

Impact of Information and Communication Technologies, Renewable Energy, and Natural Resources on Environment in Developing Countries

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Abstract

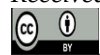
The developing countries have been recurrently confronting a range of environmental issues that pose significant challenges to their sustainable development. The inter-linkages between Information and Communication Technologies (ICT), renewable energy (RE), Natural resources (NR), and ecological footprint (EFP) are turning to be crucial in this regard. We also incorporate economic growth (EG) and Green Technology innovations along with ICT, RE, and NR to examine their influence on EFP in the developing-8 (D-8) countries. A panel data set for the period 1998-2024 for the D-8 member developing countries has been used for empirical analysis. A cross-sectional augmented autoregressive distributive lag (CS-ARDL) estimation method is employed after testing for the cross-sectional dependence. It is found that the natural resources extraction and economic growth enhance the ecological footprint in the long-run. Conversely, renewable energy consumption, ICT, and green innovation show a negative and significant impact on the ecological footprint, suggesting that ICT technologies, innovations, and renewable energy enhance energy efficiency and lower ecological damages. The empirical findings suggest that the Developing countries should concentrate on devising suitable policies to promote ICT, green innovations, and renewable energy generation to achieve environmental sustainability.

Keywords: Renewable Energy, ecological footprint, (CS-ARDL) estimation method

Introduction

The last climate summit was held in Brazil, where the countries have reaffirmed their commitment to undertake steps to reduce environmental degradation. The most common environmental issues of development countries are the high amount of fossil fuel consumption for energy leading to high environmental emissions. Many pollution-emitting industries have been established in the D-8 developing countries, so growth has become emission-intensive. The less effective regulations have prompted companies to violate the environment laws. Other important drivers of CO₂ emissions are the high energy consumption and population growth. The provision of funding for cleaner technologies for reducing the environmental impact is a critical factor in this context. In D-8 countries, the economy has been linked to environmental degradation over the years. It is due to the fact that a lot of the leading industries at the initial stage of growth are re-

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source consuming and polluting. But, once the economy reaches a certain level of GDP, the Environmental Kuznets Curve (EKC) indicates that the economy begins to invest in renewable energy technologies and the trend in emissions begins to turn.

The D-8 countries developed their industries using fossil fuels. The energy consumption has been the highest in Turkey, primarily, among these countries (Dinçer, 2022). The fossil fuel use in the Turkish economy has been playing a significant role in the environment, which has led to environmental emissions (Köne and Büke, 2019). Due to the high fossil fuel dependency, ecological sustainability was a concern (Canbay, 2021). It is quite important to figure out the drivers of environmental emissions, as well as to create a path towards reducing environmental damages, because the D-8 countries are still in the process of managing ecological emissions. The average ecological footprint per capita was estimated to be 2.6 to 2.8 global hectares (gha) per person (Sahoo & Sethi, 2021), which is equivalent to nearly 1.1 hectares over the planet's biological capacity. The ecological footprint is an inclusive indicator of environmental sustainability (Hussain et al., 2022). The shift to cleaner production emphasizes on technological innovation and the application of ecological principles. Green innovations are the drivers that affect the relationship between growth, energy consumption and environmental emissions (Zhang & Li, 2020). The energy efficient innovations lead to production of renewable energy that could alleviate the environmental damages (Ali et al., 2016; Hou et al., 2023; Sahoo et al., 2024). Investment in new green technologies is quicker in wealthier economies. But in most of the developing and developing countries, lack of financial resources is a major constraint in accessing innovative environmental technologies, relying instead on the fossil based production.

The link between natural resource rents, economic activities and environmental degradation can be traced to the 1990s when the environmental Kuznets curve theory emerged. It hypothesizes an inverted U-shaped curve between income and environmental emissions. The global ecological footprint has been greatly improved by global industrialization. One of the important contributors toward ecological degradation is energy produced by fossil fuel resources (Qing, Li, & Mehmood, 2024). Environmental degradation is caused by excessive use of natural resources and rapid economic growth contributes to environmental emissions (Danish & Ulucak, 2020). In recent times, digitalization has been one of the most pertinent factors encouraging sustainable economic growth. Research also indicates that green production and green efficiency gained through digitalization can help to cut down environmental emissions (Caglar et al., 2021; Jie et al., 2023). The rapid digitalization infrastructure in D-8 countries is an argument to investigate the influence of natural resource, digitalization and renewable energy on ecological footprints. The enhancement in efficiency through digitalization may lead to energy consumption thus augmenting carbon emissions (Gossart, 2015; Wang et al., 2019). But digitalization can also reduce ecological emissions by turning away from traditional power generation to alternative power sources such as solar or wind energy. This shift decreases the intensity of emissions and will also save on the costs of production (Jorisch et al., 2018). The adoption of smart technologies can promote energy systems in terms of sustainability. Smart grids, smart meters, battery storage and other energy storage systems that incorporate digital technologies can improve the efficiency of power systems, which can help to protect the ecosystem (Moyer & Hughes, 2012; Lange et al., 2020).

This research employs a variety of cross-sectionally dependent second generation econometric tests. To estimate the short-run and long-run coefficients, the cross-sectional ARDL (Chudik & Pesaran, 2015) is employed.

Literature Review

The last climate summit was in Brazil where countries reaffirmed their pledges to undertake actions to prevent environment degradation. The objective of the study is reducing ecological emissions, so this study is centered on the Developing-8 economies. Most of the developing countries' environmental problems are related to the high intensity level of fossil fuel consumption, which results in high environmental emissions. The emission-intensive growth model of D-8 developing countries is very high as many emission producers industries have taken a good footing. The loophole in the regulatory mechanism has encouraged businesses to flout the environmental law. Population growth and high energy consumption are also important factors of CO₂ emissions. In this context, financing clean technologies to reduce the environmental impact is crucial. Historically, economic growth has been linked with environmental degradation in D-8 member countries. This is because resource-heavy industries with a high pollution level are often the ones that run the initial growth phase. The Environmental Kuznets Curve (EKC), however, indicates that at a certain point after reaching a GDP per capita threshold, as economies begin investing in renewable energy technologies the emission curves begin to reverse.

There are also large differences in water security within the D-8 member countries. The countries with relatively high-water availability and relatively low exploitation intensity are: Bangladesh, Malaysia and Indonesia. By contrast, Egyptians and other countries such as Pakistan and Iran have very limited water availability with high levels of water exploitation, leading to high water scarcity vulnerability and water related issues. The D-8 nations have been able to develop their industries on fossil fuels (Boukhris et al, 2025, Atiq et al., 2025). First of all, among these countries, the highest energy consumption in Turkey was observed (Mukhtarov et al., 2022). The fossil fuels have been playing a significant role in the Turkish economy, and this has resulted in high environmental emissions (Köne and Büke, 2019). Largely using fossil fuels induced concern for ecological sustainability (Canbay, 2025). Since the D-8 countries have been facing difficulties to manage ecological emissions, it is the most important to identify the causes of environmental emissions and reduce the ecological damages. Global estimates of the average ecological footprint per capita were around 2.6-2.8 global hectares (Ecological Footprint Network, 2023), which is close to 1.1 global hectares (GH) above the planet's biological capacity (Sahoo & Sethi, 2021). Ecological footprint is an all-inclusive indicator of environmental sustainability (Hussain et al., 2022). The process of clean production emphasizes technology development and application of ecological laws. Green innovations are factors affecting the relationship between development, energy consumption and environment emissions (Zhang & Li, 2020). Energy-efficient innovations result in renewable energy production which may reduce environmental damages (Ali et al., 2016, Hou et al., 2023; Sahoo et al., 2024). Investment in more high-tech green technologies is much more rapid in richer economies. But, majority of the developing and developing countries face financial challenges to access the innovative environmental technologies which makes them rely on the fossil-based production.

The connection between natural resource rents, economic activity and environmental degradation dates back to 1990s with the theory of environmental Kuznets curve. It assumes that there is an inverted U-shaped relationship between income and emissions to the environment. The global ecological footprint has radically improved with the global industrialization. One of the significant causes of ecological degradation is the production of energy using fossil fuel (Qing, Li, & Mehmood, 2024). Environmental degradation as a result of the excessive extraction of natural

resources and rapid economic growth also causes environmental emissions (Danish & Ulucak, 2020). Digitalization and ICT have recently become one of the most prominent factors in sustainable economic development. In fact, there is a significant amount of research that indicates that improvements in ICT can lead to a reduction in environmental emissions, as ICT encourages cleaner production and efficiency (Caglar, Balsalobre-Lorente, & Akin, 2021; Jie et al., 2023). The fast track of ICT infrastructure in the D-8 economies inspires us to look into natural resources, ICT and renewable energy in the context of ecological footprints. The improvement in efficiency due to ICT could result in increased energy use, and therefore carbon emissions (Gossart, 2015; Wang et al., 2019). ICT can, however, also reduce the ecological emissions by shifting away from traditional energy generation methods to renewable energy sources such as solar or wind power. This transition not only lowers the intensity of emissions, but also the production costs (Jorisch et al., 2018). The adoption of smart technologies can promote energy systems in terms of sustainability. A smart grid, smart meter, energy storage, and other energy storage technologies have the potential to improve the efficiency of power systems, which protects the ecosystem (Moyer & Hughes, 2012; Lange et al., 2020, Atiq-ur-rehman et al., 2025)).

This study employs several second generation tests which take account of cross-sectional dependence. The cross-sectional ARDL (Chudik & Pesaran, 2015) is used for estimating short-run and long-run coefficients.

Empirical Methodology

Model Specification

The basic econometric specification for our study is given below as an equation (1) ,

$$EFP_{it} = \beta_0 + \beta_1 ICT_{it} + \beta_2 RE_{it} + \beta_3 NR_{it} + \beta_4 GI_{it} + \beta_5 EG_{it} + \epsilon_{it} \quad (1)$$

In the equation given above, EFP is the ecological footprint, which is a dependent variable. Information and communication technologies (ICT), Renewable energy (RE), natural resource rents (NR), green innovations (GI), and economic growth per capita (EG) are used as regressors. The notation ϵ is the error term, while ‘i’ and ‘t’ indicate cross-section and time period, respectively.

Variables and Data

A panel data set on D-8 countries for the period 1998-2024 has been collected. The countries included are Bangladesh, Indonesia, Iran, Malaysia, Türkiye, Egypt, Pakistan, and Nigeria. The ecological footprint data per hectare comes from the Global Footprint Network (GFN). The data on Economic growth, renewable energy, ICT, and natural resource rents were extracted from the WDI database. The RE is measured as renewable energy consumption, while ICT is proxied by the number of internet subscribers. Economic growth is indicated by GDP per capita, and the natural resources are measured using the natural resource rents. Green innovations data has been obtained from the OECD database. The green innovations are accounted for by collecting data on green patents, taken from the OECD Database.

Empirical Methodology

After the data collection, we apply cross-sectional dependence test. After detecting the cross-sectional dependence, we employ second-generation unit root tests of panel data. The CS-ARDL technique of estimation is the next step to obtain the short-run and long-run coefficients.

CS-ARDL model estimation

The CS-ARDL technique by Chudik and Pesaran's (2015) is employed to obtain the short-run and long-run coefficients. EFP is the environmental footprint, and Z is the vector of control variables. The estimation method can be represented mathematically as:

$$\Delta EFP_{it} = \phi_i + \delta_i(EFP_{i,t-1} - \theta_{i0} - X'_{i,t-1} \theta_i) \sum_{l=0}^{p\omega} \phi_{ij} \Delta EFP_{i,t-1} + \sum_{l=0}^{pz} \phi_{ij} \Delta X_{i,t-1} + u_{i,t} \quad (3)$$

Here, X is a vector of explanatory variables including GI, RE, NR, DIGI, and EG. The notation $u_{i,t}$ is the idiosyncratic error while δ_i represents the error correction term, which shows the convergence towards the equilibrium per period.

Empirical Results

Error! Reference source not found.1: Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
EFP	216	1.465	1.296	0.084	5.046
GI	216	9.322	7.523	-19.936	40.4
RE	216	29.377	27.36	0.44	88.68
NR	216	8.242	8.509	0.144	34.779
ICT	216	28.246	27.25	0.004	97.7
EG	216	7.783	0.927	5.996	9.434

Table 2: Cross-sectional dependence test

Series	CD-test	p-value
EFP	-0.910	0.364
GI	6.500	0.000
RE	6.020	0.000
NR	12.900	0.000
DIGI	24.040	0.000
EG	19.070	0.000

Notes: Under the null hypothesis of cross-sectional independence $CD \sim N(0,1)$

Table 3: Unit root test Results

Variable	CADF Test	
	Level	Ist. difference
EFP	1.458	-5.708**
GI	0.377	-7.352***

RE	0.966	-4.689 ***
NR	-0.767	-2.882***
ICT	4.1904***	-----
EG	-0.085	-2.909 ***

Note: *** = 1%, ** = 5% and * = 10% significance level.

Table 4: Summary of CS-ARDL Results

Dependent variable: EFP

Variable	Coefficient	Std. error	Prob.
Long-run			
EG	1.0267*	0.5417	0.0581
GI	-0.0744***	0.0155	0.000
RE	-0.0667***	0.0023	0.0001
ICT	-0.01199**	0.00519	0.022
NR	0.11805*	0.06133	0.054
Short-Run			
ECT	-0.0211***	0.0162	0.000
EG	3.3998	2.2928	0.1033
GI	0.1651***	0.0465	0.0005
ICT	-0.0180	0.0300	0.5480
NR	-0.0209	0.0201	0.309
RE	-0.02096***	0.0038	0.0001

Note: *** = 1%, ** = 5% and * = 10% significance level.

Findings and Interpretations

Table 1 shows the descriptive or summary statistics for all the variables. It is also observed that the selected variables possesses a high standard deviations. There is a possibility that the variables under consideration will be heterogeneous. Table 2 shows the Pesaran test for detecting cross-sectional dependence. The null hypothesis of cross-sectional independence has been rejected in most of the cases indicating that there is a cross-sectional dependence in data.

To identify the order of integration, the second-generation unit root tests are applied. We use the CADF testing to check the stationarity of our series. Table 3 shows the result of the CADF unit root test for each series. The results show that ICT is stationary at a level, while all other series are first difference stationary.

The values of coefficients in the short-run and long-run, derived from the CS-ARDL approach, have been reported in Table 4. The coefficient on renewable energy is negative and significant. The coefficient on green innovation is positive in the short-run but negative and significant in the long-run. It means that renewable energy and green innovations help to reduce the environmental footprint in the long-run. In the presence of renewable energy and green innovations, the production process uses less-polluting technologies due to the minimal usage of fossils. The long-run coefficient on the variable ICT is negative and statistically significant. The implication of this result can be justified by the supposition that ICT enhances energy efficiency through the reduction of environmental emissions. Additionally, ICT encourages businesses to incorporate cutting-

edge technologies into their operations and reduce transportation costs, which also lowers emissions. The minimal usage of paper due to ICT may also be supportive of environmental quality. The long-term results give a proper explanation of the relationships; however, the short-run coefficient on ICT remains statistically insignificant. The coefficient on economic growth is positive but weakly significant at the 10 % level in the long-run. The variable natural resource rents is statistically insignificant in the short-run but positive and weakly significant at the 10 % level in the long-run. It can be interpreted that the natural resource utilization increases the ecological footprint in the long-run. The natural resource rents increase the ecological footprint, damaging environmental quality due to extractions and resource use.

The term ‘ECT’ implies an error correction term which shows about 2 % adjustment towards equilibrium per year. These findings are in line with Wang, Chen, and Teng (2023).

Conclusion

The Developing-8 nations are facing a range of environmental challenges that pose significant threat to their sustainable development. This paper investigates the role of renewable energy consumption, digital technologies, green innovation, and natural resources in environmental sustainability in the D-8 developing countries. Using data for the period 1998-2024, the cross-sectional dependence is tested. Then, a CS-ARDL approach for estimation is employed to obtain the long-run and short-run coefficients. The empirical results reveal that natural resources and economic growth increase the environmental footprint. Renewable energy, ICT, and green innovation contribute towards decreasing the ecological footprint in the Developing countries considered.

The policies should emphasize the development of green innovations to reduce the ecological footprint. The policy actions should be implemented to attract investments in the renewable energy sector. The governments should encourage the corporate sector to reduce industrial and transportation emissions. The environmental regulations should be imposed strictly. The public-private partnerships will be helpful in this regard. The optimal usage of digital technologies may be promoted through lucrative incentives and better infrastructure, which may reduce the use of paper and transportation, leading to environmental sustainability.

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