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Impact of Internet Use on Ecological Footprint: Panel Data Analysis for Fragile Five Countries (Brazil, India, Indonesia, South Africa, and Turkiye)

Wpływ korzystania z Internetu na ślad ekologiczny: analiza danych panelowych dla pięciu krajów niestabilnych (Brazylia, Indie, Indonezja, Republika Południowej Afryki i Turcja)

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Abstract
In addition to the views that claim that the development of information and communication technologies will result in less environmental pollution and better environmental quality, there are also views that claim that it will increase environmental pollution. In this study, the relationship between environmental quality and information and communication technologies for the 1995–2021 period for the Fragile Five countries was examined using the panel augmented autoregressive distributed lag (ARDL) bounds test method. Ecological footprint was used to represent environmental quality, and the proportion of individuals using the internet was used to represent developments in information and communication technologies. In addition, economic growth, energy consumption, and financial development are included in the model as explanatory variables. According to the results of this study, internet use reduces the ecological footprint in both the short and long run. While financial development reduces the ecological footprint in the long run, energy consumption increases both in the short and long run. Economic growth, on the other hand, increases the ecological footprint in the short run. In line with these results, expanding internet use in the Fragile Five Countries may increase environmental quality.

Key words: fragile five countries, ecological footprint, internet use rate, economic growth, panel ARDL

Streszczenie
Oprócz poglądów, że rozwój technologii informacyjno-komunikacyjnych spowoduje mniejsze zanieczyszczenie środowiska i lepszą jakość środowiska, istnieją również poglądy, że zwiększy to zanieczyszczenie środowiska. W niniejszym badaniu zbadano związek między jakością środowiska a technologiami informacyjno-komunikacyjnymi w latach 1995-2021 w krajach Piątki przy użyciu modelu autoregresyjnego o opóźnieniach rozłożonych (ARDL). Ślad ekologiczny został wykorzystany do przedstawienia jakości środowiska, a odsetek osób korzystających z Internetu został wykorzystany do przedstawienia rozwoju technologii informacyjnych i komunikacyjnych. Ponadto, wzrost gospodarczy, zużycie energii i rozwój finansowy zostały uwzględnione w modelu jako zmienne objaśniające. Zgodnie z wynikami tego badania, korzystanie z Internetu zmniejsza ślad ekologiczny zarówno w krótkim, jak i długim okresie, podczas gdy rozwój finansowy zmniejsza ślad ekologiczny w długim okresie, zużycie energii wzrasta zarówno w krótkim, jak i długim okresie. Z drugiej strony wzrost gospodarczy zwiększa ślad ekologiczny w krótkim okresie. Zgodnie z tymi wynikami, rozszerzenie korzystania z Internetu w krajach Piątki może poprawić jakość środowiska.

Słowa kluczowe: pięć krajów niestabilnych, ślad ekologiczny, wskaźnik korzystania z Internetu, wzrost gospodarczy, panel ARDL

1. Introduction

Sustainable development emphasizes the balance and interaction among economic, social, and environmental issues. The concept of sustainable development was defined for the first time in a report titled *Our Common Future* published by the United Nations World Commission on Environment and Development in 1987. In this report, also known as the Brundtland Report, environmental awareness was emphasized. However, drawing attention to the negative effects of environmental problems on human life dates to even earlier times. The U Thant report, published in 1969, is the first comprehensive document to emphasize that environmental problems threaten human life (Waligorska, Jozwiak and Kolemba, 2023). This report was presented to the general assembly by Sithu U Thant, the secretary-general of the United Nations, on May 26, 1969. The report is also extremely important in that it states that global cooperation is necessary to combat environmental problems. Environmental awareness, which was emphasized in 1969, continued in the following years (Wojcicka and Leski, 2015). The theoretical and empirical literature on the relationships among economic, social, and environmental indicators has also rapidly increased.

Although there are many studies on the causes of environmental pollution and its effects on environmental quality, there are fewer studies examining the impact of information and communication technologies on the environment. The main reason for this is the complexity of the relationship between information and communication technologies and the environment. Information and communications technologies have both positive and negative impacts on the environment. Therefore, there is no clear conclusion about whether the increase in the use of information and communication technologies will lead to an increase or decrease in environmental quality. The results may vary depending on factors such as the economic development status of the country or countries examined, the policies they implement, the level of institutional quality, and the demographic structure. The fact that different results may emerge depending on the characteristics of the countries reveals the need to increase the number of studies on this subject. The more different countries/country groups are examined, and the results obtained are shared, the more accurate inferences can be made regarding how information and communication technologies will affect environmental quality and under what conditions.

In this study, the relationship between internet usage, one of the most fundamental indicators of information and communication technologies, and ecological footprint was analyzed. One of the main aspects of the study that will contribute to the literature is the variable used to represent environmental quality. Although there are studies in the literature examining the impact of information and communication technologies on the environment, most of these studies have used CO_2 emissions or carbon footprint as environmental quality indicators. However, environmental quality is a very comprehensive concept. Taking this comprehensive structure of environmental quality into consideration, ecological footprint was used in this study, unlike other studies. Another different aspect of the study is the group of countries discussed. An application was conducted on the Fragile Five Countries. There is no study in the literature examining the relationship between internet use and ecological footprint in the context of the Fragile Five Countries. However, because the Fragile Five countries are considered to have high economic growth potential and attract interest from foreign investors, it is thought that it is important to examine this country group.

In this study, the panel ARDL method was applied. The dependent variable is the ecological footprint. In addition to internet use as an independent variable, economic growth, energy consumption, and financial development indicators were included in the model. The dataset covers the period 1995–2021.

In this study, information about the general characteristics of the Fragile Five countries is given. Then, the theoretical and conceptual framework was explained. The concept of ecological footprint is touched upon, and the change in ecological footprint indicators of the Fragile Five Countries over time is included. The theoretical infrastructure was created by specifying the effects of information and communication technologies on the environment. Since internet usage rates are used to represent information and communication technologies, we explain how internet usage has changed over time in the countries discussed. After providing information about the methods and variables, the analysis results were shared.

2. Fragile Five Countries

The concept of the Fragile Five was first used in a report published in 2013. The countries described as the Fragile Five in the report prepared by Morgan Stanley Investment Bank are Brazil, India, Indonesia, South Africa, and Turkiye (Okur and Köse, 2021).

The economic crisis, which started in the United States in 2008 and spread to other countries over time and became global, caused the FED to change its policy. The FED tried revitalizing the economy by implementing interest rate reduction and monetary relaxation policies together (Javidiar and Ekaputra, 2019). Because of monetary expansion, some developing countries have had the opportunity to find cheap and long-term funding. They achieved high growth rates during this period. Their good economic performance and the fact that they managed to emerge from the crisis environment with little damage caused foreign capital to shift to these countries (Bayraktar, 2016).

However, as the negative effects of the global crisis slowed down and the economic recovery process took place, the FED began to reduce monetary expansion. FED's monetary restrictions caused foreign capital to start leaving the country, especially in developing countries. The outflow of foreign capital caused the national currencies of the countries to lose value (Javidiar and Ekaputra, 2019). According to Morgan Stanley Investment Bank's report, the five countries where the national currency lost the most value because of normalization in FED policy are Brazil, India, Indonesia, South Africa, and Turkiye. These countries are also called the Fragile Five (Okur and Köse, 2021). The common problems of these countries are not limited to the depreciation of their currencies. High inflation, instability in economic growth, insufficiency of capital, increased unemployment, and the current account deficit problem are the main problems that the Fragile Five countries struggle with (Canbay, 2023).

The fact that countries have a fragile economic structure brings with it many problems and negatively affects future expectations. Economic fragility causes the competitive environment to deteriorate, creating deterrent effects for new investments. Low new investments hinder the increase in production volume and employment, thus disrupting economic growth. These economic conditions make countries more vulnerable to possible crises and shocks (Unver and Doğru, 2015).

3. Ecological Footprint

The harmful effects of environmentally unfriendly production processes on nature endanger the lives of both today and future generations. Increasing awareness of the nativities caused by the rapidly deteriorating environment has brought the concept of sustainable development to the agenda (Moffatt, 2000).

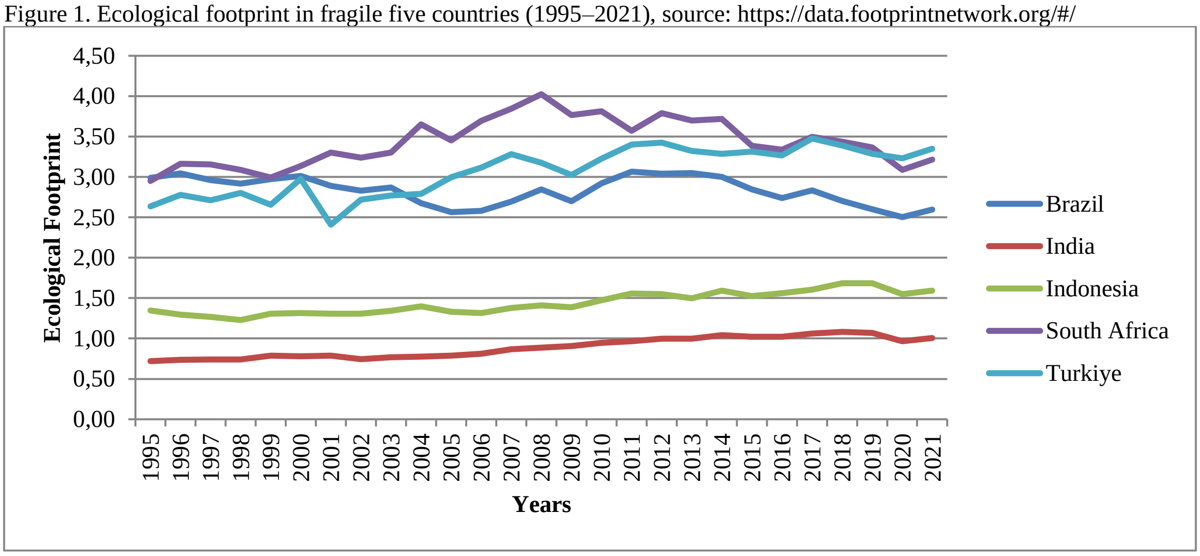
Sustainable development is a comprehensive concept. Therefore, there is no generally accepted absolute definition. However, in the definition of sustainable development made by the United Nations, time and distribution of resources are emphasized. According to the United Nations, sustainable development is acting efficiently and fairly in the distribution of existing resources to meet the needs of today's generations without ignoring the needs of future generations (Hansmann, Mieg and Frischknecht, 2012). Sustainable development does not focus solely on economic objectives or environmental objectives. Sustainable development has a three-dimensional structure, including economic, social, and environmental aspects. The main objectives of development are to increase welfare, increase social development, and create peaceful societies where justice is ensured. However, development is a process that uses and consumes natural resources (Tomislav, 2018). There is an interplay between the economic, social and environmental dimensions of sustainable development. Therefore, these three dimensions should be considered together. Sustainable development objectives try to establish a balance between these three dimensions (Jabareen, 2008). In other words, according to the sustainable development approach, countries can create environmentally friendly production and consumption systems while increasing economic growth and social welfare (Drastichova, 2024). However, striking a balance among economic, social, and environmental dimensions is not easy. Because while considering the interests of one dimension, we may have to act against the interests of other dimensions (Tomislav, 2018). For example, to increase economic growth and social welfare, production should be increased. The production process is directly connected to natural resources. However, production processes disrupt the ecosystem and reduce biodiversity. To minimize the damage to the ecosystem, new production systems should be developed and changes in production and consumption patterns should be made (Nakhle et al., 2024). For this purpose, technological developments should be used. Technological advances and digitalization can be described as the driving force of sustainable development. Information and communication technologies are of great importance in achieving the 17 Sustainable Development Goals adopted in September 2015. In the 9th goal (Goal 9: Industry, Innovation and Infrastructure), there is a direct reference to information and communication technologies. Effective use of information and communication technologies is needed to build the infrastructure necessary to ensure inclusive and sustainable development (Kolupaieva, Sheiko & Polozova, 2024).

New objectives, strategies, and national action plans are being prepared to ensure sustainable development. Because of sustainability debates, an important concept has entered our lives. This concept, expressed as *ecological footprint*, emerged in the early 1990s. The definition of ecological footprint developed by William Rees and Mathis Wackernagel continues to maintain its status by changing and transforming over time. The number of studies examining the ecological footprint is also increasing rapidly (Holden, 2004).

The ecological footprint is a concept based on resource consumption. To sustain life, it is necessary to produce and to use various resources to produce. Waste is created because of the use of resources and production activities (Hoekstra, 2009). Land and water ecosystems are needed to regenerate consumed resources and assimilate the resulting waste. The total area of land and water ecosystems necessary for resource production and assimilation of waste is called the ecological footprint (Costanza, 2000). Ecological footprint is one of the most comprehensive measurement methods for environmental sustainability because it is an indicator of the demand for local and global natural resources. It enables comparison of countries in terms of resource consumption. It also enables temporal comparison. In this way, the development and change processes of countries over time can be evaluated (Jorgenson and Clark, 2011).

The following figure shows how the ecological footprint indicator of the Fragile Five Countries has changed over time. The figure contains data for the 1995–2021 period.
The increase in the ecological footprint indicates deterioration in environmental quality. For this reason, as can be seen from the figure, the ecological footprint in India and Indonesia is lower than that in the other three countries. In other words, the environmental quality is greater in India and Indonesia. In terms of its ecological footprint, India might be considered the most successful of the Fragile Five countries. India's ecological footprint was less than 1 1995–2011. Even though it increased to 1 and above in 2012 and later, the lowest values belong to India compared with the other four countries. Indonesia's values also remained below 1 every year between 1995 and 2021.
The ecological footprint values of Brazil, South Africa, and Turkiye followed a more fluctuating course than those of the other two countries. South Africa and Turkiye's ecological footprint value in 2021 is over 3. When we look at Turkiye, while the ecological footprint value was below 3 between 1995 and 2004, it exceeded 3 in 2005 and thereafter and could not fall below 3 in the following years.
In 2021, the ecological footprint values of Brazil, Indonesia, South Africa, India, and Turkiye were calculated as 2.6, 1.59, 3.22, 1.01, and 3.35, respectively.

Figure 1. Ecological footprint in fragile five countries (1995–2021), source: https://data.footprintnetwork.org/#/



4. Relationship between Information and Communication Technologies and the Environment

Although the impact of information and communication technologies on the environment is a topic of current and increasing interest, debates on this issue continue. While information and communication technologies have positive effects on the environment, they also have negative effects (Hilty et al., 2006). Therefore, whether information and communication technologies improve environmental quality or increase environmental pollution may differ from country to country (Zeeshan Zafar et al., 2023). The positive effects of information and communication technologies on the environment are realized through three basic channels. First, information and communication technologies make environmental monitoring and control easier. Second, information and communication technologies cause structural changes and enable a more efficient use of resources. Third, information and communication technologies change lifestyle and consumption habits (Mahdavi and Sojoodi, 2021).
To reduce or prevent environmental degradation, it is necessary to first estimate in the most accurate way how much the systems used in production and all activities carried out damage the environment. Failure to accurately predict risks may reduce the effectiveness of policies. Risk forecasting is important for determining policy priorities and content. Information and communication technologies can be used to estimate optimal risk. Accurate risk management can be performed with the help of simulation models based on information and communication technologies. Taking necessary measures against environmental pollution can improve environmental quality. In addition, information and communication technologies can be used to manage risk correctly, as well as to detect risk (Majeed, 2018).
Information and communication technologies can also help improve environmental quality by developing environmentally friendly systems. The impact of innovation in reducing environmental pollution should not be overlooked. Information and communication technologies emphasize the role of innovation in the fight against environmental pollution. Innovative solutions are more important, especially in developing countries (Dastres and Soori, 2021). Developing countries implement growth-oriented policies and continue these policies, often at the

cost of polluting the environment. By focusing on innovation, production systems that will not pollute the environment should be created, and techniques that will use renewable energy resources instead of fossil fuels should be developed (Chien et al., 2021).

Although information and communication technologies can increase environmental quality, they also have negative impacts on the environment (Higon, Gholami and Shirazi, 2017). The main argument of the views that argue that information and communication technologies negatively affect the environment is based on energy consumption. Information and communication technologies increase energy consumption, and increased energy consumption also increases carbon and greenhouse gas emissions (Ehigiamusoe, 2023). Economic growth and increasing industrial production are the common goals of all countries. Information and communication technologies are a sector that stand out in ensuring economic growth. Due to the developments in information and communication technologies, the increase in industrial production and energy use due to industrial production increases environmental pollution. In countries where fossil fuel resources are used intensively, the increase in production is expected to have a higher environmental impact (Bhujabal, Sethi, and Padhan, 2021).

Internet usage rates were used in this study as one of the most fundamental indicators of information and communication technologies. The following figure shows the internet usage rates in the Fragile Five Countries. Information can be obtained about how internet use has changed 1995–2021 through the figure showing the ratio of individuals using the internet to the total population.

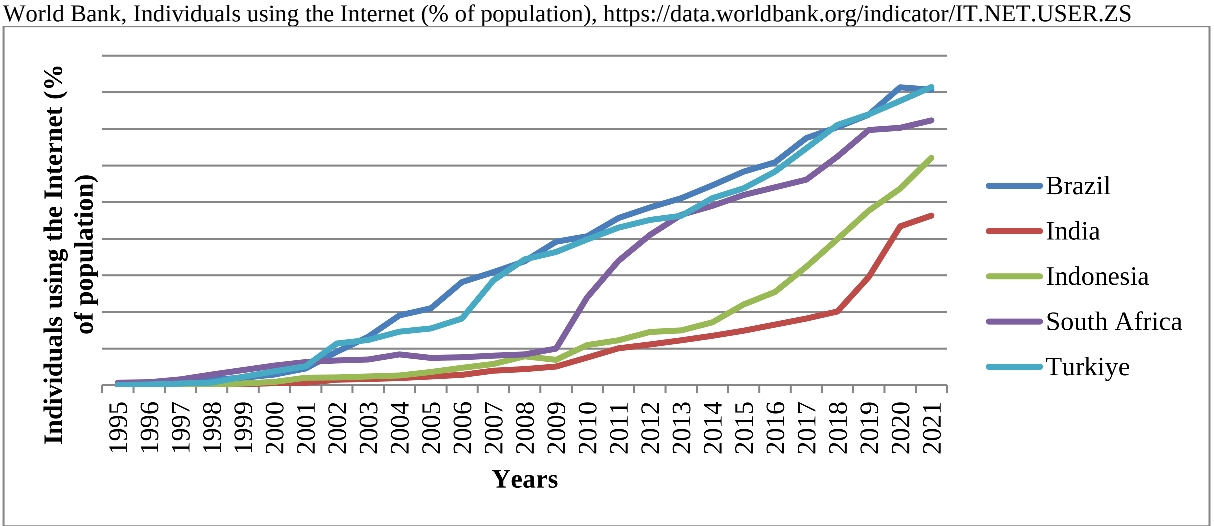
In 1995, the internet usage rate was below 1% in all the Fragile Five Countries. Internet usage rates increased over time. However, this increase is much higher in some countries. For example, the internet usage rate in Turkiye was 0.08% in 1995. By 2021, this rate will reach 81.41%. In fact, the country with the highest internet usage rate among the five countries in 2021 is Turkiye.

In Brazil, the internet usage rate increased from 0.11% in 1995 to over 80%. The Internet usage rate in Brazil is over 80% in 2020 and 2021.

The Internet usage rate in India was calculated as 0.03% in 1995. Internet usage has increased over the years in India. However, despite this increase, the internet usage rate has not exceeded 50%. The year in which India reached its highest internet usage during the 1995–2021 period is 2021 with 46.31%.

Indonesia and South Africa are countries where internet usage is higher than that in India. The internet usage rate in Indonesia was the same as that in India in 1995. However, even though India has not managed to increase this rate above 50%, internet usage in Indonesia will reach over 60% by 2021. In South Africa, internet use is 70.32% and 72.31% in 2020 and 2021, respectively.

Figure 2. Percentage of Individuals Using the Internet (% of Total Population) in Fragile Five Countries (1995-2021), source: World Bank, Individuals using the Internet (% of population), https://data.worldbank.org/indicator/IT.NET.USER.ZS



There are effects of the COVID-19 epidemic on the increase in internet usage in 2020 and beyond. The epidemic, which emerged in Wuhan, China, in December 2019 and quickly spread throughout the world, had an impact in different areas (Strielkowski et al., 2021). The epidemic has caused significant changes, affecting not only the healthcare system but also the economic and social order. One of the main factors that enable the effects of the COVID-19 outbreak to emerge is information and communication technologies (Yang et al., 2020). During the epidemic, lockdowns, closure of educational institutions and entertainment venues, and implementation of travel bans have increased the use of information and communication technologies. Due to the bans, people were forced to perform their working lives, purchase transactions, and other activities online. The use of social media, e-mail systems, shopping sites, and video chat applications has become widespread (Lee, Malcein & Kim, 2021). One of the most important factors that increased internet usage during the epidemic period is the initiation of online education. All countries, including developing countries, have switched to education systems based on internet connection. However, it should not be forgotten that it is not very easy to suddenly switch to online education in developing countries. In most developing countries, due to infrastructure problems, the internet is expensive and slow, computer ownership is low, and hardware deficiency exists. Despite all these problems, information and communication technologies have become more involved in life, and internet usage has increased (Al-Ansi, Garad & Al-Ansi, 2021).

5. Literature Review

Al-Mulali, Sheau-Ting, and Ozturk (2015) examined the effects of online shopping on environmental pollution. In the study using data from 77 developed and developing countries between 2000 and 2013, it was determined that online shopping reduces CO_2 emissions, but this result varies depending on the development level of the countries. The effect of online shopping on CO_2 emissions in developing countries is negative but insignificant. In developed countries, online shopping has a negative and significant impact on CO_2 emissions.

Salahuddin, Alam, and Ozturk (2016) studied the relationship between internet use and environmental quality in Australia. CO_2 emissions were used as an indicator of environmental quality. According to the results of ARDL, it has been observed that internet use and economic growth do not have a significant relationship with CO_2 emissions in the short term. Similarly, no significant relationship was found between internet use and CO_2 emissions in the long term.

Asongu, Le Roux, and Biekpe (2017) examined the relationship between environmental quality, information and communication technologies, and inclusive development. In the study examining Sub-Saharan African countries, the period of 2000-2012 was considered. Internet and mobile phone penetration were used as indicators of information and communication. CO_2 emission represents environmental quality. It has been concluded that environmental pollution negatively affects human development, but information and communication technologies reduce these negative effects.

Park, Meng, and Baloch (2018) examined the relationship between internet use and environmental quality in selected EU countries. CO_2 emissions are a measure of environmental quality. In addition to Internet use, economic growth, trade openness, and financial development was added to the model as explanatory variables. A long-term relationship between internet use and CO_2 emissions has been identified. According to the causality analysis, there is a one-way causality between internet use and CO_2 emissions.

Majeed (2018) investigated the effects of information and communication technologies on the environment. One hundred and thirty-two developed and developing countries were investigated. It has been observed that the effects of information and communication technologies on the environment vary according to the level of development. Information and communication technologies positively affect the environment in developed countries. In developing countries, information and communication technologies have negative effects on the environment.

Ahmed et al. (2019) investigated the relationship between globalization and the ecological footprint. Using Malaysia's data between 1971 and 2014, the Bayer and Hanck co-integration test and the ARDL bound test were applied. Globalization increases the carbon footprint but is not a significant determinant of the ecological footprint. It has been shown that population density and financial development reduce the ecological footprint.

Destek and Manga (2021) examined the effect of technological innovations on the ecological footprint. Both ecological foot and carbon emissions were used to represent environmental quality. the variables create different effects on different indicators of environmental quality. Technological innovations have significant effects in reducing carbon emissions, but they do not have a significant impact on the ecological footprint. Financialization deteriorates environmental quality by increasing both carbon emissions and the ecological footprint.

Addai, Serener, and Kirikkaleli (2022) investigated the relationship between economic growth, urbanization, and the ecological footprint. Data for the period 1998Q4–2017Q4 of Eastern European countries were used. According to the Westerlund co-integration test, it was determined that there is a co-integration relationship between the variables. According to the Dumitrescu– Hurlin causality analysis, there is a unidirectional causality from economic growth to the ecological footprint.

Rout, Gupta, and Sahoo (2022) investigated the effects of technology, energy consumption, and financial development on the ecological footprint of BRICS countries. Technology variables are divided into two groups: technological diffusion and innovation. The percentage of people who use the Internet compared to the overall population, mobile phone subscriptions, and patent applications are indicators of technological diffusion. According to the analysis results, technological diffusion and non-renewable energy use deteriorate environmental quality in the long term. Technological innovation and the use of renewable energy increase environmental quality.

Ansari et al. (2022) tested the environmental Kuznets curve for G20 countries. However, ecological footprint was used as a variable to represent environmental pollution instead of CO_2 emissions. Globalization, renewable energy consumption, and urbanization increase environmental quality by reducing the ecological footprint. Consumption of non-renewable energy decreases environmental quality.

Özpolat (2022) studied how internet use affects environmental degradation in G7 countries. Panel causality analysis and AMG estimator were applied in the study, which used data from 1990 to 2015. Bidirectional causality was determined between internet use, energy use, and ecological footprint. It was also found that internet use has a negative impact on environmental degradation. The impact of trade openness and financial development on environmental degradation is insignificant.
Charfeddine and Umlai (2023) conducted a literature review of studies examining the relationship between environmental sustainability and information and communication technologies. Studies from the period 2000–2022 were evaluated. In most studies on the subject, it has been observed that information and communication technologies improve environmental sustainability. However, there are also studies detecting a negative relationship between information and communication technologies and environmental sustainability. It was observed that the studies-detecting a negative relationship were generally analyzes conducted on *country groups*.
Ucan, Ozturk, and Turgut (2023) determined the factors that determine the ecological footprint in BRICS countries. Different results were obtained depending on the country. Energy consumption, technological development, and globalization are reducing the ecological footprint in Brazil; urbanization increases the ecological footprint. The urbanization rates in India and energy consumption in China reduce the ecological footprint. For Russia and South Africa, the coefficients were insignificant.
Zhang and Chen (2023) investigated the relationship between green finance and the ecological footprint. Co-integration analysis was carried out using China's data for the 1998Q1–2020Q4 period. According to the results of the analysis, green finance, R&D expenditures, and renewable energy increase environmental quality by reducing the ecological footprint. Therefore, increasing the green financing budget is important in ensuring environmental sustainability.
Raihan (2023) examined how technological advances and economic growth affect the ecological footprint. Data from 1985 to2020 were used in the analysis carried out on the example of China. According to the results of the ARDL analysis, economic growth deteriorates environmental quality. Technological developments alleviate the deterioration in environmental quality. In addition, according to the causality analysis, bidirectional causality was determined between technological innovation and economic growth.

6. Research Methodology

In this study, the impact of internet use on the ecological footprint of the Fragile Five Countries (Brazil, India, Indonesia, South Africa and Turkiye) for the period 1995–2021 was examined using the Panel ARDL method. In studies in the literature, the carbon footprint has mostly been used as an indicator of environmental quality. Information and communication technologies are systems based on internet use. Internet use requires energy, and most of it is still produced by coal. However, the pollution caused by burning coal is not limited to air pollution. Deterioration in any area of the ecosystem affects other areas. The use of non-renewable resources such as coal causes air pollution as well as pollution of water, agricultural areas, and forests. Therefore, it would be appropriate to consider a comprehensive indicator that addresses all these elements and to approach sustainability holistically. Ecological footprint was used in the study to eliminate these limitations.
In addition, economic growth, energy consumption, and financial development are included in the model as explanatory variables. The empirical model of the conducted study is shown in Equation 1.

$$Ln(EF_{it}) = \beta_0 + +\beta_{i1}LnNET_{it} + \beta_{i2}LnGDP_{it} + \beta_{i3}LnEC_{it} + \beta_{i4}LnFD_{it} + \varepsilon_{it} \quad (1)$$

Among the variables in the model, LnEF represents the ecological footprint (gha per capita), LnNET represents the ratio of internet use to the total population, LnGDP represents economic growth (GDP per capita - 2015 US dollars at constant prices), LnEC represents energy consumption (primary energy consumption per capita - kWh), and LnFD represents financial development and ε_{it}stands for the error term. Table 1 shows the explanations of the variables and the data source.

Table 1. Data İdentification

Variable	Description	Data Source
LnEF	Per capita Ecological Footprint (gha)	https://www.footprintnetwork.org
LnNET	Individuals using the Internet (% of population)	https://databank.worldbank.org
LnGDP	Per capita Gross Domestic Product (Costant 2015 US$)	https://databank.worldbank.org
LnEC	Per capita energy consumption (KWh)	https://www.iea.org
LnFD	Financial Development (It takes a value between 0 and 1)	https://www.imf.org/en/Home

Before conducting empirical analysis, panel data analysis checks whether the data contain cross-sectional dependency. In this study, because the cross-sectional dimension (N=5) in the panel data set is smaller than the time section dimension (T=27) (N<T), Breusch Pagan (1980) $CDLM_1$ and Pesaran et al. (2008) Bias-adjusted $CDLM_{adj}$ cross-sectional dependency tests were used.
Hypotheses of cross-section dependence tests;

$$H_0 = There\ is\ no\ cross-sectional\ dependency.$$
$$H_1 = There\ is\ cross-sectional\ dependency.$$

Equation (2) provides information on the Breusch–Pagan (1980) $CDLM_1$ test.

$$CDLM_1 = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left(\grave{p}_{ij}^2\right) \rightarrow X^2 \frac{N(N-1)}{2} \quad (2)$$

Equation (3) gives the CDLM adj test from Pesaran et al. (2008).

$$CDLM_{adj} = \left(\frac{2}{N(N-1)}\right)^{\frac{1}{2}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left[\grave{p}_{ij}^2 \left(\frac{T-K-\grave{p}_{ij}-\grave{\mu}_{Tij}}{v_{Tij}}\right)\right] \rightarrow N(0,1) \quad (3)$$

The second step after the cross-section dependence test is to examine whether the slope coefficients of the series are homogeneous. The homogeneity test, known as the delta test and introduced by Pesaran & Yamagata (2008), was used. Hypotheses of the homogeneity test:

$$H_0\text{: } The\ slope\ coefficients\ are\ homogeneous(\beta i = \beta).$$
$$H_1\text{: } The\ slope\ coefficients\ are\ heterogeneous(\beta_i \neq \beta).$$

Equations (4) and (5) give the two test statistics (small sample and large sample) that Pesaran and Yamagata recommended using for analyzing these hypotheses (Pesaran and Yamagata, 2008).

$$for\ Small\ Sample\ : \tilde{\Delta}_{a\,dj} = \sqrt{N}\frac{N^{-1}\tilde{S}-k}{var(t,k)} \quad (4)$$

$$for\ large\ sample: \hat{\Delta} = \sqrt{N}\frac{N^{-1}\hat{S}-k}{\sqrt{2k}} \quad (5)$$

The panel unit root test is used according to the cross-section dependency and homogeneity tests. In cases where there is no cross-sectional dependency in the series, the first-generation unit root test is used, and in cases where there is cross-sectional dependency, the second-generation unit root test is used. Cross-sectional dependence and heterogeneity were identified in the series. For this reason, the Cross-Sectional Augmented IPS-CIPS unit root test, adapted from the Cross-Sectional Augmented Dickey Fuller (CADF) test created by Pesaran (2007), was performed. This test was created by Pesaran and Shin and is a second-generation unit root test. The hypotheses of the CADF test are:

$$H_0\text{: } \beta_1 = \beta_2 = \beta_3 = \ldots.. \beta_n = 0\ (Series\ are\ not\ stationary)$$
$$H_1\text{: } At\ least\ one\ of\ them\ is\ different\ than\ 0\ (Series\ are\ stationary)$$

Equation 6 gives the CADF test.

$$\Delta y_{i,t} = \alpha_{i,t} + b_i y_{i,t-1} + c_i \bar{y}_{i,t-1} + d_i \Delta \bar{y}_{i,t-1} + \varepsilon_{it} \quad (6)$$

Here $\bar{y}_{i,t-1}$, $\Delta\bar{y}_{i,t-1}$ represent the lagged value and the average of the first differences in each cross-section series, respectively. After running the CADF regression for each unit i in the panel, t-statistics on the lagged value are averaged to obtain the CIPS statistic (Baltagi, 2005). CIPS statistics are obtained from equation 7 based on CADF (Pesaran, 2007):

$$CIPS = \frac{1}{N}\sum_{i=0}^{n} CADF_i \quad (7)$$

Pesaran et al. (1999) developed the Panel Autoregressive Distributed Lag (ARDL) model, which is used to examine the relationship between explanatory and dependent variables in both the short and long term. Panel ARDL can be used to estimate models with variables I(0), I(1), or both I(0) and I(1). It also allows cross-sectional dependency and heterogeneity among the series. Pooled mean group (PMG) and mean group (MG) estimators are the two estimators used in the panel ARDL method. The MG estimator allows for heterogeneity of all coefficients, intercepts, and slopes by estimating a separate equation for each country, while coefficients for the entire panel are calculated as unweighted averages of individual coefficients. The PMG estimator, on the other hand, considers a lower degree of heterogeneity because it allows heterogeneity in short-term coefficients and error variances while imposing homogeneity in long-term coefficients. The reliability of the PMG estimator relative to the MG estimator is tested by a likelihood ratio test or Hausman test based on the consistency and efficiency characteristics of the two estimators. The panel ARDL equation showing the long-term relationship can be expressed as in equation number 8 (based on model 1):

$$LnEF_{it} = \alpha_i + \Sigma_{j=1}^{p}\beta_{ij}Ln(EF)_{i,t-j} + \Sigma_{j=0}^{q}\delta_{ij}LnNET_{i,t-j} + \Sigma_{j=0}^{k}\theta_{ij}LnGDP_{i,t-j} + \Sigma_{j=0}^{l}\gamma_{ij}LnEC_{i,t-j} + \Sigma_{j=0}^{m}\lambda_{ij}LnFD_{i,t-j} + \varepsilon_{it} \quad (8)$$

In Equation 8, the time dimension is shown as t = 1, 2, 3,.....T, and the number of horizontal sections is shown as i = 1, 2, 3... N. In addition, the error correction forms of the Panel ARDL model are shown in equation 9.

$$\Delta(LnEF)_{it} = \alpha_i + \varphi_i Ln(EF_{i,t-1}) + \delta_i LnNET_{it} + \theta_i LnGDP_{i,t} + \gamma_i LnEC_{it} + \lambda_i LnFD_{it} + \Sigma_{j=1}^{p-1}\beta_{ij}^{*}\Delta Ln(EF)_{i,t-j} + \Sigma_{j=0}^{q}\delta_{ij}^{*}\Delta LnNET_{i,t-j} + \Sigma_{j=0}^{k}\theta_{ij}^{*}\Delta LnGDP_{i,t-j} + \Sigma_{j=0}^{l}\gamma_{ij}^{*}\Delta LnEC_{i,t-j} + \Sigma_{j=0}^{m}\lambda_{ij}^{*}\Delta LnFD_{i,t-j} + \varepsilon_{it} \quad (9)$$

The short-term relationship is shown by the parameters ($\beta_{ij}^{*}, \delta_{ij}^{*}, \theta_{ij}^{*}, \gamma_{ij}^{*}, \lambda_{ij}^{*}$) placed on the first differences in equation 9 above, and the coefficient of the error correction model is φ_i.

7. Empirical Results

The descriptive statistics and correlation matrix for LnEF, LnGDP, LnEC, and LnNET variables used in the study are shown in Table 2.

Table 2. Summary statistics for the series cum Correlation Matrix

	LnEF	*LnNET*	*LnGDP*	*LnEC*	*LnFD*
Mean	0.723	2.097	8.293	9.335	-0.839
Median	1.000	2.512	8.652	9.490	-0.832
Maximum	1.392	4.399	9.498	10.270	-0.405
Minimum	-0.328	-3.645	6.426	8.030	-1.373
Std. Dev.	0.533	1.985	0.807	0.666	0.227
Skewness	-0.629	-1.011	-0.722	-0.310	-0.098
Kurtosis	1.875	3.346	2.380	1.807	2.284
Jarque-Bera	16.021	23.71	13.910	10.169	3.095
Probability	0.000	0.000	0.000	0.006	0.212
Observations	135	135	135	135	135
Correlation Matrix					
LnEF	1.000				
LnNET	0.438	1.000			
LnGDP	0.942	0.567	1.000		
LnEC	0.961	0.523	0.875	1.000	
LnFD	0.308	0.622	0.356	0.417	1.000

According to the descriptive statistics shown in Table 2, the average of the LnEF variable is 0.723, the maximum value is 1.392, and the minimum value is -0.328. According to skewness values, all variables took a negative value, whereas according to kurtosis values, all variables took positive values. According to the Jarque–Bera normality test, all variables except LnFD are normally distributed. In addition, the correlation between the LnEF variable and other variables in the model is positive.
The variables used in the model, the cross-sectional dependence tests applied, and the delta homogeneity test results are shown in Table 3.

Table 3. Cross-section Dependency and Homogeneity Test Results

	Variables				
CD Tests	*LnEF*	*LnNET*	*LnGDP*	*LnEC*	*LnFD*
$CDLM_1$	22.171 (0.000) *	25.653 (0.000) *	28.032 (0.000) *	22.602 (0.000) *	17.053 (0.000) *
$CDLM_{adj}$	42.545 (0.000) *	31.377 (0.000) *	42.720 (0.000) *	40.416 (0.000) *	20.424 (0.000) *
	Homogeneity Test				
$\tilde{\Delta}$	7.570 (0.000) *				
$\tilde{\Delta}adj$	8.583 (0.000) *				

Note: * indicates the 1% significance level.

According to the results of the cross-sectional dependency tests in Table 3, the H0 hypothesis was rejected because the probability values for all variables were less than 1% significance level. That is, there is a cross-sectional dependence for all variables. This shows that a positive or negative shock occurring in any country in the panel may affect other countries as well. In addition, when we examine the homogeneity tests performed for the variables in Table 3, the H0 hypothesis is rejected because the probability values of the delta tests ($\tilde{\Delta}$ and $\tilde{\Delta}adj$) are less than the 1% significance level. The variables were heterogeneous. The CIPS test was applied as the second-generation unit root test because the variables showed cross-sectional dependence and heterogeneity. Table 4 shows the results of the CIPS test.
According to the results obtained from the CIPS[1] unit root test in Table 4, the variables LnEF, LnGDP, and LnEC show stationarity at this level. However, they become stationary after the first differences are taken. That is, the LnEF, LnGDP, and LnEC variables are I(1). The LnNET and LnFD variables are stationary at their level values. Therefore, LnNET and LnFD variables are I(0). Because the variables used in the model are stationary at different

[1] The critical values of the CIPS statistic are taken from the study of Pesaran (2007).

levels, the Panel ARDL/MG test was applied for the long-term and short-term relationships. Table 5 shows the results of the Panel ARDL/MG test.

Table 4. CIPS Unit Root Test Results

	Level		First difference		
Variables	**Constant**	**Constant and Trend**	**Constant**	**Constant and Trend**	**Result**
LnEF	-1.725	-1.863	-3.226***	-3.177***	I(1)
LnNET	-2.550**	-3.240***	-3.927	-3.902	I(0)
LnGDP	-1.510	-1.712	-3.663***	-4.164***	I(1)
LnEC	-2.102	-2.485	-3.395***	-3.515***	I(1)
LnFD	-2.660***	-2.503	-4.395	-4.781***	I(0)

Note: *, **, and *** indicate the 10%, 5%, 1% significance levels, respectively. CIPS critical values for the constant model: -2.57 for 1%, -2.33 for 5%, and 2.21 for 10%. CIPS critical values for the constant and trend models: -3.10 for 1%, -2.86 for 5%, and 2.73 for 10%.

Table 5. Panel ARDL/MG Estimation Results

Model: **ARDL (1, 1, 1, 1)**	**Long run**		**Short run**	
Variables **(Dependent Variable: *LnEF*)**	**Coefficient**	**Probability**	**Coefficient**	**Probability**
LnNET	-0.023	0.076*	-0.027	0.004***
LnGDP	0.053	0.858	0.474	0.012**
LnEC	0.842	0.000***	0.538	0.000***
LnFD	-0.111	0.005***	-0.29	0.746
Constant Term			-4.764	0.001***
Hausman Testi **Chi^2 (Probability)**	52.42 (0.000)	**ECT_{t-1}**	-0.606 (0.000)	**Observations:** 130 **Countries:** 5

Note: *, **, and *** indicate the 10%, 5%, 1% significance levels, respectively.

According to the Hausman Test results in Table 5, the Panel ARDL/MG results should be interpreted because the probability value is less than 5%. Looking at the long-term coefficients of the model, the coefficient of the LnNET variable is negative and statistically significant. In other words, increasing the percentage of internet users in the total population reduces the ecological footprint in the long term. The coefficient of the variable LnGDP is positive but statistically insignificant. Although the effect of GDP per capita on the ecological footprint is positive in the long term, this effect is not statistically significant. The coefficient of the variable LnEC is positive and statistically significant. Increasing primary energy consumption per capita increases the ecological footprint eventually. The coefficient of the variable LnFD is negative and statistically significant. Increased financial development reduces the ecological footprint eventually. Therefore, while internet usage and financial development reduce the ecological footprint in the long run, energy consumption increases it.

According to the short-run coefficients, the coefficient of the LnNET variable is negative and statistically significant. The short-run coefficient of the LnGDP variable is positive and statistically significant. The short-run coefficient of the LnEC variable is positive and statistically significant. The short run coefficient of the LnFD variable is negative and statistically insignificant. Increasing internet usage increases the ecological footprint in the short term. Therefore, in the short term, while internet use reduces the ecological footprint, economic growth and energy consumption increase it.

When the error correction term of the Panel ARDL/MG model is considered (ECTt-1), the error correction coefficient is negative and statistically significant at the 1% significance level. It can be stated that the error correction model is meaningful and operates correctly. The coefficient of the error correction term was calculated to be -0.606. That is, 60% of the deviations that occur in the short term are balanced in the next period.

In the Panel ARDL/MG estimator, it is possible to examine the short- and long-run coefficients of the variables separately for each country. Table 6 shows the coefficient results on a country-by-country basis according to the Panel ARDL/MG estimator.

According to Table 6, the increase in the proportion of internet users in the total population and financial development in Brazil reduces the ecological footprint in the long term. The increase in primary energy consumption per capita increases the ecological footprint. In India, an increase in the rate of internet users and GDP per capita reduces the ecological footprint in the long term. The increase in primary energy consumption per capita increases the ecological footprint In Indonesia, the increase in GDP per capita and primary energy consumption per capita increases the ecological footprint in the long term. The increase in the number of internet users and financial development in South Africa reduces the ecological footprint eventually. The increase in GDP per capita increases the ecological footprint. Increasing the number of internet users in Turkiye reduces the ecological footprint in the long term. The increase in primary energy consumption per capita increases the ecological footprint.

Table 6. Panel ARDL/MG Estimation Results for Countries

Countries	**Variables**	**Long run**		**Short run**	
	(Dependent Variable: *LnEF*)	**Coefficient**	**Probability**	**Coefficient**	**Probability**
Brazil	***LnNET***	-0.002	0.029**	-0.002	0.471
	LnGDP	0.229	0.711	0.571	0.469
	LnEC	1.161	0.073*	0.577	0.414
	LnFD	-0.478	0.065*	-0.237	0.213
	Constant Term			-7.883	0.064*
	ECT_{t-1}			-0.636	0.022**
India	***LnNET***	-0.001	0.058*	-0.002	0.379
	LnGDP	-0.350	0.011**	-0.122	0.704
	LnEC	1.079	0.000***	0.544	0.042**
	LnFD	-0.145	0.107	-0.216	0.087*
	Constant Term			-7.004	0.001***
	ECT_{t-1}			-0.611	0.001***
Indonesia	***LnNET***	-0.001	0.545	-0.004	0.953
	LnGDP	0.267	0.042**	0.031	0.901
	LnEC	0.256	0.091*	0.538	0.018**
	LnFD	-0.056	0.697	-0.004	0.963
	Constant Term			-3.155	0.000***
	ECT_{t-1}			-0.780	0.000***
South Africa	***LnNET***	-0.002	0.003***	-0.007	0.751
	LnGDP	0.947	0.000***	0.830	0.001***
	LnEC	0.116	0.702	0.222	0.398
	LnFD	-0.146	0.084*	-0.066	0.639
	Constant Term			-9.758	0.001***
	ECT_{t-1}			-0.870	0.000***
Turkiye	***LnNET***	-0.004	0.013**	-0.001	0.564
	LnGDP	-0.473	0.133	0.256	0.168
	LnEC	1.472	0.001***	0.846	0.000***
	LnFD	-0.049	0.774	0.274	0.001***
	Constant Term			-5.447	0.011**
	ECT_{t-1}			-0.621	0.010**

Note: *, **, and *** indicate the 10%, 5%, 1% significance levels, respectively.

According to the short-term coefficients calculated for the countries, increasing primary energy consumption per capita in India increases the ecological footprint in the short term. Increasing financial development decreases the ecological footprint. The increase in primary energy consumption per capita in Indonesia reduces the ecological footprint in the short term. The increase in GDP per capita in South Africa increases the ecological footprint in the short term. The increase in primary energy consumption per capita and financial development in Turkiye increases the ecological footprint in the short term.

When we examine the error correction terms (ECTt-1) for countries, the error correction coefficients are negative and statistically significant at the 5% significance level in all countries. The error correction model is statistically significant and works well in all countries. The coefficient of the error correction term was calculated as -0.636 in Brazil, -0.611 in India, -0.780 in Indonesia, -0.870 in South Africa, and 0.621 in Turkiye. Of the deviations that occur in the short term, 63% in Brazil, 61% in India, 78% in Indonesia, 87% in South Africa, and 62% in Turkiye are compensated in the next period.

8. Conclusions and Recommendations

Since there is no consensus on the effects of information and communication technologies on the environment, research can be conducted with the help of empirical studies based on countries and country groups. Based on the idea that the impact of information and communication technologies on the environment may differ between countries and regions, the Fragile Five countries were the subject of research in this study. In line with the data between 1995 and 2021, short- and long-term effects were evaluated by applying the Panel ARDL test method.

Panel ARDL/MG results were interpreted based on the Hausman test. For the panel in general, according to the long-term results of Panel ARDL/MG, increasing internet use and financial development reduces the ecological footprint. Increasing per capita GDP and energy consumption increases the ecological footprint. However, the effect of GDP per capita is statistically insignificant. In the long run, according to country-based results, increased internet usage in Brazil, India, South Africa, and Turkiye reduces the ecological footprint. The coefficient of the ecological footprint variable in Indonesia is negative but statistically insignificant. In Indonesia and South Africa, increasing per capita GDP increases the ecological footprint, whereas in India, increasing per capita GDP reduces the ecological footprint. The increase in primary energy consumption per capita in Brazil, India, Indonesia, and Turkiye increases the ecological footprint. Increasing financial development in Brazil and South Africa reduces the ecological footprint.

According to the short-term results of Panel ARDL/MG for the panel in general, internet use and financial development negatively affect the ecological footprint. While the effect of internet use is statistically significant, financial development is not significant. Increasing per capita GDP and per capita primary energy consumption increases the ecological footprint. In the short term, according to country-based results, the increase in primary energy consumption per capita in India increases the ecological footprint, and the increase in financial development reduces the ecological footprint. The increase in primary energy consumption per capita in Indonesia reduces the ecological footprint. Increasing per capita GDP in South Africa increases its ecological footprint. Increasing per capita primary energy consumption and financial development in Turkiye increases the country's ecological footprint.

Analysis of the Fragile Five Countries reveals that the rate of internet usage reduces their ecological footprint in the long term. For this reason, within the framework of the example of the Fragile Five countries, findings have been obtained that support the view that information and communication technologies increase environmental quality. These findings are like studies in the literature by Asongu et al. (2017), Majeed (2018), Destek and Manga (2021), Özpolat (2022), and Raihan (2023).

Since it has been concluded that internet use reduces the ecological footprint in the Fragile Five Countries, studies can be conducted to increase internet usage rates. Internet usage in the Fragile Five countries has been increasing over time. However, this rate can be increased in all countries, and individuals who do not use the internet can adapt to this technology. First, the reasons why individuals do not use the internet should be determined. If the reason is insufficient infrastructure, policies should be implemented to strengthen the infrastructure and eliminate technical obstacles. The public's level of awareness should be raised, and informative studies should be conducted on the areas of internet use and the functions of the internet. To address security concerns, cyber security measures should be increased and legal measures to protect personal data should be increased.

Limitations of Research and Recommendations for Future Studies

In this study for the Fragile Five countries, the period 1995–2021 was considered due to the data constraints of the countries. In future studies, more contributions can be made to the literature by using different variables and new models for different country groups (OECD, G7, EU, G20, etc.).

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