1.69	0.17	0.17	0.43	1.69	0.17	1.00	0.08	0.08	0.17	0.17	0.43	0.43
IP-9	0.43	1.69	1.69	1.69	1.69	9.52	0.17	9.52	1.00	0.43	1.69	1.69	1.69	1.69
IP-10	1.00	9.52	9.52	1.69	1.69	9.52	1.69	9.52	1.69	1.00	1.69	1.69	1.69	9.52
IP-11	0.43	1.69	1.69	1.00	1.00	1.69	1.00	1.69	0.43	0.17	1.00	1.69	0.85	1.69
IP-12	0.43	1.69	0.85	0.43	0.43	1.69	0.43	1.69	0.43	0.43	0.43	1.00	0.17	1.69
IP-13	0.85	9.52	1.69	1.69	1.69	1.69	0.85	1.69	0.43	0.17	0.85	1.69	1.00	1.69
IP-14	0.17	1.69	0.17	0.43	0.17	1.69	0.17	1.69	0.17	0.08	0.17	0.43	1.34	1.00

Step 6: The importance weights of each factor were calculated using the Equation 16 and are given in Table 10.

Table 10. Importance weight and ranking of criteria

Factors	*Weights before normalization*	*Normalized importance weights*	*Ranking*
Innovation strategies	43.34	0.15	2
Corporate memory	5.65	0.02	13
Idea suggestion/Reward system	23.77	0.08	5
Innovation project teams	14.45	0.05	8
Innovation board	13.09	0.05	9
Sector and market structure	4.78	0.02	14
Financial support/Incentives	23.27	0.08	6
Human resources	6.73	0.02	12
R&D investments	34.59	0.12	3
Technology roadmap	61.43	0.21	1
Systematic management of innovation projects	16.02	0.06	7
Project portfolio	11.76	0.04	10
Open innovation processes and external stakeholder collaborations	25.50	0.09	4
Innovation training	9.35	0.03	11

When Table 10 is examined, it is seen that the “Technology roadmap” factor is the most important factor affecting innovation productivity with its importance weight value of 0.209. “Innovation strategies” emerged as the second and “R&D investments” as the third important criteria. “Sector and market structure” and “Corporate memory” were determined as the last two factors.

Then, sensitivity analysis was performed depending on the scenarios given in Table 11 in order to determine whether the ranking of factors would be different according to different factor weights. Here, it is aimed to evaluate how stable the results and decisions taken from the Pythagorean fuzzy AHP method are. Because changing the weights will show us how reliable the judgments are and how they may change under different conditions. Therefore, it will help us to make our judgments easier, depending on whether the rankings have changed or not. It will ultimately help optimize our decisions by identifying which factor affects innovation productivity the most.

Table 11. Combinations of scenarios with different factor weights

Scenarios	*Combinations*	*Scenarios*	*Combinations*
Scenario 1	Current		
Scenario 2	IP-1 CLI, The Rest current	Scenario 16	IP-1 CHI, The Rest current
Scenario 3	IP-2 CLI, The Rest current	Scenario 17	IP-2 CHI, The Rest current
Scenario 4	IP-3 CLI, The Rest current	Scenario 18	IP-3 CHI, The Rest current
Scenario 5	IP-4 CLI, The Rest current	Scenario 19	IP-4 CHI, The Rest current
Scenario 6	IP-5 CLI, The Rest current	Scenario 20	IP-5 CHI, The Rest current
Scenario 7	IP-6 CLI, The Rest current	Scenario 21	IP-6 CHI, The Rest current
Scenario 8	IP-7 CLI, The Rest current	Scenario 22	IP-7 CHI, The Rest current
Scenario 9	IP-8 CLI, The Rest current	Scenario 23	IP-8 CHI, The Rest current
Scenario 10	IP-9 CLI, The Rest current	Scenario 24	IP-9 CHI, The Rest current
Scenario 11	IP-10 CLI, The Rest current	Scenario 25	IP-10 CHI, The Rest current
Scenario 12	IP-11 CLI, The Rest current	Scenario 26	IP-11 CHI, The Rest current
Scenario 13	IP-12 CLI, The Rest current	Scenario 27	IP-12 CHI, The Rest current
Scenario 14	IP-13 CLI, The Rest current	Scenario 28	IP-13 CHI, The Rest current
Scenario 15	IP-14 CLI, The Rest current	Scenario 29	IP-14 CHI, The Rest current

The results of the sensitivity analysis conducted with a total of 29 scenarios are given in Figure 1.

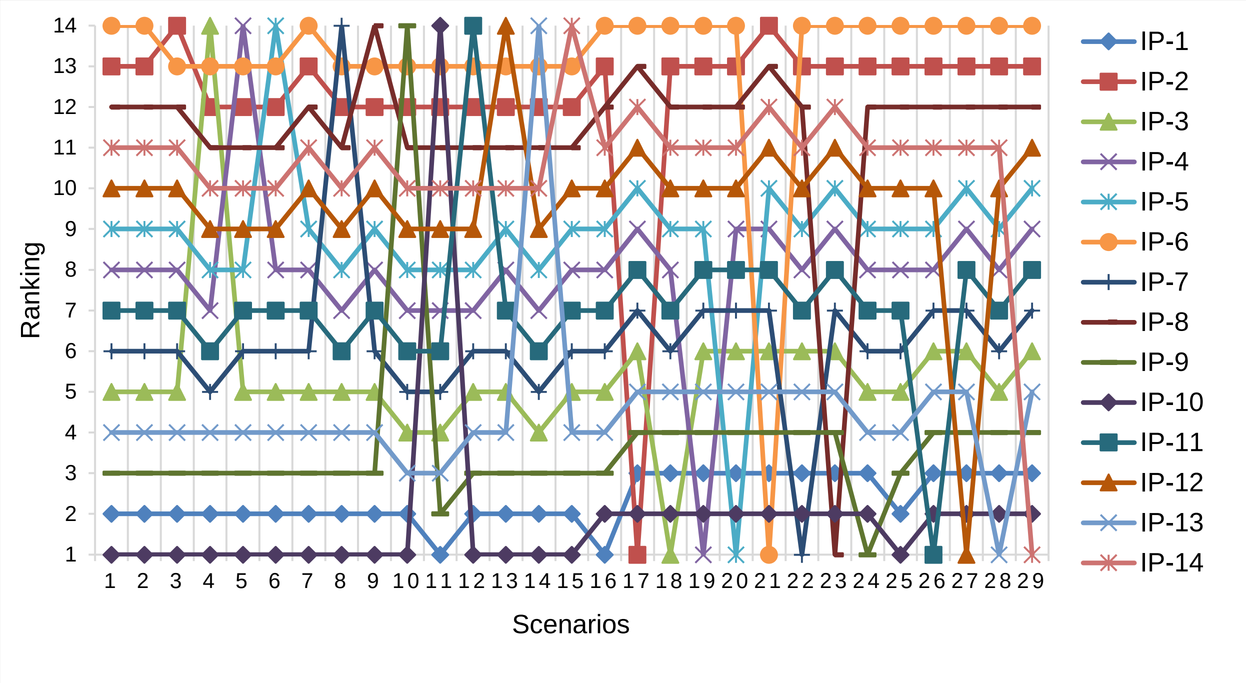

Figure 1. Changes in sensitivity analysis results

In the first stage of the sensitivity analysis, all factors were given CLI importance weights, respectively, while the weights of the other factors were not changed (scenarios 2-15). In these scenarios, except for Scenario 11, the IP-10 (Technology roadmap) factor took the first place. When we give CLI importance weight to the IP-10 (Technology roadmap) factor, this factor is in the last place, while IP-1 (Innovation strategy) is in the first place. This result shows that the Technology roadmap factor is not of low importance, but is certainly of high importance.

In the second stage of the sensitivity analysis (scenarios 16-29), CHI importance weights were given to all factors, respectively, while the weights of other factors were not changed. In these scenarios, each factor given CHI importance was ranked 1st. In this analysis, IP-10 took the 2nd place in all scenarios except the 25th scenario, and the 1st in the 25th scenario. IP-1, on the other hand, took the 3rd place in these scenarios.

Looking at all the scenarios in the analysis in general, IP-10 ranked first, IP-1 ranked second, and IP-9 ranked third in 15 scenarios. When the CLI and CHI importance weights were given to the factors, the rankings of almost all factors changed by 1 place.

When the analysis results are evaluated, it can be said that the IP-10 (Technology roadmap) factor is the most important factor affecting innovation productivity. IP-1 (Innovation strategies) and IP-9 (R&D

investments) factors seem to be important factors after the technology roadmap. IP-6 (Sector and market structure) and IP-2 (Corporate memory) factors were found to be in the last place and as the factors that least affect innovation factors. It can be said that the results of the Pythagorean Fuzzy AHP Method are sensitive and can be used in solving ranking problems as in this study.

5. CONCLUSION

In today's conditions, there is a compelling competitive environment for businesses with the effect of globalization. In this competitive environment, businesses are increasing their investments in innovation day by day, as they are aware that they need to turn to innovation, which the whole world has been focusing on and working on recently, in order to continue their existence. Because, from the point of view of countries, the most important reason for this is that it plays an important role in sustainable development, social welfare, increase in employment, providing national competitive advantage and raising the quality of life. When it is considered for companies, it is a very important tool that allows entering new markets, reducing costs, thus increasing efficiency and profitability, increasing product and service quality, and increasing productivity. However, some factors need to be considered in order to make innovations faster and with added value.

Therefore, in this study, it is aimed to rank the factors affecting innovation productivity according to their importance by using the Pythagorean fuzzy AHP method. In this way, it is aimed for enterprises to innovate and increase their productivity by taking into account the most important factors.

According to the results obtained from the study, it has been determined that the preparation of technology roadmaps has the largest impact on innovation productivity. When we look at the purpose of the technology roadmap, it is a tool that visualizes the technologies required to launch new products or services that will meet the needs and requirements of customers, and they are very effective and should be considered especially in the execution of innovation projects. In addition, they act as an important bridge in the management of innovative projects and portfolios that are compatible with the strategies of the enterprises. Therefore, since the technology roadmaps of the enterprises are related to many factors, the preparation of these maps will also increase the innovation productivity. In this context, it is parallel to the aim of ranking this factor in the first place.

When we look at the other results obtained from the study, innovation strategies appear as the second important factor. They will increase their innovation productivity as it will be a guide for businesses to determine innovation strategies that indicate how and with what they will carry out their innovations and guide them. Since R&D investments, which is one of the important factors, are a direct route to innovation, companies need to increase their investments for R&D. When we look at the effect of open innovation and collaborations, it is seen that the learning and knowledge dissemination that occurs thanks to the cooperation and close relations with organizations increases innovation productivity. This result shows parallelism with the study of Güler and Kanber (2011). Therefore, since our country is in a much weaker position in terms of cooperation between the actors in the system compared to other EU countries, all actors of the innovation system such as companies, universities-public research institutions, R&D institutions, governments, support and bridge organizations, financing institutions act together for the success of innovation. Policies should be developed and they should be in long-term relations with each other.

Looking at the situation in general, according to the Global Innovation Index (GII) report, in which the annual performance of 132 countries' economies is evaluated, Türkiye has risen to 37th place in 2022 by rising 4 places, and has managed to enter the top 40 for the first time by rising 14 places in the index in the last two years. However, in order for these rankings to be higher, businesses need to produce innovative products/services that produce more added value. For this, they need to know what to do first.

When the results obtained from the study are examined, it is revealed that enterprises should first draw up their technology roadmaps, determine their strategies accordingly, and increase their innovation productivity by making R&D investments to realize all these. In this respect, the study will provide an important guide to the managers of the enterprises that want to increase the innovation productivity, on which areas to focus on and will help these managers to make the right decisions and provide benefits to the business in terms of both time and cost.

Considering the study, it is the first study in which the factors affecting innovation productivity are examined and ranked according to their importance. Therefore, the factors used in the study will be a ready guide for researchers who want to work on innovation productivity issues and they will be able to use the results obtained from this study in their studies. In the future, a study can be conducted in which more factors are considered and the costs of these factors are taken into account and different methods are compared.

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Miraç Tuba Çelik: Literature review, Methodology, Analysis, Writing-original draft, Modelling, Writing-review and editing *Aytaç Yıldız:* Conceptualization, Methodology, Analysis, Writing-original draft, Modelling, Writing-review and editing

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It was declared by the author(s) that scientific and ethical principles have been followed in this study and all the sources used have been properly cited.

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VERİMLİLİK DERGİSİ
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The Impact of R&D Expenditures on Economic Growth in Türkiye: New Evidence from Machine Learning Method

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ABSTRACT

Purpose: This study analyzes the impacts of R&D expenditures on economic growth in Türkiye.

Methodology: In this study, we explore the impact of R&D expenditure on economic growth in Türkiye. Annual time series from 1990 to 2021 are considered for this research examination based on the data availability. R&D expenditure, Gross Domestic Product (GDP) per capita, gross fixed capital formation, labor force, and tertiary ratio variables are used for the analysis and obtained from the World Bank. Based on machine learning, analyses were conducted using the Kernel Regularized Least Square method.

Findings: The empirical analysis using KRLS shows that higher spending on research and development leads to a significant boost in economic growth. Furthermore, labor force participation, school enrolment (tertiary) ratio, and gross fixed capital formation are all significantly and positively associated with economic growth in Türkiye.

Originality: The contribution of the paper is twofold: (1) it provides new scientific evidence based on the machine learning econometric method, the Kernel Regularized Least Square (KRLS); (2) many papers in the literature have only examined the relationship between R&D expenditures and economic growth, without controlling for other variables. We have used possible control variables such as labor force participation rate, school enrolment (tertiary) ratio, and gross fixed capital formation, which are also linked to economic growth models.

Keywords: Productivity, KRLS method, Research and Development, Economic Growth, Innovation.

JEL Codes: O47, O32, O38.

Türkiye'de Ar-Ge Harcamalarının Ekonomik Büyüme Üzerindeki Etkisi: Makine Öğrenmesi Yönteminden Yeni Kanıtlar

ÖZET

Amaç: Bu çalışma, Türkiye'de Ar-Ge harcamalarının ekonomik büyüme üzerindeki etkilerini analiz etmektedir.

Yöntem: Bu çalışmada, Türkiye'de Ar-Ge harcamalarının ekonomik büyüme üzerindeki etkisi araştırılmaktadır. Veri mevcudiyetine bağlı olarak bu araştırmada 1990'dan 2021'e kadar olan yıllık zaman serileri kullanılmıştır. Ar-Ge harcaması, kişi başına Gayri Safi Yurtiçi Hasıla (GSYH), gayri safi sabit sermaye oluşumu, işgücü ve okula kayıt (yükseköğretim) oranı değişkenleri Dünya Bankası'ndan temin edilmiştir. Makine öğrenimine dayalı olarak, analizler Kernel Düzenlenmiş En Küçük Kare yöntemi kullanılarak gerçekleştirilmiştir.

Bulgular: KRLS kullanılarak yapılan ampirik analiz, araştırma ve geliştirmeye yapılan daha yüksek harcamaların ekonomik büyümede önemli bir artışa yol açtığını göstermektedir. Ayrıca, işgücüne katılım, okula kayıt (yükseköğretim) oranı ve gayrisafi sabit sermaye oluşumu Türkiye'deki ekonomik büyüme ile anlamlı ve pozitif bir şekilde ilişkilidir.

Özgünlük: Bu makalenin katkısı iki yönlüdür: (1) makine öğrenimi ekonometrik yöntemi olan Kernel Düzenlenmiş En Küçük Kare (KRLS) yöntemine dayalı yeni bilimsel kanıtlar sunmaktadır; (2) literatürdeki birçok makale, diğer değişkenleri kontrol etmeden sadece Ar-Ge harcamaları ve ekonomik büyüme arasındaki ilişkiyi incelemiştir. Bu çalışmada, ekonomik büyüme modelleriyle bağlantılı olan işgücüne katılım oranı, okullaşma (yükseköğretim) oranı ve gayrisafi sabit sermaye oluşumu gibi olası kontrol değişkenleri de analizde kullanılmıştır.

Anahtar Kelimeler: Verimlilik, KRLS yöntemi, Araştırma ve Geliştirme, Ekonomik Büyüme, İnovasyon.

JEL Kodları: O47, O32, O38.

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1. INTRODUCTION

Innovation, Research and Development (R&D) are pivotal drivers of economic growth in the modern world. They form a dynamic relationship, where innovation acts as a catalyst for technological advancements, and R&D serves as the engine that fuels these innovations. Innovation refers to the process of creating novel products, services, or processes that offer significant value to individuals, businesses, or society as a whole. It involves the application of new ideas, technologies, and methodologies to enhance efficiency, quality, and sustainability. Innovation is a driving force behind economic growth as it promotes productivity gains and fosters a competitive edge for nations, industries, and businesses (Stokey, 1995).

Innovation leads to the development of new industries and the revitalization of existing ones. This generates jobs, stimulates demand, and encourages entrepreneurship (Pessoa, 2010). Furthermore, innovative solutions often address societal challenges, such as climate change, healthcare, and poverty, yielding additional economic and social benefits. R&D is the systematic and scientific exploration of new knowledge, leading to the development of innovative products, services, or processes. It serves as a bridge between theoretical concepts and practical applications, transforming ideas into tangible advancements. Governments, businesses, and academia invest in R&D to expand their knowledge base, improve existing technologies, and discover new ones. These investments spur a cycle of innovation by enabling the creation of cutting-edge products and services, propelling economic development and growth. This relationship has been theoretically analyzed by many models (Griliches, 1979; Romer, 1990; Aghion and Howitt, 1990; Grossman and Helpman, 1991: 15-16). R&D has been crucial in industries like pharmaceuticals, technology, and renewable energy, where constant innovation is fundamental for long-term success.

The expansion and increase in economic activity in a country over a given period is called economic growth. This phenomenon typically signifies the overall worth of products and services generated during a specific timeframe. Over time, the growth phenomenon has been theorized, and growth theories have emerged. The Solow Growth Model, which was put forward by Solow (1956) and is the predecessor of growth theories, deals with the fundamental growth factors of the economy. Theory suggests that economic growth is pushed by factor accumulation (capital and labor) and exogenous technological development. While factor accumulation has diminishing returns at a certain point (law of diminishing returns), sustainable growth, in the long run, is realized through technological progress that increases total factor productivity. Economic growth theories have evolved and have been enriched with more comprehensive approaches, especially endogenous growth theories that have addressed technological the source and sustainability of technological progress in detail. Romer (1986) laid the foundation of R&D-based growth models. This study is constructed related to endogenous growth theories by examining R&D expenditures.

Increasing economic welfare in a country is through sustainable economic growth, which increase the number of resources individuals can utilize and thus the welfare they will gain from using these resources. The type of economic growth directly affects welfare. For example, an economic growth model in which the increase in welfare is felt only by a particular population segment may lead to social unrest by increasing inequality. In addition, another view shaped around the ideas of Kuznets (1955) is that income inequality will increase in the initial phases of economic growth; however, income inequality will begin to fall after a certain point. In conclusion, in spite of its ethical controversies, economic growth is seen as the most crucial resource of welfare increase. Therefore, it is targeted by almost all countries.

Technological development is one of the most important ways of achieving sustainable economic growth. It has been analyzed by many economists since Solow (1957) in terms of its effects on economic growth. Hence, countries formulate strategies to accelerate technological developments to sustain economic growth and maintain competitive advantages. R&D expenditures, at the center of these strategies, are recognized as one of the strongest drivers of innovation and technological progress. In its most general definition, R&D is the generation of knowledge and ideas about new ways of organizing or using new materials or compounds and preparing innovative designs for new goods and services (Griliches, 1991). R&D expenditures realized through public and private sector investments cover areas such as discovering new knowledge, improving existing technologies, and developing innovative solutions. Countries that prioritize R&D generally gain significant advantages such as increasing their technological capabilities, becoming competitive in the universal market, and raising the living standards of their citizens.

R&D expenditures are key to ensuring and sustaining technological development and innovation, and thus economic growth. The effects of R&D expenditures on economic growth are pretty diverse. These expenditures foster a continuous innovation cycle, enabling the development of new products, services, and processes that support economic growth. Moreover, new technologies and knowledge diffuse across different sectors of the economy, increasing productivity and competitiveness; therefore, R&D investments improve overall productivity, especially in the long run. As technological advances increase, economies begin to achieve higher levels of output, income, and employment, thereby improving the living standards of society (Jones and Williams, 2000; Grossman and Helpman, 1994). While the relationship between R&D expenditure and economic growth is widely recognized, the magnitude and mechanisms of their interaction vary in different contexts. Factors such as the quality of institutions, the effectiveness of intellectual property protection, the availability of skilled human capital and the extent of cooperation between academia, industry and government institutions all shape the outcomes of R&D investments. As a result, R&D expenditures will increase the technological development potential of countries, enabling the production of new goods and services, resulting in higher levels of income and economic growth.

In sum, as the global economy becomes increasingly dependent on knowledge and innovation, the role of R&D expenditures in supporting economic growth becomes more prominent. This paper investigates the relationship between R&D expenditures and economic growth in Türkiye. In doing so, it underlines the significance of R&D investments as a transformative force that promotes not only technological progress but also social welfare via economic growth.

The contribution of the paper is twofold: (1) it provides new scientific evidence based on the machine learning econometric method, the Kernel Regularized Least Square (KRLS); (2) many papers in the literature have only analyzed the relationship between R&D expenditures and economic growth without using control variables. Therefore, we have used possible control variables, such as labor force participation rate, school enrolment (tertiary) ratio, and gross fixed capital formation.

The rest of the paper is structured as follows: the second section provides the theoretical background of the study; the third section briefly summarizes related literature, section four presents data and methodology; the fifth section reports empirical analysis and discussion; finally, the sixth section concludes the study and proposes relevant policy implications.

2. THEORETICAL BACKGROUND

Economic growth, which in its most basic definition can be characterized as an increase in the quantity or value of goods and services produced, has been one of the primary economic goals of societies and one of the main areas of study for economists throughout history. However, growth theories emerged in the post-World War II period when economic growth was badly needed. These theories aimed to analyze what affects a country's potential output in the long run, how these factors trigger economic growth and which factors are more determinant for growth. Economic growth theories can be categorized into two main groups: exogenous and endogenous growth theories. This distinction is made according to whether technological developments are affected by factors of production or not. Under the assumption that technological developments are not affected by factors of production, we talk about exogenous growth models, whereas in the opposite case, we talk about endogenous growth models.

The model proposed by Solow (1956), which can be considered as the predecessor of the exogenous growth models, examines how capital accumulation and technological development, which are considered as exogenous, and population and labor force growth affect economic growth. According to this model, economic growth is in a certain interaction with production inputs and an increase in these inputs will increase economic growth. However, the source of economic growth in the long run is technological developments. There are certain assumptions in this model. These can be characterized as the diminishing efficiency of capital, perfect competition and full employment conditions, a closed single-good market and perfect substitution between production inputs (Ehrlich, 1990). Through this model, the differences in GDP per capita between countries and the "convergence hypothesis" explained that these differences would tend to decrease over time. This model, which remained valid until the 1980s, was later abandoned due to the realization that the assumption of diminishing returns to capital is not always valid and the acceptance that technological developments are not an exogenous factor. In this period, new economic growth theories emerged in which technological developments were taken as an endogenous variable. Starting with Romer (1986) and later developed by economists such as Lucas (1988), Barro (1990), Aghion and Howitt (1990) and Grossman and Helpman (1991: 15-18), endogenous growth models have altered the perspective on economic growth. In this period, unlike Solow, a growth model that takes technological developments as an endogenous variable was developed. Again, unlike previous growth theories, factors such as government intervention, human capital accumulation and R&D activities were added to endogenous growth theories and the impact of these factors on economic growth was analyzed.

Romer (1986), inspired by Arrow's (1962) "learning by doing" approach, emphasized the importance of knowledge accumulation. According to this approach, the accumulation of knowledge over time leads to an increase in the quality of goods and services produced and a decrease in their costs. Romer emphasized that this effect can be considered as an extra input that will increase economic growth. Therefore, according to Romer's model, the accumulation and spill-over of knowledge through production and investment processes is the most important driver of economic growth in the long run.

Lucas (1988), on the other hand, used the concept of human capital, which can be characterized as a measure of the quality of the labor force, to explain the economic growth process. According to this approach, the way to achieve economic growth in the long run is determined by the human capital level of the labor force and the investments made in human capital. On the other hand, Barro (1990) investigated the effect of public expenditure on productive areas on economic growth. According to Barro's findings, public spending and investments in productive sectors are believed to contribute to long-term economic growth by creating positive externalities.

Schumpeter (1942: 81-86) can be considered as the first economist who aimed to endogenize technological developments, the source of the "creative destruction" process, which he characterized as the continuous improvement of goods and services produced, in the economic growth model. Aghion and Howitt (1990) and Grossman and Helpman (1991:15-18) furthered this effort and included technological developments as an endogenous variable in their economic growth models. Accordingly, the continuity of economic growth in the long run can only be realized through R&D activities that will ensure technological development. Countries with intensive R&D activities will be able to grow faster than other countries by gaining comparative advantages over time. Another important point here is the adjustments to be made by the public sector in resource allocation through incentives for R&D activities. Countries that can effectively allocate resources to R&D activities that will accelerate technological developments can achieve long-term and stable growth.

3. LITERATURE REVIEW

Many researchers have analyzed R&D expenditures regarding their effect on economic growth. Some researchers have found a positive and significant relationship between R&D expenditures and economic growth (Ali et al., 2021; Gumus and Celikay, 2015; Horowitz, 1967; Falk, 2007; Guloglu and Tekin, 2012; Moustapha and Yu, 2021; Wu and Zhou, 2007; Peng, 2010; Ulku, 2004; Bayarçelik and Taşel, 2012). For example, Ali et al. (2021) examined the impact of R&D expenditures on economic growth in 100 countries with the most significant economic size for 1995-2015. They showed that R&D investments have a positive association with economic growth in the long run, but this effect is higher in developed countries. Similarly, Gumus and Celikay, using data from 52 countries for the period 1996-2010, concluded that R&D expenditures have a positive and significant effect on economic growth in the long run for all countries. Horowitz (1967) found that R&D increase correlated positively with regional economic growth in various U.S. states from 1920 to 1964. Falk (2007), in his study on OECD countries for the period 1970-2004, found that the share of firms' R&D expenditures in GDP and the ratio of R&D expenditures in high-tech sectors in total expenditures have a strong and positive effect on GDP per capita and GDP per hour worked. Similarly, Moustapha and Yu (2021) analyzed the impact of R&D expenditures on economic growth in 35 OECD countries over the 2000-2016 period. They found that a 1% increase in R&D expenditures would lead to a 2.83% increase in real GDP growth rate. Guloglu and Tekin (2012) also found that R&D expenditures and economic growth have a positive and significant relationship for the period 1991-2007 for thirteen OECD high-income countries. Wu and Zhou (2007) examined the cointegration and causality relationship between R&D expenditures and economic growth in China for the period 1953-2004. They found that there is a long-run cointegration relationship between R&D and GDP and that there is a bidirectional causal relationship from R&D to GDP and vice versa in the long run. Peng (2010), on the other hand, found a long-run relationship between R&D expenditures and economic growth in China for the period 2000-2007. Analysis results uncovered that when R&D expenditures increase by 1%, GDP will increase by 0.9243%. In a study conducted by Ulku (2004), an examination of patent and R&D information for twenty OECD countries and ten non-OECD countries revealed a favorable correlation relating GDP per capita and innovation. Lastly, Bayarçelik and Taşel (2012) concluded that R&D expenditures and the number of employees in R&D have a positive and significant effect on economic growth.

The impact of R&D expenditures on economic growth, on the other hand, may vary across countries as well as income levels. Some researchers discovered a negative or no significant relationship between R&D expenditures and economic growth in specific contexts. For example, in their study Samimi and Alerasoul (2009) conducted in thirty developing countries between 2000 and 2006, concluded that there is no significant relationship between R&D expenditures and economic growth since R&D expenditures remain low in these countries. For developed countries, Susanto et al. (2023) conducted a study using the data of five countries (USA, China, Japan, Germany, and the United Kingdom) from 1996 to 2018 showed that R&D expenditures had no significant impact on economic growth within these countries. Similarly, Sylwester (2001) analyzed the relationship between R&D expenditures and economic growth in 20 OECD countries and G-7 countries and found no strong relationship for OECD countries but a positive relationship between industrial R&D expenditures and economic growth for G-7 countries.

When the studies conducted for Türkiye are analyzed, it is observed that similar results are obtained. Altin and Kaya (2009) analyzed the period 1990-2005 and found no relationship between R&D expenditures and economic growth in the short term. However, in the long term, a causality relationship was found from R&D expenditures to growth. Taban and Şengür (2014), on the other hand, utilizing data for the period 1990-2012, found that R&D expenditures and the number of employees in R&D positively affect economic growth in long term. Similarly, Korkmaz (2010) explored a long-run cointegration between R&D expenditures and economic growth in the 1990-2008 period, showing they affect each other. Yaylalı et al. (2010) examined the relationship between R&D expenditures and economic growth in Türkiye for the period 1990-2009. In this study where cointegration test was applied, a unidirectional relationship was found from R&D expenditures to economic growth. Akıncı and Sevinç (2013), on the other hand, found a unidirectional causality from R&D expenditures to economic growth for Türkiye between 1990-2011.

However, some studies do not directly examine the relationship between R&D expenditures and economic growth but provide insights into its impact on economic growth. For example, the spillover effects of R&D expenditures were examined and it is found that a significant and positive relationship between R&D expenditures and total factor productivity exist in the long run (Coe and Helpman, 1995). Wakelin (2001) examined the relationship between productivity growth and R&D expenditures in 170 firms in the UK and found that a firm's R&D expenditures have a positive and important role in affecting productivity growth. Similarly, Zachariadis (2003) found a positive and significant relationship between R&D expenditures and technological development. Some studies have examined the factors affecting innovation. Griffith et al. (2004) examined different sectors in 12 OECD countries and found that R&D is crucial for both technological catch-up and innovation. Schmookler (1966) concluded that technologists and R&D expenditures are related to the number of patents, which is an important indicator of innovation.

In conclusion, the economic literature shows that R&D expenditures positively and significantly impact economic growth in many countries. However, this impact may vary inversely or insignificantly depending on factors such as the income level of countries and the source of R&D financing.

4. DATA and METHODOLOGY

4.1. Data

In this study, we explore the impact of R&D expenditure on economic growth in Türkiye. Annual time series from 1990 to 2021 are considered for this research examination based on the availability of data. R&D expenditure, GDP per capita, labor force, gross fixed capital formation, and tertiary ratio variables are gathered from the WDI (World Bank Data Indicator). We include the control variables based on the economic growth models and related literature, considering the main drivers of economic growth in an economy. Hence, we use labor force and capital formation as the key factors of production. Additionally, we add school enrolment (tertiary) variable as a proxy of human capital (Tsai et al., 2010; Ogunleye et al., 2017). Data sources and other details are displayed in Table 1. Furthermore, we converted all the series into natural logarithms to mitigate heteroskedasticity and interpret the coefficients into a percentage.

Table 1. Variable *description*

Code	*Indicator Name*	*Source*
EG	GDP per capita (constant $ 2010)	World Bank
RD	Research and Development Expenditure (% of GDP)	World Bank
L	Labor force participation rate	World Bank
K	Gross fixed capital formation (% of GDP)	World Bank
H	School enrolment, tertiary (% gross)	World Bank

4.2. Methodology

In the current study, we use Kernel-based Regularized Least Squares (KRLS) method, which has been recently developed by Hainmueller and Hazlett (2014). Kernel-based Regularized Least Squares (KRLS) is a machine learning method recently used in econometrics and statistics for regression analysis. It is an extension of the standard linear regression that incorporates the concept of kernel methods for modeling non-linear relationships between variables.

In traditional linear regression, the relationship between the independent variables (features) and the dependent variable (target) is assumed to be linear. However, many real-world relationships are not strictly linear. On the contrary, Kernel methods offer a means of capturing non-linear connections by converting the initial feature space into a higher-dimensional space through the use of a mathematical kernel function.

The KRLS method provides a flexible and convenient modeling approach that bridges the gap between the constrained GLMs frequently used by researchers and the more flexible but often less clear machine learning methods (Hainmueller and Hazlett, 2014). At the same time, KRLS is user-friendly and helps researchers protect their conclusions from bias due to incorrect specifications without requiring them to sacrifice the interpretability and statistical properties they assess. This methodology falls into a model category that exhibits well-behaved and easily attainable marginal effects due to a continuously differentiable solution surface, which is determined through closed-form estimation. Furthermore, it readily permits the application of statistical inference through closed-form expressions and exhibits favorable statistical characteristics even with reasonably moderate assumptions. Enabling more comprehensive interpretations, the resulting model is directly interpretable, similar to linear regression. The estimator generates individual estimates of partial derivatives, which describe the isolated effects of each independent variable at each specific data point within the covariate space. Researchers have the option to examine the distribution of these individual estimates at specific points to gain a deeper understanding of the variation in marginal effects. Alternatively, they can calculate an average from these estimates to obtain an average partial derivative, which is akin to a β coefficient obtained from linear regression.

KRLS is also used for estimating models that may have complex relationships between variables. KRLS draws inspiration from machine learning techniques to address regression and cataloging tasks without being constrained by linearity or additivity assumptions. This approach builds an adaptable hypothesis space that employs kernels as radial basis functions. It identifies the optimal-fitting surface within this space by minimizing a least squares problem that considers complexity penalties (Wilson and Wright, 2017). This method is particularly fitting for inquiries in the realm of social science due to its ability to circumvent rigid parametric assumptions. Simultaneously, it facilitates an interpretation framework reminiscent of generalized linear models. Moreover, it allows for intricate interpretations to explore nonlinearities, interactions, and heterogeneous effects. The strengths of KRLS encompass its capacity to mitigate misspecification bias through a versatile and intelligible machine-learning methodology.

Kernel regression is a non-parametric approach based on linear and non-linear least squares regression. It is a generalization of linear regression that uses kernel functions to map the input data into a higher-dimensional space (Ferwerda et al., 2017). The kernel function is used to weight the contribution of each data point in the regression. On the flip side, linear regression represents a parametric method, presupposing a linear connection between the input and output variables. It estimates the parameters of the model employing least squares (LS) optimization.

Hence, the KRLS method can furnish more precise estimations compared to parametric models as well as specific non-parametric models. In this manner, it emerges as a robust substitute for other econometric models ie OLS. Therefore, we can basically express the model as in Equation 1.

$$y = g(x) + \varepsilon \tag{1}$$

In this context, "y" represents per capita GDP, "*g(.)"* represents an undisclosed functional relationship, " x " represents a set of factors influencing economic growth, such as R&D expenditures, labor force participation rate, gross fixed capital formation, and tertiary enrollment ratio, and " ε " represents a unique error term. The choice of variables aligns with previous research in the field (e.g. Minviel and Bouheni, 2022; Blanco and Prieger, 2016). The KRLS method presupposes that the target function *g(x)* can be estimated or approximated in the following manner (Equation 2):

$$g(x) = \sum_{i=1}^{N} c_i k(x, x_i) \tag{2}$$

Here, $k(x, x_i)$ represents similarity measurement, denoted as x, and *N* input, denoted as x_i, while c_i signifies the weight associated with each input pattern. Please take into account that equation (2) shares some resemblance with generalized linear models (GLMs) to a certain extent. It is important to highlight that KRLS holds a higher degree of naturalness and potency compared to GLM (Hainmueller and Hazlett, 2014). Similarity measurement can be computed thanks to a Gaussian kernel function (Equation 3):

$$k(x, x_i) = \exp\left(-\frac{\|x - x_i\|^2}{\sigma^2}\right) \tag{3}$$

where $\|x - x_i\|$is the Euclidian distance between the covariate vectors *x* and x_i and $\sigma^2 \in R^+$ is the bandwidth of the kernel function. Tikhonov regularization estimates the model, enabling the selection of the optimal function that aligns with the data, in accordance with the following principle (Equation 4):

$$\underset{g \in H}{\operatorname{argmin}} \sum_i \big(V(g(x_i), y_i)\big) + \lambda R(g) \tag{4}$$

Here, $V(f(x_i), y_i)$ denotes a loss function that quantifies the discrepancy of the function at each observation, while R represents a "regularizer" that gauges the intricacy of the function *g*. The scalar parameter $\lambda \in \mathbb{R}+$ influences the balance between fitting the model and its complexity. Elevated λ values lead to greater penalization for function complexity, prioritizing model fit, whereas lower λ values yield the opposite outcome. *H* symbolizes a flexible function space associated with a specific kernel choice, often referred to as the reproducing kernel Hilbert spaces. When utilizing squared loss for *V* and the square of the L_2 norm for the "regularizer," the resultant Tikhonov regularization problem is formulated as in Equation 5.

$$\underset{g \in H}{\operatorname{argmin}} \sum_i (g(x_i) - y_i)^2 + \lambda \|g\|_K^2 \quad (5)$$

with $\|g\|_K^2 = \sum_i \sum_j c_i c_j k(x_i, x_j)$, where x_i and x_j are vectors of continuous independent variables. λ is selected via cross-validation (CV) criterion.

In the study, we examine the role of R&D expenditures on economic growth in Türkiye, taking into account labor force participation, school enrolment (tertiary) rate, and gross fixed capital formation. Similar to Warsame et al. (2023), who also benefit from KRLS method in time series setting, the model specification of the paper is as in Equation 6.

$$EG_t = \beta_0 + \beta_1 RD_t + \beta_2 LF_t + \beta_3 H_t + \beta_4 K_t + \varepsilon_t \quad (6)$$

5. EMPIRICAL RESULTS and DISCUSSION

5.1. Descriptive statistics

Table 2 provides an overview of the statistical summaries for the variables. It reveals the mean values of per capita GDP (8.9); R&D expenditures (-0.5), labor force participation rate (17.02), tertiary ratio (3.7), and gross fixed capital formation ratio (3.2). The labor force participation rate has a lesser variation (0.17), whereas the tertiary ratio has a higher variation (0.71) than other variables.

Table 2. Summary statistics

Variable	*Obs*	*Mean*	*Std.Dev.*	*Min*	*Max*
lngdppc	32	8.965	.291	8.567	9.499
lnrd	32	-.556	.464	-1.446	.122
lnlaborforce	32	17.028	.174	16.794	17.33
lntertiary	32	3.697	.717	2.576	4.779
lncapital	32	3.225	.132	2.888	3.396

The results of Pairwise correlations indicate that GDPpc is positively associated with R&D expenditure, labor force, tertiary ratio, and capital stock, as shown in Table 3. Similarly, R&D has a positive correlation with the labor force and tertiary ratio, as expected.

Table 3. Correlation matrix

	lngdppc	*lnR&D*	*lnlaborforce*	*lntertiary*	*lncapital*
lngdppc	1.0000				
lnR&D	0.9429	1.0000			
lnlaborforce	0.9626	0.9096	1.0000		
lntertiary	0.9860	0.9466	0.9789	1.0000	
lncapital	0.7092	0.5263	0.6045	0.6463	1.0000

5.2. The KRLS estimation result

The outcomes of the KRLS estimation are displayed in Table 4. Unlike the Ordinary least square (OLS), which assumes constant marginal effects, the KRLS observes pointwise marginal coefficients for each variable. Consequently, it becomes feasible to assess whether the impact of each independent variable on economic growth fluctuates across different time periods. The model fit of the result is good, as indicated by R^2. R&D expenditures, labor force participation, school enrollment (tertiary ratio), and gross fixed capital are statistically significant.

The average marginal effect estimate suggests that one unit increase in R&D expenditure contributes to economic growth by about 0.16% on average. R&D expenditure increases economic growth by 0.09%, 0.18%, and 0.21% in the 25th, 50th, and 75th percentiles, respectively. R&D expenditure has increasing marginal effects on economic growth. It plays a crucial role in increasing economic growth. This result is pertinent to previous studies concluding that R&D expenditure leads to higher economic growth such as Bozkurt (2015) in Türkiye, and Gumus and Celikay (2015) in cross-country analysis.

On average, labor force participation positively and significantly affects economic growth. A 1% increase in labor force participation causes an increase in economic growth by about 0.40%. LF also has increasing marginal effects on per capita GDP, meaning that the labor force is the main driver of economic activity. LF has the highest significant effect on economic growth in Türkiye compared to other regressors.

An average increase in school enrolment (tertiary ratio) increases economic growth by 0.11%. This variable is used as a proxy for human capital in our study. Hence, H increases per capita GDP by about 0.07%, 0.10%, and 0.15% in the 25th, 50th, and 75th percentiles, respectively. It is found that human capital promotes economic growth in Türkiye. Human capital refers to the skills, knowledge, abilities, and experiences that individuals accumulate through education, training, work experiences, and personal development. It plays a vital role in promoting economic growth in several way, ie. increased productivity, innovation and technological advancement, and knowledge spillovers. This finding is parallel to the results of Chatterji (1998) who investigates the potential importance of tertiary education in the growth process. Similarly, Karaalp (2017) noted that human capital, which is also proxied by tertiary education, fosters economic growth in Türkiye.

Furthermore, gross fixed capital formation (K) is positively linked to economic growth. An average increase in capital formation exerts an increase in per capita GDP by 0.20%. Gross fixed capital formation has a constructive role in increasing per capita GDP by about 0.005%, 0.32%, and 0.47% in the 25th, 50th and 75th percentiles, respectively in Türkiye. Gross Fixed Capital Formation (GFCF) refers to the total value of investments made in physical assets such as buildings, machinery, equipment, and infrastructure that contribute to the expansion of a country's productive capacity. GFCF plays a critical role in driving economic growth for several reasons such as increased productive capacity, higher productivity, and job creation. This finding corroborates with ample studies that produced the same result. For instance, Abbas et al. (2020) reported that capital fixed formation in twenty-four emerging economies boost economic growth.

To ensure the reliability and stability of the results, we conducted various post-estimation examinations, including assessments for tolerance, lambda, goodness-of-fit, and looloss, as detailed in Table 4. The results of these tests, as reported in Table 4, demonstrate the absence of serial correlation and heteroskedasticity in the study's results. Furthermore, the model's stability, evaluated in Table 5, proves favorable. This assertion is supported by the fact that the test statistic is smaller than the 1% critical value, and the CUSUM curve depicted in Figure 1 remains within the confidence bands on the graph. Consequently, it can be deduced that there is no discernible structural discontinuity within the dataset.

Table 4. KRLS estimation result

	Average	*SE*	*T-statistics*	*P-value*	*P25*	*P50*	*P75*
lnRD	0.160134	0.020393	7.852	0.000	0.094965	0.180612	0.217551
lnLF	0.408165	0.058317	6.999	0.000	0.276121	0.418962	0.550455
LnH	0.115481	0.012273	9.410	0.000	0.078301	0.104772	0.153712
LnK	0.209305	0.053187	3.935	0.000	0.005312	0.325755	0.477381
Obs	32						
Lambda	0.07841						
Tolerance	0.032						
Sigma	4						
Eff.df.	12.49						
R^2	0.9947						
Looloss	0.1337						

Table 5. Parameter stability test

Type	*Test statistic*	*1% Critical Value*	*5% Critical Value*	*10% Critical Value*
recursive	0.9247	1.1430	0.9479	0.8499

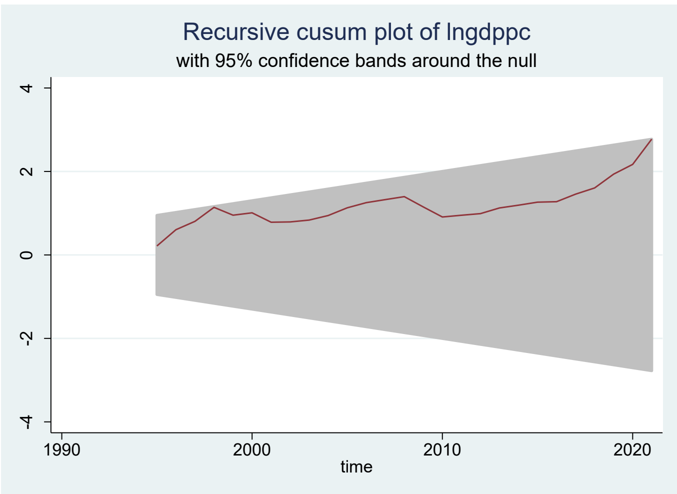

Figure 1. CUSUM test

6. CONCLUSION

Technological developments have become one of the most critical inputs of economic growth for the last 30 years. Technological breakthroughs made by countries increase social welfare through their economic effects. In this context, R&D expenditures stand out as the most significant source of technological development. To drive innovation, economic growth, and global competitiveness can also be maintained via R&D expenditures. They foster a culture of creativity, exploration, and problem-solving that propels societies forward and ensures their adaptability in an ever-evolving world.

R&D activities are important since it involves the creation of new knowledge, technologies, and processes. They drive innovation productivity by leading to the development of novel products, services, and solutions that can revolutionize industries and improve overall quality of life. Furthermore, R&D investments contribute to increased innovation productivity by enhancing efficiency, optimizing processes, and fostering the creation of new industries and markets. This, in turn, boosts economic growth as more efficient and innovative methods lead to higher output. Moreover, R&D activities provide opportunities for researchers, scientists, and engineers to advance their skills and knowledge. This contributes to a country's human capital development and positions it as a hub for expertise and innovation.

In the context of this study, we investigate the relationship between R&D expenditures and economic growth in Türkiye for the period from 1990 to 2021, with a focus on endogenous growth models. Our analysis reveals that R&D expenditures in Türkiye have a noteworthy and statistically significant positive influence on economic growth. Specifically, a 1% increase in R&D expenditures leads to an average economic growth increase of 0.16%. Furthermore, our empirical results, obtained through the KRLS method, indicate that factors such as labor force participation, tertiary school enrollment ratio, and gross fixed capital formation are all significantly and positively associated with economic growth in Türkiye. A particularly intriguing discovery is that R&D expenditure exhibits increasing marginal effects on economic growth, underscoring its pivotal role in stimulating and enhancing economic growth in the country. Our findings are in line with Wu and Zhou (2007) and Bayarçelik and Taşel (2012) who also reported positive association between R&D expenditure and economic growth, whereas contradicts with the results of Samimi and Alerasoul (2009), studying 30 developing countries' and claim that R&D expenditures have no direct effect on economic growth.

The rise in economic growth attributed to increased R&D expenditures underscores the significance of investing in research and development. To attain sustainable economic growth in Türkiye, it is imperative to foster collaborative R&D initiatives involving both the public and private sectors while also providing support to individual researchers. Promoting economic growth through increased research and development (R&D) expenditures in Türkiye requires a comprehensive approach that involves various stakeholders, policies, and strategies. For instance, the government should allocate a higher percentage of the national budget to R&D activities and offer tax incentives or subsidies to businesses that invest in R&D. From the educational perspective, Türkiye should strengthen education systems to produce a skilled workforce in science, technology, engineering, and mathematics (STEM) fields. Also, schools should support programs that encourage students to pursue careers in R&D.

In conclusion, providing financial support and incentives for startups and small businesses engaged in R&D will support innovation productivity and economic growth. Implementing these measures collectively can create an ecosystem that fosters innovation and R&D, contributing to sustainable economic growth in Türkiye. It's crucial for policymakers, industry leaders, and academia to work together to create an environment that supports long-term research and development initiatives. By doing so, we can catalyze a sustainable economic growth cycle, leveraging the high potential for future returns associated with R&D investments.

Our current study discusses the relationship between R&D expenditures and economic growth in a broader perspective taking the whole R&D expenditures. The future studies can handle this topic taking into account the details of R&D expenditures in several sectors.

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Author Contributions
Yasin Acar: Conceptualization, Methodology, Analysis, Writing-original draft, Modelling, Writing-review and editing *İbrahim Kesici*: Literature Review, Conceptualizaton, Data Curation, Writing-review and editing

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Compliance with Ethical Standards
It was declared by the authors that the tools and methods used in the study do not require the permission of the Ethics Committee.

Ethical Statement
It was declared by the authors that scientific and ethical principles have been followed in this study and all the sources used have been properly cited.

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