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# The impact of digitalization, technological and financial innovation on environmental quality in OECD countries: Investigation of N-shaped EKC hypothesis

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ABSTRACT

This research article aims to determine the interrelationships between digitalization, technological and financial innovation, and environmental quality in selected Organization for Economic Cooperation and Development (OECD) countries. This study also tests the validity of the N-shaped Environmental Kuznets Curve (EKC) hypothesis. To this end, we utilize a rigorous three-stage panel data econometrics approach. The empirical outcomes entail that financial innovation decreases carbon emissions, whereas technological innovation and digitalization increase carbon emissions in the OECD countries. The results further underscore that across all models, the first level of gross domestic product (GDP) harms environmental quality. On the flip side, the second level of GDP tends to improve environmental quality. However, the third level of GDP deteriorates environmental quality. In conclusion, the empirical findings corroborate the N-shaped EKC hypothesis in OECD countries, urging policymakers to adopt more sustainable development practices.

## 1. Introduction

To cope with the unprecedented environmental challenges quite a few countries across the globe are striving to come up with pragmatic green economic policies to realize sustainable economic development. These measures on behalf of the countries are not only indispensable owing to resource constraints but also stipulated the increasing pressure of global warming. Technological innovation is a vital factor in realizing efficient economic growth (EG) in this modern era [1–3]. Advocating digital economy is second to none with respect to high-quality development in the wake of pervasive digital technologies [4]. Digital transformation enables intelligent manufacturing such as artificial intelligence, cloud computing, and big data applications, which realize technology-based manufacturing [5,6]. It is also a fact that the development of our economy, society, and technology depends heavily on digitalization, technological innovation, and financial innovation. These developments have the potential to greatly improve environmental quality and tackle major environmental problems worldwide [6]. This introduction focuses on EG as it examines the relationship between these developments and how they affect environmental quality. It is worthy of mentioning the impact of urbanization on environmental quality through economic growth, as well as energy efficiency. There is a mechanism by which urbanization affects carbon emissions by affecting economic growth, energy efficiency, and final energy consumption rates in the industrial sector and residential sector [7].

This research examines the connection between EG and $CO_2$ emissions, providing helpful insights for tackling environmental sustainability concerns and offering helpful guidance. It emphasizes the N-shaped EKC hypothesis in OECD economies by integrating technological innovation (TI), and financial innovation (FI). The N-shaped EKC theory

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investigates environmental problems in OECD economies with an emphasis on deforestation, air quality, and water. The theory offers a framework for comprehending this intricate link and directing legislative action in the direction of a more sustainable future [8]. It implies that environmental deterioration rises with economic development and falls at a certain point. Investigating the connection between EG, environmental quality, and technological innovation can be done by including ICT, TI, and FI in the theory.

In emerging economies, research on digitalization (DG) and $CO_2$ has revealed a negative relationship, whereas studies in Asian and Middle East and North Africa (MENA) countries have revealed a positive impact. Global $CO_2$ emissions are decreased and sustainable EG is promoted by digital adaptation. Beyond a certain point, digitalization contributes to a reduction in carbon emissions, making DG an effective tool for lowering global $CO_2$ emissions [6,9]. The study finds that FI positively impacts $CO_2$ emissions, but negatively impacts $CO_2$ in all models. Targeted financial incentives, like carbon pricing and green bonds, can promote eco-friendly initiatives. DG and TI reduce $CO_2$, but their long-term environmental impact may be impacted by energy and electronic device use. Policymakers should balance DG and TI advancements, adopt targeted measures, and understand the curve's turning points. Implementing these recommendations can lead to a greener, prosperous global society.

By taking insights from these studies, the present research employs the theoretical underpinnings of the N-shaped EKC. By integrating the role of ICT, TI, and FI into the conceptual framework, the study endeavors to validate this theoretical construct within the context of OECD economies. Inspired by the quest that the OECD countries may realize sustainable economics progression? this research endeavor aims to unravel long-term intricacies among digitalization, technological and financial innovation, and environmental quality. Determining the long-run associations between these variables will enable us to delineate the extent and the direction to which these variables influence environmental quality, and will affirm whether the N-shaped EKC truly holds for these countries. The insights obtained from this investigation will not only spur more curiosity but will espouse knowledge for informed policies to strike a balance between economic progression and environmental sustainability. Put differently, this study will equip policymakers to steer the wheels of the OECD economies through ecologically friendly drivers. Against this bacdrop, this study aims to answers to the following questions.

1) Is there a long-term relationship between DG, TI, FI, EG and $CO_2$ emissions in OECD countries?
2) What are the long-term quantitative effects of DG, TI, FI and EG on $CO_2$ emissions in OECD countries?
3) Is the N-shaped EKC hypothesis valid for OECD countries?
4) What is the direction of causality between TI, FI, EG and $CO_2$ emissions in OECD countries?

## 2. Theoretical framework

An extant number of researchers have conducted their studies to examine the interplay between economic growth (GDP) and environmental quality (EQ) in the context of EKC hypothesis [10]. Initially, researchers predominantly focused on validating the inverted U-shaped EKC, which suggests that environmental degradation initially increases with economic growth but eventually declines after reaching a certain level of development. Many studies successfully demonstrated this pattern across various countries [11–15].

The relationships between environmental pollution and economic growth are explained by three different mechanisms [16]. The first is the scale effect. Accordingly, if an increase in economic activities is achieved without changing the nature of economic activities, then the total amount of pollution produced increases. The second is the compound effect. Accordingly, if the competition between countries when trade is liberalized is due to differences in environmental regulations, then the damage to the environment will increase. Finally, according to the technical effect, the level of pollution in production will decrease, on the one hand, due to the liberalization of trade and the transfer of modern technologies by foreign investors to the local economy, and on the other hand, due to the increase in income and the political structure's desire for a cleaner environment. Shafik [17] notes that local air pollution tends to be addressed when countries reach middle-income levels. This is often explained as because air pollution problems tend to become more serious in middle-income economies, but also because there are greater benefits and more affordable costs.

As environmental concerns continued to gain significance globally, researchers began shifting their emphasis towards the N-shaped EKC. This shift in focus towards the N-shaped EKC hypothesis stems from several factors. Firstly, there is a growing recognition that environmental degradation is not automatically reversed once a certain level of economic development is reached [18]. Secondly, as countries undergo further economic development, the complexities of environmental challenges become more apparent. The issues at stake go beyond simple pollution reduction and extend to more intricate problems such as climate change, biodiversity loss, and resource depletion. These multifaceted environmental issues require more comprehensive approaches and cannot be fully captured by a simple U-shaped curve [19]. Thirdly, advancements in research methodologies and access to comprehensive datasets have allowed researchers to delve deeper into the nuanced relationship between economic growth and environmental quality. For instance, by incorporating additional factors such as technological progress, structural changes in the economy, and the role of environmental policies, scholars have sought to provide a provide a more comprehensive understanding on the relationship between GDP and $CO_2$. Torras and Boyce [20] offer two explanations for such a situation: The first possibility is that scale effects dwarf composition and technology effects as the scope for further improvements in power distribution is exhausted or they create diminishing returns in terms of technological change that reduces pollution. Another possibility is that rising personal income in high-income countries is associated with increasing power inequality.

The increasing adoption of financial innovation and digital technology has profoundly altered our way of life and work. Digitalization can improve energy use, reduce greenhouse gas emissions, and enhance transportation efficiency. It has become a potent tool for promoting sustainability and addressing environmental issues. It can also improve building comfort and energy efficiency, enabling autonomous driving systems and route optimization. Digital transformation improves corporate resources, profitability, and innovation by reducing information asymmetries, improving internal control, and managing excessive financialization [21]. Scholars are investigating the intersection of digitalization, innovation, and sustainability to identify opportunities for addressing global concerns and promoting equitable societies. Studies are exploring green financial development, technical innovation, and environmental regulations. In this respect, researchers have examined various factors related to green technology innovation, including technology capabilities, knowledge base, strategic orientation, market environment, institutional environment, and external financial environment [22].

It is possible to discuss the effects of digital technologies on sustainability by dividing them into three classes. These are the effects resulting from the production, use and disposal of digital technology waste. While the production and destruction effects of these effects constitute direct and completely negative effects of digital technologies on sustainability; The effects of use include both positive and negative consequences. While operating digital technologies requires a great deal of energy, on the other hand, the use of digital technologies in production has many indirect and positive effects. The impact of digitalization in the industry on the sustainable environment may ultimately vary depending on the magnitude of the positive and negative effects in question. Businesses should determine their digitalization strategies in a way that will positively affect environmental sustainability [23].

Academic debate on corporate financialization and digital transformation, with some arguing it improves financial performance and competitive advantage, while others argue it's unreliable [21,24–27]. DG, FI, and EG impact EQ, requiring a dynamic study to understand the benefits and challenges for a sustainable future. According to a study conducted in OECD countries, EQ is positively impacted by technical innovation, and institutional quality, while negatively impacted by financial development. To mitigate the negative consequences of financial development on the environment, promoting sustainable financial innovations and green financing is essential [28]. Green finance is a new FI product that seeks to help both the economy and the environment. Green finance enterprises prioritize environmental research, addressing resource depletion and degradation, while preserving renewable resources and quality of life. [29,30], show green economic development positively impacts greenhouse gas emissions, and resource consumption, and aims for sustainable growth, environmental conservation, and employment [31]. Advancements in ICT have led to digital finance as a novel money management approach, contrasting traditional banking and online banking in their operations [32].

## 3. Empirical Support

### 3.1. Economic growth and environmental quality

There are many studies in the literature on the relationship between EG and EQ, especially on testing the validity of the EKC hypothesis in this context. However, in these studies, the inverted U-shaped EKC hypothesis is generally tested more. Among the current studies, Doğan et al. [33] intensified their research on the relationships between environmental taxes and carbon emissions for G7 countries, and they also confirmed the validity of the EKC hypothesis by using both economic growth and economic complexity variables, as a result of their research.

Balsalobre-Lorente et al. [34] investigated the validity of the N-shaped EKC hypothesis for the developing economies of Central and Eastern Europe, and as a result of the study, the validity of the N-shaped EKC hypothesis is confirmed for the relevant countries. In addition, the study also explains that economic complexity-globalization interaction factors have a positive impact on environmental quality by reducing per capita carbon emissions. In another study, Balsalobre-Lorente et al. [35] investigated the effects of EG on environmental quality using the economic complexity index for BRICS countries. As a result of the research, it was confirmed that the EKC hypothesis is valid for the relevant countries. Esmaeili et al. [36] investigated the effect of foreign direct investments, EG represented by the economic complexity index and the interaction of economic complexity-foreign direct investment on CO2 emissions in N-11 countries at different quantiles. As a result of the research, the validity of the EKC hypothesis was confirmed for N-11 countries, and it was also determined that the interaction of economic complexity and foreign direct investment positively affects environmental quality.

Some studies in the literature also obtain detailed results on individual countries rather than specific country groups. Sun et al. [37], the inverted U-shaped EKC hypothesis was confirmed for China. Bekun [38] confirmed that the EKC hypothesis is also valid for South Africa. However, Bekun [39] differs from the general literature results by concluding that economic growth reduces $CO_2$ emissions in India. Hossain et al. [40], as a result of the research conducted for India, confirm the existence of an N-shaped EKC hypothesis in India when $CO_2$ is used as the dependent variable, but when the ecological footprint is the dependent variable, the N-shaped EKC cannot be confirmed.

Maduka et al. [41] confirm the validity of the N-shaped EKC hypothesis for Nigeria in both short and long-term analyses, quantile regression results also confirm this result. Shahbaz et al. [42], as a result of their research on the 10 countries that emit the most emissions, it was determined that EG causes EQ deterioration by increasing the ecological footprint. Sinha et al. [43] carried out a very different study and analyzed the global inequality in access to energy and separated this situation into its components using the Kaya-Theil decomposition method. Jahangir et al. (2022) study, the relationship between the economic globalization index and $CO_2$ was analyzed for 78 developing countries from different continents of the world, and as a result, the negative effect of the economic globalization index on environmental quality was determined. Although a different economic variable was used in the study, there was no change in the general result in the literature.

It shows that the EKC hypothesis is confirmed in almost all of the results. In other words, with economic development, environmental quality first decreases and then increases. As stated by Shafik [17], countries neglect local air pollution until they reach a certain income level, but air pollution problems are taken more seriously at the middle-income level. As seen in the literature reviews above, the literature on testing the N-shaped EKC hypothesis is relatively limited. Studies on the N-shaped EKC hypothesis, which may have important consequences for environmental quality, need to be intensified.

### 3.2. Digitalization and environmental quality

The advent of the fourth industrial revolution has sparked a significant wave of digitalization and technological advancement. Since the decade pertaining to the 2000s, a growing number of academic practitioners have delved into exploring the dynamics of digitalization on the EQ. Literature is evident that an enormous number of researchers have documented the decisive role of DG in mitigating $CO_2$. For instance, Danish et al. [9] conducted their research in the context of emerging economies and found the negative relationship between DG and $CO_2$. Usman et al. [44] performed a similar study for the case of Asian Economies and unveiled the favorable impact of digital adaptation on the EQ. Wang et al. (2022) highlighted that digital adaptation plays a compelling role in promoting sustainable economic expansion while dropping global $CO_2$. Ben Lahouel et al. (2022) investigated the dynamic relationship between DG and $CO_2$ in the case of MENA countries and found that DG offers various solutions to address environmental challenges. Faisal et al. [45] did similar research for the case of fast emerging economies. The key findings of the study showed that digitalization helps to reduce the level of carbon emissions beyond a certain threshold. Hence, the study reported the favorable impact of DG on the EQ. Añón Higón et al. (2017) indicated DG as a powerful tool that helps to abate the global $CO_2$. Li et al. [46] also drew the same conclusions for the case of BRI nations. The study suggests that investment in digital infrastructure can pave the way to a more sustainable future. Islam & Rahaman [47] investigated the impact of DG on $CO_2$ after considering the potential asymmetries for the case of GCC economies and found the promising role of DG in alleviating the environmental problems. Yukarıda teorik çerçeve kısmında açıklandığı gibi dijitalleşmenin çevre için çeşitli olumlu ve olumsuz etkilerinin olduğu, sürdürülebilir çevre üzerine net etkisinin de bu etkilerin üstünlüğüne bağlı olduğu belirtildi. As explained in the theoretical framework section above, it was stated that digitalization has various positive and negative effects on the environment, and its net effect on the sustainable environment depends on the dominance of these effects. Accordingly, the greater the positive effects of the opportunities offered by digitalization, such as smart transportation systems, smart energy systems, and optimal stock estimation, will contribute more to environmental sustainability.

While a surfeit number of studies documenting the favorable impact of DG on EQ, some researchers hold opposing views. They view digitalization as a paradoxical blade [48]. Such researchers contend that digitalization can exacerbate environmental issues instead of mitigating them because the penetration of DG is aligned with the intense amount of energy consumption. For instance, Batool et al. [49] performed their analysis on East and South Asian Economies and found the positive relationship between DG tends to increase $CO_2$ in the long run. Uddin et al. [50] conducted their research for the case of G20 economies and unveiled that DG leads to an upsurge in the $CO_2$. Hence, the study did not find any favorable impact of DG on the EQ. Tsimisaraka et al. [51] showed that DG has the potential to address the environmental problems in the short run, but it significantly elevated the level of $CO_2$ in the long run. Godil et al. [52] also showed that DG is not favorable for the EQ in the Long run. Shobande & Asongu [53] did a comparative study and found that DG holds significant influence in promoting environmental sustainability in South Africa, while the study identified significant environmental challenges associated with the use of DG in Nigeria.

Triangulating the above literature, it is reasonable to propose that DG-EQ nexus remains an enigmatic paradox with no clear consensus among the researchers. Hence, more studies are required to warrant a better understanding of the actual impact of digitalization.

### 3.3. Technological innovation and environmental quality

The academic discourse is evident with multiple attempts of the researchers to explore the relationship between TI and EQ. However, the findings of existing studies are caught in a web of conflicting viewpoints. For instance, one strand of researchers reported the positive, while others reported the negative relationship between TI and EQ. For instance, Weina et al. [54] utilized the annual time series data of Italy and found the negative association between TI and $CO_2$. The study concluded that TI plays an important role in fostering environmental sustainability. Mongo et al. [55] did similar research in the context of Europe and unveiled the substantial contributions of TI in mitigating $CO_2$. Chen & and Lee [56] gathered the data from 96 global economies and tested the impact of TI and R&D expenditures on $CO_2$. The outcomes of the study yielded promising evidence regarding the beneficial role of TI in mitigating $CO_2$ levels. The study further substantiated the positive effect of R&D investment in coping up with various environmental disputes. Ahmed et al. [57] also confirmed the beneficial role of TI in mitigating environmental problems in the case of South Asian Economies. Yii & Geetha [58] performed their analysis on Malaysia and unveiled negative association between TI and $CO_2$. The study showed that advanced technologies possess the capacity to generate a specified level of output while consuming fewer units of energy. Naqvi et al. [59] also discussed the significant contributions of technological advancement in reducing $CO_2$ in the case of G7 economies. Bai et al. [60] showed that TI is favorable for the EQ as it promotes the sustainable expansion of the economy. Amin et al. [61] utilized the data of South Asian Countries and found the significant contributions of TI in lessening global environmental disputes.

On the flip side, Villanthenkodath and Mahalik [62] does not find any significant contribution of TI in the reduction of $CO_2$. They contended that the utilization of advanced technologies may be fruitful for the EQ in the short run, but it may lead an unintended consequences in the long run. Wang et al. [6] demonstrated that the use of advanced machinery is associated with intense energy consumption, which may have adverse consequences for EQ in the long run. Wang et al. [63] utilized the provincial data of China and showed the insignificant contributions of TI in the reduction of $CO_2$. The study concludes that the utilization of advanced technologies does not help to mitigate environmental disputes until or unless they are energy efficient. Summarizing the above debate, it is reasonable to propose that the extant body of research pertaining to TI-EQ yields skeptical evidence with no definite consensus among researchers. Hence, more studies are required to ascertain a more comprehensive understanding of the actual impact of TI.

In conclusion, digitalization, technological innovation, and financial innovation have a significant impact on environmental quality. While these developments have the potential to greatly improve environmental quality and tackle major environmental problems worldwide, it is important to recognize that economic expansion has an impact on environmental quality, but it can also lead to increased pollution and resource consumption. Future sustainability may result from an understanding of how these variables interact, and it is essential to promote sustainable financial innovations and green financing to reduce the damaging consequences of financial development on the environment.

### 3.4. Financial innovation and environmental quality

The studies on the nexus between FI and EQ are not very rich in the available body of scholarly literature. Only a handful of researchers have endeavored to investigate the relationship between FI and EQ. For instance, Zhan et al. [64] investigated the impact of FI on the $CO_2$ of China and found that FI plays an important role in lessening environmental problems. Huo et al. [65] also demonstrated that FI fosters environmental sustainability. Jianguo et al. [66] analyzed the data of BRICS countries and documented the compelling role of FI in the pursuit of carbon neutrality targets. Tao et al. [48] established the significant importance of fintech development in attaining carbon neutrality targets. Likewise, Najam [67] unveiled the promising impact of FI in curtailing $CO_2$ emissions and achieving carbon neutrality targets. Udeagha & Muchapondwa [68] demonstrated that FI provides the means to access eco-friendly and energy-efficient technologies that helps to alleviate the environmental problems. Cheng et al. [69] conducted their study exclusively within the confines of China, utilizing city-level data, and revealed a negative association between FI and EQ. Li et al. [70] found that FI helps to fund cleaner energy projects and subsequently helps to lessen global environmental disputes. Hence, the study documented the significant contributions of FI in improving EQ. Chishti and Sinha [71] utilized the data of BRICS countries and discerned the negative association between FI and $CO_2$. Authors concluded that FI plays an important role in mobilizing the capital towards environmentally friendly projects which is advantageous for the EQ. Jamshidi et al. [72] also demonstrated the notable contributions of FI in curtailing $CO_2$. Authors concluded that FI facilitates the expansion of renewable projects and scales up the cleaner technologies which subsequently help to promote environmental sustainability.

Summarizing the above literature, it is reasonable to propose that the scholarly pursuit of FI-EQ nexus garnered relatively limited attention when compared to other domains. As such, there is much potential to research this area, specifically in the context of OECD economies.

### 3.5. Research gap

To the extent of the authors' best knowledge, none of the research is conducted in the OECD countries to validate the N-shaped EKC which is a significant research gap. In addition, there is little research examining the impact of FI on EQ. In these studies, no research has been found for OECD countries. Moreover, a new FI measure utilized in the studies of Beck et al. [73] and Bernier & Plouffe [74] was used in this study. In this context, this study will contribute to the literature.

## 4. Data and estimation Methodology

This study mainly aims to determine the impact of digitalization (DG), technological innovation (TI), and financial innovation (FI) on environmental quality (EQ). Additionally, the validity of the N-shaped EKC hypothesis will be determined for OECD countries to identify the role of economic growth (GDP) on EQ. The study utilizes annual data between 2009 and 2019 for 17 OECD countries (Belgium, Canada, Czechia, Denmark, Finland, Germany, Israel, Italy, Lithuania, Norway, Poland, Portugal, South Korea, Spain, Turkey, the UK, The USA). The dependent variable and measurement of EQ used in the study is carbon emissions ($CO_2$), which is frequently used in the literature [75–83]. The first independent variable used in the study is FI, measured by research and development expenditure and intensity (Value Added) in the financial sector, following Beck et al. [73] and Bernier & Plouffe [74].

This data was obtained from the ANBERD (Analytical Business Enterprise Research and Development) database. The second independent variable is TI, measured by the literature by patent applications [84–88]. The third independent variable represents DG and is measured by the internet usage rate within the population [82,89–92]. The fourth independent variable, representing GDP and consistent with studies testing the N-shaped EKC curve, is represented by GDP per capita [93–96]. All variables have been transformed into their logarithms to ensure homoscedasticity. The following 12 models were developed within the scope of the research:

$$CO_{2i,t} = \beta_0 + \beta_1 FI_{i,t} + \beta_2 GDP + \varepsilon_{i,t} \tag{1}$$

$$CO_{2i,t} = \beta_0 + \beta_1 TI_{i,t} + \beta_2 GDP + \varepsilon_{i,t} \tag{2}$$

$$CO_{2i,t} = \beta_0 + \beta_1 DG_{i,t} + \beta_2 GDP + \varepsilon_{i,t} \tag{3}$$

$$CO_{2i,t} = \beta_0 + \beta_1 FI_{i,t} + \beta_2 DG_{i,t} + \beta_3 GDP + \varepsilon_{i,t} \tag{4}$$

$$CO_{2i,t} = \beta_0 + \beta_1 TI_{i,t} + \beta_2 DG_{i,t} + \beta_3 GDP + \varepsilon_{i,t} \tag{5}$$

$$CO_{2i,t} = \beta_0 + \beta_1 FI_{i,t} + \beta_2 TI_{i,t} + \beta_3 DG + \beta_4 GDP + \varepsilon_{i,t} \tag{6}$$

$$CO_{2i,t} = \beta_0 + \beta_1 FI_{i,t} + \beta_2 DG_{i,t} + \beta_3 GDP + \beta_4 GDP^2 + \varepsilon_{i,t} \tag{7}$$

$$CO_{2i,t} = \beta_0 + \beta_1 TI_{i,t} + \beta_2 DG_{i,t} + \beta_3 GDP + \beta_4 GDP^2 + \varepsilon_{i,t} \tag{8}$$

$$CO_{2i,t} = \beta_0 + \beta_1 FI_{i,t} + \beta_2 TI_{i,t} + \beta_3 DG + \beta_4 GDP + \beta_5 GDP^2 + \varepsilon_{i,t} \tag{9}$$

$$CO_{2i,t} = \beta_0 + \beta_1 FI_{i,t} + \beta_2 DG_{i,t} + \beta_3 GDP + \beta_4 GDP^2 + \beta_5 GDP^3 + \varepsilon_{i,t} \tag{10}$$

$$CO_{2i,t} = \beta_0 + \beta_1 TI_{i,t} + \beta_2 DG_{i,t} + \beta_3 GDP + \beta_4 GDP^2 + \beta_5 GDP^3 + \varepsilon_{i,t} \tag{11}$$

$$CO_{2i,t} = \beta_0 + \beta_1 FI_{i,t} + \beta_2 TI_{i,t} + \beta_3 DG_{i,t} + \beta_4 GDP + \beta_5 GDP^2 + \beta_6 GDP^3 + \varepsilon_{i,t} \tag{12}$$

Equation (1) represents the cross-sectional units denoted by $i = 1,\ldots,N$, the periods denoted by $t = 1,\ldots,T$, and the error terms denoted by $\varepsilon_{it}$. $\beta_1,\ldots\ldots,\beta_5$ measure the effects of the independent variables on the dependent variable.

## 5. Empirical Procedure

In this section, a three-stage panel data strategy has been used to determine the effect of DG, TI, and FI on EQ. In the first stage of the research, tests for slope homogeneity and cross-sectional dependence (CSD) were conducted. Next, the 2nd generation unit root and cointegration tests were applied. In the final stage, causality and long-term relationships between variables were estimated.

Consideration of CSD is necessary in panel data analysis. Failure to account for it can result in biased and inconsistent results in the developed panel model [97]. In this study, to test for CSD, the Breusch-Pagan LM test developed by Breusch & Pagan [98], the Pesaran scaled LM ($CD_{LM}$) and Pesaran CD tests developed by Pesaran [97], and the Bias-Corrected Scaled LM ($LM_{adj}$) test developed by Pesaran, Ullah, and Yamagata [99] were applied. In these tests, the rejection of the null hypothesis ($H_0$) and acceptance of the alternative hypothesis ($H_1$) imply the presence of CSD among the series. These 4 tests are indicated in Equations (10)–(13), respectively.

$$LM = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij}^{\,2} \tag{13}$$

$$CD_{LM} = \sqrt{\frac{1}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(T\widehat{\rho}_{ij}^{\,2} - 1\right) \tag{14}$$

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=1+1}^{N}\widehat{\rho}_{ij}\right) \tag{15}$$

$$LM_{adj} = \left(\frac{2}{N(N-1)}\right)^{1/2}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij}^{2}(T-K-1)\frac{\widehat{\rho}_{ij} - \widehat{\mu}_{Tij}}{v_{Tij}} \sim N(0,1) \tag{16}$$

After the CSD test, slope homogeneity was calculated using the Δ tests developed by Pesaran, Ullah, & Yamagata [99]. In the presence of serial correlation and heteroskedasticity, the delta (Δ) tests developed by Blomquist & Westerlund [100] are utilized. The HAC version of the homogeneity test, based on the Delta test, is shown in Equations (14)–(17).

$$\Delta_{HAC} = \sqrt{N}\left(\frac{N^{-1}S_{HAC} - k}{\sqrt{2k}}\right) \tag{17}$$

$$S_{HAC} = \sum_{i=1}^{N} T\left(\widehat{\beta}_i - \widehat{\beta}\right)'\left(\widehat{O}_{iT}V_{iT}^{-1}\widehat{O}_{iT}\right)\left(\widehat{\beta}_i - \widehat{\beta}\right) \tag{18}$$

$$\widehat{\beta} = \left(\sum_{i=1}^{N} T\widehat{O}_{iT}V_{iT}^{-1}\widehat{O}_{iT}\right)^{-1}\sum_{i=1}^{N}\widehat{O}_{iT}\widehat{V}_{iT}^{-1}X_i'M_T y_i \tag{19}$$

$$\widehat{V}_{iT} = \widehat{\Gamma}_i(0) + \sum_{j=1}^{T-1}K\left(\frac{j}{M_{iT}}\right)\left[\widehat{\Gamma}_i(j) + \widehat{\Gamma}_i(j)'\right] \tag{20}$$

In the existence of CSD, the 2nd-generation panel unit root tests are employed. Specifically, the Cross-Sectionally Augmented IPS (CIPS) and Cross-Sectionally Augmented ADF (CADF) panel unit root tests developed by Pesaran [101] are utilized. Pesaran [101] used Equations (18) and (19) for the CADF unit root test.

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + u_{it} \tag{21}$$

$$u_{it} = \gamma f_t + \varepsilon_{it} \tag{22}$$

In the lack of autocorrelation in the factor or error term, the CADF regression is given by Equation (21).

$$\Delta y_{it} = \alpha_i + \rho_i y_{i,t-1} + d_0\overline{y}_{t-1} + d_1\Delta\overline{y}_t + \varepsilon_{it} \tag{23}$$

In the presence of autocorrelation in the factor or error term, the equation can be expanded by adding the first differences of $y_{it}$ and $\overline{y}_{it}$. It can be extended as shown in Equation (22).

$$\Delta y_{i,t} = \alpha_i + \rho_i y_{i,t-1} + c_i\overline{y}_{t-1} + \sum\nolimits_{j=0}^{p} d_{i,j}\Delta\overline{y}_{t-j} + \sum\nolimits_{j=0}^{p}\beta_{i,j}\Delta y_{i,t-j} + \mu_{i,t} \tag{24}$$

To estimate the CIPS statistic in Equation (23), the means of the t-statistics of lagged variables are taken.

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} CADF_i \tag{25}$$

It is important to use an appropriate cointegration test based on the findings of CSD, slope homogeneity, and stationarity. So, the Westerlund & Edgerton [102] Panel LM bootstrap cointegration test is preferred. The cointegration test that takes into account CSD is based on the Lagrange multiplier factor developed by McCoskey & Kao [103]. The equations from which the panel cointegration test is derived can be shown in Equations (24) and (25).

$$\gamma_{it} = \alpha_i + x_{it}'\beta_{it} + Z_{it} \tag{26}$$

$$Z_{it} = \mu_{it} + V_{it}\ V_{it} = \sum\nolimits_{J=1}^{t}\eta_{ij} \tag{27}$$

In Equation (26), the partial sum of the error term $Z_{it}$ is represented as $S_{it}^2$, and the long-run variance of $\mu_{it}$ is denoted as $\widehat{\omega}_i^{-2}$. The cointegration test conducted by Westerlund & Edgerton [102] under CSD uses the following LM statistic to test for cointegration with bootstrap critical values:

$$LM_N^+ = \frac{1}{NT^2} \sum_{i=1}^{N} \sum_{t=1}^{t} \widehat{\omega}_i^{-2} S_{it}^2 \tag{28}$$

In the regression model, in the presence of heteroskedasticity, autocorrelation, or CSD, either the standard errors should be corrected without touching the parameter estimates or, if they exist, appropriate methods should be used to estimate them [104]. In this study, the panel-corrected standard error (PCSE) approach developed by Beck & Katz [105] was preferred as it is robust against these issues and applicable when $T < N$. The PCSE model is given by Equation (27).

$$y_{it} = x_{it}\beta + \varepsilon_{it} \tag{29}$$

where $i$ represents the quantity, ranging from 1 to $m$; $t$ takes on values from 1 to $\mathscr{T}$i; $\mathscr{T}$i indicates the count of time periods in panel $i$; and $+\varepsilon_{it}$ stands for a potential disturbance that could exhibit autocorrelation along the time dimension $t$, or show simultaneous correlation across the panel dimension $i$. This model is written in panel form and is represented by Equation (30).

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} \beta + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_m \end{bmatrix} \tag{30}$$

In a model characterized by heteroskedastic disturbances and simultaneous correlation, but devoid of autocorrelation, it is presumed that the disturbance covariance matrix is as follows:

$$\sum [\varepsilon\varepsilon'] = \Omega = \begin{bmatrix} \sigma_{11}I_{11} & \sigma_{12}I_{12} & \dots & \sigma_{1m}I_{1m} \\ \sigma_{21}I_{21} & \sigma_{22}I_{22} & \dots & \sigma_{2m}I_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{m1}I_{m1} & \sigma_{m2}I_{m2} & \dots & \sigma_{mm}I_{mm} \end{bmatrix} \tag{31}$$

In this context, $\sigma_{ii}$ represents the variability of the disturbances for the i-th panel, while *si* gnifies the covariance of disturbances between panels *i* and *j* when their periods align. Furthermore, *I* denotes a $\mathscr{T}$i by $\mathscr{T}$i identity matrix associated with balanced panels.

The causality test proposed by Dumitrescu & Hurlin [106] can be performed in heterogeneous panels, when $N > T$ or $T > N$, and in the presence of CSD [106]. The linear model that tests the causality between X and Y is as follows.

$$y_{i,t} = \alpha_i + \sum_{k=1}^{K} \beta_{ik} y_{i,t-k} + \sum_{k=1}^{K} \gamma_{i,k} X_{i,t-k} + \varepsilon_{it} \tag{32}$$

In Equation (30), $X_{i,t}$ and subscript represents the stationary variable observations for each *i* in time *t*. It is assumed that the coefficients vary across *i* but remain constant. It is also assumed that the lag length is the same for each *i*, and the panel is balanced.

## 6. Results and discussion

This section presents empirical findings on the relationship between $CO_2$ and the variables FI, TI, DG, and GDP.

### 6.1. Descriptive statistics and correlation matrix outcomes

Table 2 shows the descriptive statistical outcomes (see Table 1). According to the results, the average $CO_2$ emissions per capita for OECD countries are found to be 8.30 metric tons. The average intensity of R&D expenditure in the financial sector, which measures FI, is calculated as 3.25%. The countries with the highest FI levels are Portugal (12.3%) and Finland (11.6%), while the lowest are Turkey (0.1%) and South Korea (0.9%). The average level of DG is determined to be 77.18. The countries with the highest DG levels are Denmark and the United Kingdom, while the lowest are Turkey and Italy.

Table 3 shows the outcomes of the correlation relationship among the variables. A negative relationship exists ($r = -0.35$) between FI and $CO_2$. In other words, a one-unit increase in the FI level causes a 35% decrease in $CO_2$. Additionally, a strong and positive relationship ($r = 0.62$) is found between TI and $CO_2$. Furthermore, a positive relationship exists between $CO_2$ and DG as well as GDP. In conclusion, as the level of FI decreases and the levels of DG, TI, and GDP increase, the level of $CO_2$ also increases.

### 6.2. CSD, unit root, and Hogeneity test result

This section shows the CSD, unit root, and slope homogeneity test results for the variables used in this study.

Table 4 shows the CSD test results for the variables $CO_2$, FI, TI, DG, and GDP used in the study. All variables are found to be statistically significant ($p < 0.05$). Meaning, $H_0$, which states “there is no CSD,” is rejected, indicating the existence of CSD for all series.

The slope homogeneity test results are given in Table 5. $H_0$, which indicates the presence of slope homogeneity, is rejected. In other words, the models developed in the study exhibit slope heterogeneity.

In Table 6, the stationary nature of the dependent and independent variables is examined through CADF and CIPS tests. CADF and CIPS tests are used when CSD is present. The analysis results show that all variables are stationary in the 1st differences. In other words, $H_0$, which states “the series has unit roots” is rejected.

In Table 7, after determining the stationary nature of the variables, the long-term cointegration association between the variables was identified using the second-generation method, Westerlund-Edgerton’s

**Table 1**
Data description.

| Variable(s) | Pictogram | Unit measurement(s) | Source |
|---|---|---|---|
| Carbon emissions | $CO_2$ | $CO_2$ emissions (metric tons per capita) | WDI |
| Financial innovation | FI | Financial sector R&D expenditures Intensity | ANBERD |
| Technological innovation | TI | Patent applications, nonresidents | WDI |
| Digitalization | DG | Individuals using the Internet (% of population) | WDI |
| Income | GDP | GDP per capita (constant 2010 US$) | WDI |

Note: ANDERD (Analytical Business Enterprise Research and Development database); WDI (world development indicator(s)).

**Table 2**
Descriptive statistics.

| Variable(s) | Obs | Mean | Std.dev | Min | Max |
|---|---|---|---|---|---|
| $CO_2$ | 187 | 8.300476 | 3.438666 | 3.695956 | 17.43174 |
| FI | 187 | 0.032517 | 0.040883 | 0.00002 | 0.218908 |
| TI | 187 | 30698.45 | 71153.71 | 81 | 295327 |
| DG | 187 | 77.18707 | 13.80389 | 36.4 | 98.04643 |
| GDP | 187 | 37520.58 | 19210.4 | 8989.503 | 102913.5 |

**Table 3**
Correlation matrix.

| Variable(s) | $CO_2$ | FI | TI | DG | GDP |
|---|---|---|---|---|---|
| $CO_2$ | 1.0000 | | | | |
| FI | −0.3527 | 1.0000 | | | |
| TI | 0.6224 | −0.2324 | 1.0000 | | |
| DG | 0.1347 | 0.0072 | 0.1404 | 1.0000 | |
| GDP | 0.3346 | 0.0589 | 0.1618 | 0.6122 | 1.0000 |

**Table 4**
Cross-sectional dependence test results.

| Variable(s) | $CO_2$ | FI | TI | DG | GDP |
|---|---|---|---|---|---|
| Breush-Pagan LM | 584.410*** (0.000) | 475.317*** (0.000) | 391.709*** (0.000) | 1114.87*** (0.000) | 451.297*** (0.000) |
| Pesaran scaled LM | 26.158*** (0.000) | 19.543*** (0.000) | 14.473*** (0.000) | 58.322*** (0.000) | 18.086*** (0.000) |
| Bias-corrected scaled LM | 25.308*** (0.000) | 18.693*** (0.000) | 13.623*** (0.000) | 57.472*** (0.000) | 17.236*** (0.000) |
| Pesaran CD | 11.596*** (0.000) | 6.620*** (0.010) | 5.621*** (0.000) | 32.565*** (0.000) | 13.708*** (0.000) |

**Note:** The *p*-values are given in parentheses. *** denotes significance at 1% level.

**Table 5**
Test of slope homogeneity.

| Models | Statistics | P-Values |
|---|---|---|
| $\tilde{\Delta}$ | 11.538 | <0.000 |
| $\tilde{\Delta}$ adj | 9.752 | <0.000 |

**Table 6**
CADF and CIPS unit root test results.

| Variable(s) | CADF test statistic for constant | | CIPS test statistic for constant | |
|---|---|---|---|---|
| | Level | first difference | level | first difference |
| $CO_2$ | −1.034 | −2.443*** | −1.257 | −4.391*** |
| FI | −1.313 | −2.956*** | −1.789 | −5.452*** |
| TI | −0.983 | −2.297*** | −1.023 | −4.059** |
| DG | −2.343** | −5.422*** | −3.191*** | −7.591*** |
| GDP | −2.195* | −4.874*** | −2.353** | −6.784*** |

Note: *, ** and *** denote significance at 10%, 5%, and 1% levels, respectively.

**Table 7**
Westerlund-Edgerton's LM bootstrap cointegration test results.

| Test | LM Statistics | Asymptotic-p Value | Boostrap-p Value |
|---|---|---|---|
| $LMN^T$ | 14.364 | 0.0000 | 0.797 |

Note: The number of bootstrap iterations is 1000. The test result is obtained with the constant and trend models.

[102] LM Bootstrap test. Due to the presence of CSD in the variables, the Bootstrap-p value should be considered. For the model examining the impact of independent variables FI, TI, DG, and GDP on the dependent variable $CO_2$, the Bootstrap-p value exceeds 0.10. Therefore, $H_0$ is accepted. It can be claimed that a cointegration relationship exists.

### 6.3. Long-run coefficients from the PCSE model and causality test result

Table 8 presents the results of 12 developed models using the PCSE method. The developed models examine the impact of FI, TI, DG, and GDP (GDP, $GDP^2$, $GDP^3$) on carbon emissions ($CO_2$) for OECD countries. The impacts of the independent variables on the R-squared ($R^2$) were compared using single, pairwise, and triple models. Additionally, the validity of the N-shaped EKC hypothesis was tested by adding variables for GDP (GDP), the square of GDP ($GDP^2$), and the cube of GDP ($GDP^3$) to these models.

In the PCSE analysis, FI was included in 7 models. According to the results, in all models, FI has a significant and negative effect on $CO_2$. So, as the level of FI increases in OECD countries, the level of $CO_2$ decreases. The model combining DG and TI with FI increases the explanatory power and R-squared value for $CO_2$. These results indicate that FI is a positive factor for enhancing EQ.

Research is aligned with the broader strand of literature and implies that the increase in FI is significantly aligned with the reduction in carbon emissions [65,71,72]. Undoubtedly, FI, when directed toward sustainable investments and green financing, accelerates the transition to a greener economy which paves the way toward environmental sustainability. As highlighted in various studies, targeted financial incentives, such as green bonds and carbon pricing mechanisms, can steer capital towards environmentally friendly projects, fostering positive environmental outcomes and also contributing to a low carbon economy [67].

The second independent variable, TI, significantly and positively affects $CO_2$. Thus, as the level of TI increases, the level of $CO_2$ also increases. The model combining FI, DG, and TI enhances the explanatory power and R-squared value for $CO_2$. Therefore, an increase in the number of patents representing TI in OECD countries has a detrimental effect on EQ. According to this result, it can be said that TI cannot be used effectively in OECD countries. On the other hand, patent applications are used to represent the TI variable in this study. The findings can be confirmed using different variables such as R&D expenditures. The third independent variable, DG, shows a negative relationship with $CO_2$. Meaning, a rise in DG results in a rise in carbon emissions. Similarly, the model combining FI, TI, and DG enhances the explanatory power for $CO_2$. Therefore, an increase in the level of DG in OECD countries is harmful to EQ. This result can be explained as the negative effects of digitalization in OECD countries are more dominant than the positive effects, in other words, digital technologies cannot be used effectively.

To some extent, these findings are in contrast to an extant body of literature [44,45,57,107], but we have potential reasoning to justify such relation in the light of existing studies [48,51]. One possible justification is that the consumption of TI and DG is aligned with the intense amount of energy consumption. In such economies, where energy is produced with unconventional sources, the DG and TI may increase the share of energy-oriented $CO_2$ to total $CO_2$ which can lead to adverse consequences for EQ in the long run [62]. Moreover, the rapid pace of advancement in TI and DG might lead to increased consumption of electronic devices which can hamper the EQ [108].

In the study, the impact of GDP as the final independent variable on EQ was tested using the N-shaped EKC hypothesis. The results indicate that in all models, the first level of GDP hurts EQ for OECD countries. On the other hand, the second level of GDP has contributed to reducing $CO_2$. Maduka et al. [41] associated this improvement in EQ with the adoption of various technologies and innovations that significantly contribute to sustainability. However, the third level of GDP (LGDP3) has led to a rise in $CO_2$. Even though at the third stage of GDP (GDP3), the negative impact on EQ is not as strong as at the first level of GDP (GDP), it still has an adverse effect. Jahangir et al. (2023) explained this phenomenon in the third stage of GDP (GDP3) as a slowdown in innovation and the overshadowing of innovation growth by efforts to improve GDP. In conclusion, these findings confirm the validity of the N-shaped EKC hypothesis. Similar findings were obtained by Shehzad et al. [93] for Algeria, Jahanger et al. [96]) for the largest nuclear energy-producing countries, and Fakher et al. [94] for OPEC countries. However, Liu et al. [12] found a U-shaped EKC curve for 125 countries, Sun et al. [37] for China, Jahangir et al. (2022) for 78 developing countries, and Hossain et al. [40] for India.

In conclusion, the empirical findings regarding the impact of FI, TI, DG, GDP, GDP2, and GDP3 variables on EQ are illustrated in Fig. 1. FI has a positive effect on EQ, while DG and TI increase $CO_2$. Increasing R&D intensity in the financial sector of OECD countries and developing environmentally friendly and sustainable TIs are crucial for mitigating $CO_2$. Another crucial finding is the differentiation of the environmental impact of OECD countries at different income levels.

**Table 8**
Findings of long-run elasticity estimates.

| Variables | (Model 1) | (Model 2) | (Model 3) | (Model 4) | (Model 5) | (Model 6) | (Model 7) | (Model 8) | (Model 9) | (Model 10) | (Model 11) | (Model 12) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | $CO_2$ | $CO_2$ | $CO_2$ | $CO_2$ | $CO_2$ | $CO_2$ | $CO_2$ | $CO_2$ | $CO_2$ | $CO_2$ | $CO_2$ |
| FI | −1.89* (2.35) | – | – | −10.297*** (3.72) | – | −2.13** (3.26) | −2.51** (3.53) | – | −1.78* (3.00) | −2.70* (3.24) | – | −1.65* (3.10) |
| TI | – | 7.31*** (1.33) | – | – | 7.75*** (1.78) | 7.54*** (3.53) | – | 7.95*** (1.25) | 8.37*** (3.00) | – | 11.13*** (1.41) | 11.11*** (2.35) |
| DG | – | – | 11.67*** (0.007) | 12.27*** (0.087) | 12.54*** (0.006) | 12.58*** (0.006) | 4.09*** (0.01) | 4.11*** (0.009) | 3.93*** (0.01) | 3.87*** (0.012) | 4.67*** (0.001) | 4.81*** (0.01) |
| GDP | 15.59*** (0.0001 | 15.53*** (0.0001) | 2.52** (0.0001) | 2.58*** (0.0001) | 2.32** (0.0001) | 2.38** (0.0001) | 5.11*** (0.0001) | 5.08*** (0.003) | 5.03*** (0.002) | 6.87*** (0.002) | 6.90*** (0.017) | 6.80*** (0.01) |
| $GDP^2$ | – | – | – | – | – | – | −4.76*** (1.14) | −4.79*** (1.90) | −4.78*** (3.09) | −6.29*** (1.30) | −6.41*** (1.21) | −6.39*** (1.21) |
| $GDP^3$ | – | – | – | – | – | – | – | – | – | 5.59*** (2.29) | 5.78*** (2.77) | 5.81*** (6.76) |
| Constant | 12.43*** (3.45) | 13.64*** (2.87) | 17.95*** (3.86) | 19.87*** (3.96) | 14.87*** (2.61) | 14.87*** (2.71) | 12.11*** (2.37) | 14.53*** (4.76) | 18.54*** (6.73) | 9.21*** (1.19) | 8.97*** (1.64) | 9.12*** (1.94) |
| Observations | 187 | 187 | 187 | 187 | 187 | 187 | 187 | 187 | 187 | 187 | 187 | 187 |
| R-squared | 0.7318 | 0.7761 | 0.8092 | 0.8160 | 0.8644 | 0.8686 | 0.8414 | 0.8763 | 0.8871 | 0.8673 | 0.9009 | 0.9053 |
| Number of groups | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 |

Note. Standard errors are in parentheses.

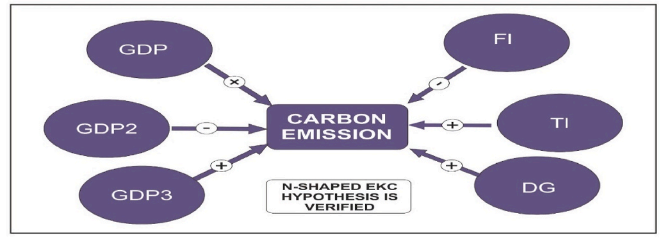


**Fig. 1.** Graphical exhibition of empirical conclusions.

After estimating the long-run elasticity coefficients, the causal relationship between $CO_2$, FI, TI, DG, and GDP variables was determined using the Dumitrescu-Hurlin test, as presented in Table 9. The results indicate a unilateral causality from FI to $CO_2$. Similarly, a unilateral causality from TI to $CO_2$ was found. Furthermore, a bilateral causal relationship between DG and $CO_2$ was identified. Finally, a bilateral causality was observed between GDP and $CO_2$.

## 7. Conclusion and policy implications

Environmental issues have become a paramount focus for researchers and policymakers alike. For decades, researchers have been conducting their studies to unravel a range of factors to address global environmental concerns and this debate continues. The advent of the fourth industrial revolution has sparked a significant wave among researchers to conduct research from another angle. In this pursuit, various researchers and academic practitioners have delved into exploring the dynamics of digitalization (DG), technological innovation (TI), and financial innovation (FI) vis-à-vis their potential impacts on environmental quality (EQ). However, despite the decade of research, researchers do not reach a definite consensus regarding their actual impact. Consequently, there is an increasing call for further exploration of this avenue, specifically in the context of OECD economies. Indeed, the importance of conducting research in the realm of OECD economies cannot be overstated. As influential players in the global arena, these advanced economies bear a significant responsibility in shaping environmental outcomes. Therefore, the present research aims to investigate the contributions of DG, TI, and FI on the environmental quality under the theoretical lenses of environmental Kuznets curve (EKC) theory. Specifically, the study endeavors to validate the N-shaped pattern of the EKC in the context of OECD economies. To achieve this goal, data covering the period 2009–2019 for 17 OECD economies were analyzed empirically with panel data analysis.

The outcomes of the study revealed interesting findings. According to the empirical results, FI has a positive effect, but DG and TI have negative effect on environmental quality. The first income (GDP), the second income (GDP2), and the third income levels (GDP3) have a negative, positive, and negative impact on environmental quality, respectively. The income results of the study show the successful validation of the N-shaped EKC hypothesis in the context of OECD economies.

**Table 9**
Dumitrescu-Hurlin panel causality test results.

| | W-bar | Z-bar | P-values |
|---|---|---|---|
| $CO_2 \nrightarrow FI$ | 1.482 | 1.405 | 0.159 |
| $FI \nrightarrow CO_2$ | 1.793 | 2.313 | **0.020** |
| $CO_2 \nrightarrow TI$ | 1.477 | 1.390 | 0.164 |
| $TI \nrightarrow CO_2$ | 4.126 | 9.116d | **0.000** |
| $CO_2 \nrightarrow DG$ | 3.103 | 6.132 | **0.000** |
| $DG \nrightarrow CO_2$ | 3.660 | 7.756 | **0.000** |
| $CO_2 \nrightarrow GDP$ | 2.015 | 2.960 | **0.003** |
| $GDP \nrightarrow CO_2$ | 2.515 | 4.417 | **0.000** |

Note: The maximum lag length is taken as 1.

The study's findings are imperative because they offer incisive recommendations for OECD economies' strategy to promote environmental sustainability. Before all else, there is a pressing need to promote sustainable financial innovations that prioritize green financing and investments. Encouragement of the use of certain financial incentives, such as green bonds and carbon pricing systems, can efficiently channel capital towards environmentally friendly initiatives, resulting in beneficial environmental significance and achieving the objective of a low-carbon economy. Policymakers must also strike a delicate balance in managing the advancements of DG and TI. While benefiting from the potential of these technologies, regulations must be enacted to mitigate their energy-intensive consumption and potential environmental repercussions. In this context, emphasis should be placed on renewable energy sources in energy use, and carbon capture, use, and storage technologies should be developed. At the same time, measures should be taken for the disposal of hazardous digital waste, and if possible, the use of recyclable materials in the production of digital technologies should be expanded. In addition, policymakers should adopt measures that are specific to each income level, taking into account the various effects on environmental quality across various financial tiers. It is important to adopt targeted measures that include sustainable development, carbon emission reduction, and stepped-up environmental protection for economies with different income levels. The N-shaped EKC's successful validation in the context of OECD economies highlights the importance of comprehending the curve's crucial turning points and formulating strategies appropriately. We believe that by putting these policy recommendations into practice, policymakers may steer their economies toward a future that is more ecologically resilient and sustainable, promoting favorable environmental outcomes and fostering a greener, more prosperous global society. According to the Energy Outlook 2024 report published by The Economist Intelligence Unit (EIU), it is stated that fossil fuels will still be the leader in energy consumption, in particular, approximately 40% of this consumption will be petroleum products and approximately 30% will be coal. It is anticipated that approximately 14% of total consumption will come from renewable energy. Although an increase in energy demand is predicted globally, this is not the case for Europe. This situation is promising, considering that OECD countries generally consist of European countries [109]. In this case, the focus should be on promoting renewable energy technologies.

Future studies, when investigating the relationships between variables, the short-term coefficients for relevant countries can be obtained and compared with the long-term coefficients. Thus, information can be obtained about whether the short-term policies are in congruence with the long-term policies. Another future research avenue could be that OECD countries should be classified according to their development levels and comprehensive examination should be undertaken in a similar way as in this study. Additionally, ecological footprint can be used instead of $CO_2$ to represent environmental quality in prospective studies. We hope to cover these suggestions in our future work.

## CRediT authorship contribution statement

**Assad Ullah:** Investigation, Writing – original draft, Writing – review & editing. **Mesut Dogan:** Conceptualization, Data curation, Formal analysis, Methodology. **Amber Pervaiz:** Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **Azaz Ali Ather Bukhari:** Writing – original draft, Writing – review & editing. **Hilmi Tunahan Akkus:** Conceptualization, Writing – review & editing. **Husna Dogan:** Writing – review & editing.

## Data availability

Data will be made available on request.

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