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How does technological innovation affect the ecological footprint? Evidence from E-7 countries in the background of the SDGs

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ABSTRACT

Although technological innovation plays a critical role in promoting sustainable development and environmental sustainability, there are few studies in the existing literature that address this relationship. This study aimed to investigate the relationship between technological innovation (TI), renewable energy consumption (REC), natural resource rent (NRR) and ecological footprint (EF) of E-7 countries (i.e. Brazil, China, India, Indonesia, Mexico, Russia and Turkiye) from 1992 to 2018 in order to ensure environmental sustainability in the context of the Sustainable Development Goals (SDGs). Analysis was performed using the ARDL estimator, robustness test and Dumitrescu-Hurlin panel causality (DHC) test. Long-term empirical estimates from the PMG-ARDL technique have shown that a 1 % increase in TI and REC reduces EF by 0.064 % and 0.234 %, respectively, i.e. increases environmental sustainability. At this point, it is possible to say that TI and REC contribute to the achievement of SDG-7 and 13 in E-7 countries while NRR and real income (GDP) were found to impede the achievement of SDG-7 and 13 in E-7 countries through an increase in EF. The results were confirmed using robustness techniques. In the DHC test results, while there is a unidirectional causality from TI to EF, from EF to NRR and trade openness, a bidirectional causality was found between GDP and EF. This study suggests that policymakers should focus on introducing environmentally friendly equipment to reduce environmental degradation, increase the share of RECs and focus on sustainable development within the framework of the SDGs.

1. Introduction

Especially after the industrial revolution, the increasing demand for energy increased the consumption of natural resources (NR) as the world's population grew, which led to an increase greenhouse gas emissions and many studies argue that energy consumption (EC) has an increasing impact on environmental pollution (Adebayo et al., 2023a; Dam et al., 2023). While energy consumption is an important catalyst for economic growth and economic development, it also causes environmental degradation. As economies grow and develop, the increasing demand for energy result in environmental degradation when derived from fossil fuels. However, if it is derived from renewable energy sources, such degradation will be reduced to a great extent (Mujtaba et al., 2022).

Therefore, attention should be paid to protecting the environment while providing sustainable growth (Afshan and Yaqoob, 2022). After the SDGs were approved by the United Nations in 2015, countries started to make efforts to achieve these goals, which, however, have remained far from the SDGs (Anwar et al., 2022).

The United Nations has held many important meetings and conventions on climate change and globalisation. The two most important agreements in this context are the Kyoto Protocol and the Paris Climate Agreement. They are in line with the United Nations Development Programme's (UNDP) SDGs, and green technology is not ignored in the measures taken to combat environmental degradation (Celik and Alola, 2022). In addition, the recent Conferences of the Parties (COP26 and COP27) are also important in terms of the decisions made and the issues that attracted attention. At COP26, countries committed to reducing greenhouse gas emissions, halting deforestation, achieving net zero emissions by 2050, accelerating the phase-out of coal and ending international fossil fuel finance (Adebayo et al., 2023a; Ozturk et al., 2023). Furthermore, the recent Conference of the Parties COP 27, hosted by Egypt, emphasised the importance and urgency of the transition to a

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Abbreviations

AMG	Augmented Mean Group
CCEMG	Common correlated effects mean group
CIPS	Cross-sectionally augmented Im Pesaran Shin
CO2	Carbon dioxide
COR	Corruption
CS	Capital stock
CSD	Cross-section dependency
DHC	Dumitrescu-Hurlin panel causality
DOLS	Dynamic ordinary least square
EC	Energy consumption
ECC	Electricity consumption
ECT	Error correction term
ED	Education
EEF	Energy efficiency
EF	Ecological footprint
EKC	Environmental Kuznets curve
EPU	Economic policy uncertainty
ETAX	Environmental Taxes
EU	European Union
FD	Financial development
FDI	Foreign direct investment
FIS	Fiscal decentralization
FMOLS	Fully modified ordinary least squares
GCF	Gross capital formation
GDP	Real income
GEG	Green growth/production
GFN	Global footprint network
GHG	Greenhouse gas
GIN	Green investment
GOE	Government final consumption expenditure
GTI	Green technological innovation
HC	Human capital
HDI	Human development index
ICT	Information and communication technologies
IDI	Infrastructure development
IND	Industrial structure
INE	Informal economy
INF	Inflation rate
IQ	Institutional quality
KOF	Globalization
LCF	Load capacity factor
LP	Labor productivity
MR	Market regulation
NR	Natural resource
NREC	Nonrenewable energy consumption
NRR	Natural resource rents
PC	Petroleum consumption
PEC	Primary energy consumption
PMG-ARDL	Pooled Mean Group - Autoregressive Distributed Lag
POP	Population
R&D	Research and development
RD	Research and development expenditure
REC	Renewable energy consumption
SDG	Sustainable Development Goals
TI	Technological innovation
TINR	Patent applications of nonresidents
TIR	Patent applications of residents
TMA	Trademark applications
TO	Trade openness
TOR	Tourism
UNDP	United Nations Development Program
URB	Urbanization
WDI	World Development Indicator

low-carbon economy (Akram et al., 2023). This study, conducted in the context of the United Nations SDGs (UN-SDGs 7, 11, 12 and 13), provides important evidence for a sustainable environment (Udeagha and Muchapondwa, 2022; Liu et al., 2023).

Sustainable development is a global phenomenon that plays a critical role in the survival of humanity today (Ulucak et al., 2019). In the current climate, the increasing use of fossil fuels makes it difficult for countries to achieve SDG-7, which is based on access to clean and affordable energy sources (Zhao et al., 2022a). The nature and amount of energy that countries produce and use to sustain their productive activities is considered to have a significant impact on achieving ecologically sustainable economic growth (Khan et al., 2021; Adebayo, 2022). According to the SDGs, most countries have great difficulties in meeting SDG 12 on responsible consumption and production and SDG 13 on climate action. One of the main causes of this problem is the high consumption of resources in industrialisation and GDP (Balsalobre-Lorente et al., 2021b). Excessive consumption of NRRs poses serious threats, such as deforestation and global warming (Dong et al., 2017). While NRs, which play a crucial role in a country's economic development, aren't considered harmful to the environment, their extraction is (Hassan et al., 2019; Aladejare, 2022). An agreement on the impact of NR on environmental sustainability is lacking in the existing literature.

Studies in the literature have focused heavily on the relationship between GDP, energy consumption, trade openness (TO), financial developments, globalisation, urbanisation and environmental degradation. With technological developments in recent years, the relationship between environmental degradation and technology has begun to be studied by researchers. There are different views on this relationship in the literature. For example, Cheng et al. (2021) emphasise that promoting TI is a common solution to address environmental degradation, especially in developing countries. It is emphasised that TI, which gains importance together with ecological measures, reduces environmental degradation and improves environmental quality (Adebayo et al., 2022). From another perspective, it is believed that environmental degradation will increase with the use of technology in economic growth and the expansion of production activities that are detrimental to environmental sustainability (Khan et al., 2017; Greening et al., 2000). Although per capita incomes and production capabilities are high in developed countries, the associated technologies are not at the desired level due to the still high dependence on fossil fuels and the insufficient level of RECs (Jahanger et al., 2022a).

This study is important in several respects. Firstly, while most of the previous studies consider total energy consumption in determining the determinants of environmental pollution, renewable energy consumption is used in this study. Second, this study uses the ARDL-PMG method, which is an advanced and robust econometric technique, instead of the traditional ARDL method. This current econometric technique has several advantages and is well-suited to produce reliable, valid and robust estimates. Third, this study includes NRR and REC variables in the model instead of total energy consumption, which is often used in the literature. Fourth, the effects of TI, NRR and REC on environmental degradation were analysed by the ARDL cointegration method, using annual data from 1992 to 2018 in E-7 countries. In addition, it aims to provide answers to countries on their way to environmental sustainability by examining the relationship between rapidly developing technology and environmental pollution today. Finally, this study will assist policymakers and decision-makers in designing appropriate environmental and energy policies, taking into account the impact of TI, NRR, GDP, REC and TO.

The remainder of the study comprises the literature review in the second chapter, the data, model and methodology in the third, the analysis results and the discussion in the fourth, and the conclusion and policy recommendations in the fifth chapter.

2. Literature review

Many great theories and approaches exist in the literature to explain the relationship between pollution and technology. This study is based on the double-edged sword of technology and the environmental Kuznets curve (EKC) theories. According to the double-edged sword of technology theory, technology can have both positive and negative effects on the environment (Zhou et al., 2021). For example, technological progress can increase energy efficiency while producing new sources of pollution, has a complex impact (Ma et al., 2022).

There are many studies in the literature describing the relationship between income and environmental degradation based on the EKC hypothesis (Stern et al., 1996; Dinda, 2004; Apergis and Ozturk, 2015; Pata et al., 2023; Bekun, 2024). In explaining this relationship, other economic, political, geographical, socioeconomic and demographic variables have been examined in addition to income. As studies on these variables in the literature include different dynamics, methodologies and macroeconomic variables, the results are inconclusive and may vary across regions. However, while the literature focuses mainly on income, energy consumption, foreign trade and financial development as determinants of pollution, there are very few studies on technological progress. Therefore, this study discusses the impact of TI on pollution.

On the other hand, EKC theory suggests that technological progress can reduce pollution and that new technologies will contribute to environmental sustainability by enabling more efficient production and energy use. Existing studies in the literature have defined variables such as research and development (R&D), patents, technological innovation (TI), information and communication technologies (ICT) and gross domestic product (GDP) as technology indicators. They have found that the impact of TI on environmental pollution is mixed (Ganda, 2019).

This study examines the impact of technological innovation on environmental pollution in the E-7 countries. Shahbaz et al. (2018) argue that technological developments and changes in energy systems and energy efficiency can affect environmental performance. Mughal et al. (2022) emphasise that policies on the energy use of environmentally friendly technologies can significantly control pollution. In building the econometric model in this study, the studies of Zhang et al. (2021), Adebayo et al. (2022a) and Mughal et al. (2022) were used. In the analysis of the existing literature, the relationship between technological innovation, natural resources, renewable energy and real income on environmental pollution is examined under four headings.

2.1. The impacts of technological innovation on environmental degradation

One of the most important catalysts for economic growth is technological change. In particular, technology, as used in endogenous growth theory, plays an important role in economic growth and environmental degradation. TI, which significantly improves environmental quality, also reduces environmental problems (Saleem et al., 2022). However, the link between environmental degradation and TI and NR has received less attention. The relationship between technology and the environment has been discussed in the literature within the framework of EKC theory.

Under the EKC hypothesis, TIs use cleaner technologies, improve production processes and contribute to environmental improvements. In addition, renewable energy technologies are becoming increasingly affordable and accessible, making them an attractive option for individuals, businesses and governments (Dam et al., 2023b). Recently, studies by Celik and Alola (2022), Esquivias et al. (2022) and Raihan and Voumik (2022) have discussed the relationships between TI, energy consumption, GDP and environmental degradation.

Table 1 highlights recent global studies on the impact of technology, macroeconomic, demographic and socio-cultural factors on environmental degradation. These studies, which cover different time periods and samples, generally conclude that TI reduces environmental degradation (Luo et al., 2021; Adebayo et al., 2022; Wei and Lihua, 2023). These findings are consistent with the results of our empirical analyses. However, Ullah et al. (2023) used the CS-ARDL method in their study on the environmental impact of TI on G7 countries, and, as a result of their empirical analysis, they concluded that TI increases environmental pollution. Similarly, Jiang and Khan (2023) studied the relationship between TI and environmental pollution in the Belt and Road Initiative countries for the period 1995–2019. They found that TI increased environmental pollution in the long run in the Belt and Road Initiative countries. On the other hand, Ma et al. (2022) in their study on BRICS countries found mixed effects of TI on pollution.

Many studies have described the relationship between technology and environmental degradation. In these studies, different variables such as TI, green TI, R&D expenditure and information and communication technology are used as technology variables. A comprehensive literature summary of these studies using technology as a variable is given in Table 1.

2.2. Impacts of natural resources on environmental degradation

Environmental degradation and the NR nexus are critical aspects of sustainable development. EF is a measure of the impact of human activities on the environment, including the consumption of NR, which are the raw materials and components used to produce goods and services that are essential for human survival and well-being. Human activities, such as consumption and production, are the main drivers of natural resource depletion and environmental degradation. EF measures the amount of land, water and other NR required to sustain human activities and the extent to which these activities exceed the Earth's capacity to regenerate these resources (Zhang et al., 2021).

EF can be reduced by using NR more efficiently, reducing waste and pollution, and adopting more sustainable production and consumption patterns. This can include, for example, using renewable energy sources, recycling and reusing materials, reducing water use and adopting sustainable land use practices. It is also important to ensure that NR are used in a sustainable and equitable manner. This includes adopting policies and practices that promote the conservation and sustainable use of NR, protect biodiversity, and support the rights and livelihoods of local communities that depend on these resources. NRRs are fees paid for the use of natural resources. As NRRs, fees paid for the use of natural resources, increase, they have a positive impact on EF (Afshan and Yaqoob, 2022).

NR include resources such as water, air, soil, forests and energy resources, and human activities increase the consumption of these resources. In addition, activities such as industry, agriculture, mining, transport and energy production are directly related to the use of NR. As a result, the release of waste and pollutants into the environment causes pollution. Recently, researchers have focused on the consumption of natural resources rather than on total energy consumption. In the literature, NRR is preferred as a proxy for natural resource consumption. The impact of NRR on EF is mixed in the literature. For example, while Hassan et al. (2019) found this relationship to be positive in their study for Pakistan, Bekun et al. (2019) found it to be negative for the EU. Furthermore, Yang and Khan (2021) examined the impact of natural resources on environmental degradation in SAARC countries using annual data from 1996 to 2018. The results show that environmental degradation in the SAARC region is exacerbated by natural resources. Usman et al. (2022) studied the effect of NRR on EF in the financially richest countries in the period 1990–2018. In the empirical evidence of the study, it was found that NRR increases EF in the long run.

Table 1
Studies focusing on the impact of technology variables on environmental degradation.

Panel	Study	Region	Time period	Variables	Methodology	Long run results	Causality relationship results
Panel (a) The impact of technology innovation on environmental degradation	Ganda (2019)	Economic Co-operation and development countries	2000–2014	CO2, TI, RD, GDP, REC, RES, FDI, PEC, FD, POP	OLS, FE, System-GMM	REC decrease CO2; GDP, EC, FDI and PEC increase CO2; TI, RES, RD, HC and FD mixed CO2	Not investigated
	Gormus and Aydin (2020)	Top 10 innovative economies	1990–2015	EF, GDP, TIR, REC, KOF,	MG, AMG	TIR decrease CO2	Not investigated
	Luo et al. (2021)	Selected Asian Countries	2001–2019	CO2, TI, GDP, EC, GIN, FDI, TO, POP	FMOLS, DOLS, AMG, CCEMG; Granger causality	TI and GIN decrease CO2; GDP, EC, FDI, TO and POP increase CO2	GIN, EC and TO ↔ CO2; TI, GDP, FDI and POP → CO2
	Adebayo et al. (2022)	BRICS countries	1990–2019	CO2, TI, GDP, FDI, REC, NRR	CS-ARDL; Dumitrescu-Hurlin causality	TI, FDI, REC and NRR decrease CO2; GDP increase CO2	GDP and REC ↔ CO2; FDI, REC and NRR → CO2
	Celik and Alola (2022)	High-tech investing economies	2000–2018	CO2, GDP, LP, EC, TI, RD, ICT, CS	POLS, GLS; Dumitrescu-Hurlin panel causality	CS decrease CO2; GDP, EC, TI, RD and ICT increase CO2; LP mixed CO2	TI, ICT and CS → CO2
	Esquivias et al. (2022)	Emerging Asian Economies	1990–2019	CO2, COR, GCF, HDI, GDP, GTI, TI, REC, NREC, NRR, POP	Panel quantile regression	GCF, HDI, TI, REC, NREC, decrease CO2; GDP, GTI, POP and NRR increase CO2	Not investigated
	Jianguo et al. (2022)	OECD economies	1998–2018	CO2, GDP, EC, IQ, TI, FD	SYS-GMM	TI and IQ decrease CO2; GDP, EC, FD increase CO2	Not investigated
	Khan et al. (2022)	Belt and road initiative countries	1979–2019	CO2, GDP, FDI, FD, TO, RD, TIR, TINR, REC, POP	OLS, FE, Two steps difference GMM, Two steps SYS-GMM	TO, TIR, REC and POP decrease CO2; FD, FDI, TINR increase CO2; GDP, RD mixed CO2	Not investigated
	Liu et al. (2022)	E-7 countries	1996–2018	CO2, GDP, REC, TI, IQ, POP	FGLS, Panel quantile estimations	REC, TI and IQ decrease CO2; GDP and POP increase CO2	Not investigated
	Ma et al. (2022)	BRICS countries	1991–2019	CO2, GDP, TI, FDI, TMA	ARDL, NARDL; Panel Granger causality	GDP, FDI and TMA increase CO2; TI mixed CO2	GDP, TI and TMA ↔ CO2; CO2 → FDI
	Obobisa et al. (2022)	African countries	2000–2018	CO2, GDP, TI, REC, NREC, IQ	AMG, CCEMG;	REC and TI decrease CO2; GDP, NREC and IQ increase CO2	Not investigated
	Udemba et al. (2022)	China	1980–2018	CO2, GDP, FD, REC, TI	NARDL, DOLS; Hacker and Hatemi-J causality	FD, REC, TI, GDP(−) FD (+), REC(+) and TI(+) decrease CO2; GDP, GDP (+), FD(−), REC(−) and TI(−) increase CO2	GDP, FD ↔ CO2; TI and REC → CO2
	Raihan and Voumik (2022)	India	1990–2020	CO2, GDP, TI, FD, REC, URB	ARDL, FMOLS, DOLS, CCR	REC and TI decrease CO2; GDP, FD and URB increase CO2	Not investigated
	Wei and Lihua (2023)	ASEAN countries	1995–2018	CO2, GDP, TI, TOR	CS-ARDL, CCEMG, AMG	TOR and TI decrease CO2; GDP increase CO2	Not investigated
	Wenlong et al. (2022)	10 Asian economies	1995–2018	GHG, EEF, TI, TO, IQ	CS-ARDL, CCEMG, AMG	EEF and TI decrease GHG; IQ and TO increase GHG	Not investigated
	Zhao et al. (2022b)	G-7 economies	1995–2018	CO2, GDP, TI, REC	CS-ARDL, CCEMG, AMG	REC and TI decrease CO2; GDP increase CO2	Not investigated
	Chen et al. (2023)	Bangladesh	1972q1-2020q4	CO2, GDP, TI, PC	ARDL, FMOLS; Granger causality	TI decrease CO2; GDP and PC increase CO2	GDP, TI and PC → CO2
Panel (b) The impact of green technology innovation on environmental degradation	Destek and Manga (2021)	BEM countries	1995–2016	CO2, REC, NREC, GTI, FD	FE, CUP-FM, CUP-BC	GTI and REC decrease CO2; NREC and FD increase CO2	Not investigated
	Hussain and Dogan (2021)	BRICS countries	1992–2016	EF, GDP, EC, GTI, IQ	CS-ARDL, AMG, CCEMG	GTI and IQ decrease EF; GDP and EC increase EF	Not investigated
	Abbas et al. (2022)	BRICS countries	1990–2020	CO2, GTI, GDP, REC, MR, TO, FDI	MG, PMG, ARDL	GTI, REC and MR decrease CO2; GDP and TO increase CO2	Not investigated
	Afshan and Yaqoob (2022)	China	1990–2017	EF, GDP, GTI, FD, NRR	QARDL; Granger causality	GTI decrease EF; GDP, NRR and FD increase EF	GDP, GTI, NRR and FD ↔ EF
	Chu (2022)	OECD countries	1995–2015	EF, GDP, GTI, INE, TO, EC, REC	Panel quantile estimation; Dumitrescu-Hurlin panel causality	GTI, REC, INE, TO decrease EF; EC increase EF; GDP mixed EF	GTI, EC and REC ↔ EF; INE, TO and GDP→ EF
	Esquivias et al. (2022)	Emerging Asian Economies	1990–2019	CO2, COR, GCF, HDI, GDP, GTI, TI, REC, NREC, NRR, POP	Panel quantile regression	GCF, HDI, TI, REC, NREC, decrease CO2; GDP, GTI, POP and NRR increase CO2	Not investigated

(continued on next page)

Table 1 (*continued*)

Panel	Study	Region	Time period	Variables	Methodology	Long run results	Causality relationship results
	Habiba et al. (2022)	Twelve top emitting countries	1991–2018	CO2, GDP, FD, GTI, REC, NREC, TO, POP	AMG, CCEMG; Dumitrescu-Hurlin panel causality	GTI and REC decrease CO2; GDP, FD, NREC, TO and POP increase CO2	FD, GTI, REC and POP ↔ CO2; GDP, TO, NREC → CO2
	Hao and Chen (2022)	E-7 countries	1990–2020	CO2, REC, GDP, GTI, FDI, TO, FD, INF, GOE	ARDL, FMOLS, DOLS, CCR	REC, FD decrease CO2; GDP, INF, GOE increase CO2	Not investigated
	Hussain et al. (2023)	BRICS economies	1992–2020	EF, GDP, POP, REC, GTI, EPU	CS-ARDL, CCEMG, AMG; Pair-wise causality	REC and GTI decrease EF; GDP, POP and EPU increase EF	GDP and POP ↔ EF; GTI → EF, EF → REC and EPU
	Razzaq et al. (2022)	China	1990–2018	EF, GDP, IDI, URB, GTI	QARDL	High: GTI decrease EF; GDP, IDI and URB increase EF	Not investigated
	Saleem et al. (2022)	Asian economies	1990–2018	CO2, REC, GDP, GTI, GEG, FD, ETAX	CS-ARDL, AMG Dumitrescu-Hurlin panel causality	FD, ETAX, GEG and GTI, decrease CO2; GDP increase CO2; REC mixed CO2	REC, GTI, ETAX and GEG ↔ CO2; GDP and FD → CO2
	Serener et al. (2022)	Sweden	1995q1-2019q4	CO2, GDP, GTI, FD, REC	FARDL; Fourier TY causality	REC and GTI decrease CO2; GDP and FD increase CO2	GDP, EC and REC → CO2
	Udeagha and Muchapondwa (2022)	South Africa	1960–2020	CO2, GDP, EPU, GTI, KOF, FIS	FMOLS, DOLS, CCR; Frequency-domain causality	GTI and FIS decrease CO2; GDP, EPU and KOF increase CO2	GDP, EPU, GTI, KOF and FIS → CO2
Panel (c) The impact of ICT on environmental degradation	Park et al. (2018)	EU countries	2001–2014	CO2, GDP, ECC, FD, ICT, TO	PMG, FMOLS, DOLS; Dumitrescu-Hurlin panel causality	FD, GDP and TO decrease CO2; ECC and ICT increase CO2	TO ↔ CO2; GDP, ICT, ECC and FD → CO2
	Avom et al. (2020)	Sub-Saharan Africa	1996–2014	CO2, GDP, ICT, EC, FD, TO	OLS, FE, RE	TO decrease CO2; ICT, GDP, EC and FD increase CO2	Not investigated
	Celik and Alola (2022)	High-tech investing economies	2000–2018	CO2, GDP, LP, EC, TI, RD, ICT, CS	POLS, GLS; Dumitrescu-Hurlin panel causality	CS decrease CO2; GDP, EC, TI, RD and ICT increase CO2; LP mixed CO2	TI, ICT and CS → CO2
	Dogan and Pata (2022)	G-7 countries	1986–2017	LCF, GDP, RD, ICT, REC	CS-ARDL, AMG	GDP, RD, REC and ICT increase LCF	Not investigated
	Zhang et al. (2022)	Developing countries	1996–2019	CO2, ICT, GDP, KOF, FD, ED	Cup-FM, Cup-BC; Dumitrescu-Hurlin panel causality	ICT decrease CO2; GDP, KOF, FD and ED increase CO2	ICT, KOF, FD, GDP and ED ↔ CO2
Panel (d) The impact of R&D on environmental degradation	Churchill et al. (2019)	G-7 countries	1870–2014	CO2, GDP, RD, POP, TO	CCEMG	RD decrease CO2; POP and TO increase CO2	Not investigated
	Celik and Alola (2022)	High-tech investing economies	2000–2018	CO2, GDP, LP, EC, TI, RD, ICT, CS	POLS, GLS; Dumitrescu-Hurlin panel causality	CS decrease CO2; GDP, EC, TI, RD and ICT increase CO2; LP mixed CO2	TI, ICT and CS → CO2
	Dogan and Pata (2022)	G-7 countries	1986–2017	LCF, GDP, RD, ICT, REC	CS-ARDL, AMG	GDP, RD, REC and ICT increase LCF	Not investigated
	Yunzhao (2022)	E-7 economies	1995–2018	CO2, REC, ETAX, RD	CUP-FM, CUP-BC; Dumitrescu-Hurlin causality	REC, ETAX and RD decrease CO2	REC, ETAX and RD ↔ CO2

Notes: → is unidirectional causality, ↔ is bidirectional causality and ≠ is no causality relationships. *EF*: Ecological footprint, GHG: Greenhouse gas emission, CO_2: Carbon emissions, LCF: Load capacity factor, NRR: Natural resources rents, FDI: Foreign direct investment, GDP: Gross domestic product, EC: Energy consumption, PEC: primary energy consumption, REC: Renewable energy consumption, MR: Market regulation, TI: Technology innovation, GTI: Green technology innovation, NREC: Nonrenewable energy consumption, TIR: Patent applications of residents, TINR: Patent applications of nonresidents, LP: Labor productivity, RD: Research and development expenditure, ICT: Information and communication technology goods exports, CS: Capital stock, EPU: Economic policy uncertainty, KOF: Globalization, FIS: Fiscal decentralization IQ: Institutional quality, IND: Industrial structure, TO: Trade openness, TMA: Trademark applications, POP: Population, PC: Petroleum consumption, FD: Financial development, HC: Human capital, COR: corruption, HDI: Human development index, TOR: Tourism, EEF: Energy efficiency, ETAX: Environmental Taxes, INE: Informal economy, GCF: Gross capital formation, INF: Inflation rate, GOE: Government final consumption expenditure, IDI: Infrastructure development, GEG: Green growth/production, GIN: Green investment, ED: Education, ECC: Electricity consumption.

Furthermore, a unidirectional causality from NRR to EF was found. Balsalobre-Lorente et al. (2023), also examine the long-term impact of natural resource rents on environmental sustainability in 36 OECD economies with annual data from 2000 to 2018, using the AMG and two-level GMM methods. The results of the analysis show that natural resource rents increase CO_2 emissions.

Shah et al. (2022) investigated the relationship between NR and CO_2 emissions in four ASEAN economies from 1990 to 2019 using the CCEMG and AMG methods. The study found that NRR reduces CO_2 emissions and they emphasised that NRR improves environmental quality. Adebayo et al. (2023b) examined the relationship between NRR and environmental pollution in BRICS countries over the period 1990–2019. As a result of the empirical analysis of the study, NRR was found to reduce pollution in the long run. Azam et al. (2023) studied the impact of NRR on environmental pollution in France for the period 1990–2018 and empirical analysis suggests that NRR has a negative and statistically significant effect on environmental degradation. Using annual data for the period 1992–2020 in E-7 countries, Hussain et al. (2023) concluded that NRR increases EF. Similarly, Voumik et al. (2023), examined the impact of natural resource rent on CO_2 emissions in South Asian countries using CS-ARDL, AMG, MG and co-correlated effect averaging methods with data covering the years 1972–2021. According to the results of the analyses, the coefficients of natural resource rent are negative, indicating that natural resources support the reduction of environmental damage by reducing CO_2 emissions.

Nwani and Adams (2021) analysed the effect of NRR on CO_2 emissions for 93 countries using MG and AMG methods with annual data for the period 1995–2017. The study reports that the effect of NRR on CO_2 emissions is positive for governments with a low quality and negative for governments with a high quality. Onifade et al. (2023) analysed the impact of NRR on CO_2 emissions using QR, DOLS and FMOLS methods. They used annual data for the MENA region for the period 1990–2018. The study found that the impact of NRR on CO_2 emissions is insignificant at the low quantiles, but positive at the high quantiles.

2.3. The impacts of renewable energy on environmental degradation

Fossil fuel-based energy consumption contributes to increasing environmental pollution worldwide; therefore, the transition to alternative energy sources is of great importance for sustainable development (Adebayo and Ullah, 2023). The link between environmental degradation and RECs is a critical aspect of sustainable development (Balsalobre-Lorente et al., 2021a; Pata et al., 2023). Renewable energy sources such as hydropower, biomass, solar, wave and wind have the potential to significantly reduce the EF of energy consumption. Traditional energy sources, such as fossil fuels, have a significant EF and contribute to air and water pollution, climate change and habitat destruction. In contrast, renewable energy sources have much lower environmental impacts and emit little to no greenhouse gases, making them a more sustainable choice (Adekoya et al., 2022).

However, the EF of RECs depends on several factors, such as the scale and location of renewable energy projects, the materials used in their construction, and the maintenance and disposal of these systems. For example, the production and disposal of solar panels and wind turbines contribute to the EF, and large-scale hydropower projects can have significant impacts on local ecosystems (Çakmak and Acar, 2022). It is, therefore, important to consider the full life cycle of renewable energy systems and their environmental impacts when assessing their EF. This includes the extraction and processing of raw materials, manufacturing, transport, installation, operation and decommissioning.

Similar to studies investigating the relationship between GDP and environmental degradation, those investigating the impact of energy on environmental degradation show mixed results depending on the methodology used, the sample group or the time period. In the empirical analyses explaining the impact of energy on environmental degradation in the literature, traditional studies have included total energy consumption in the model (Dam et al., 2022), while more recent studies have included RECs in the model. This is because total energy consumption, consisting of REC and NREC, has a positive impact on environmental pollution (Acaravci and Ozturk, 2010; Al-Mulali and Ozturk, 2015; Dogan and Turkekul, 2016), while renewable energy has a negative impact on environmental pollution (Jebli et al., 2020; Pata et al., 2023). Dam et al. (2023a) found that renewable energy reduces environmental pollution. This finding is consistent with the results of our empirical analyses.

Yuping et al. (2021) studied the impact of REC on CO_2 emissions for Argentina for the period 1970–2018 using Maki cointegration, ARDL and gradual shift causality methods. The empirical results of the study show that the series are cointegrated and that REC reduces CO_2 emissions in the long run. In addition, a unidirectional causality has been found from the REC to the CO_2 emissions. Ali et al. (2023) examined the relationship between REC and environmental pollution in South American countries. As a result of different estimation methods, researchers have discovered that REC has a negative impact on environmental pollution. Zimon et al. (2023) studied the impact of REC on CO_2 emissions in the 1972–2021 time period in South Korea. The empirical analysis results of their study imply that in the long run, REC reduces CO_2 emissions, that is, improves environmental quality. Pata (2018) studied the effect of REC on CO_2 emissions in Turkiye between 1974 and 2014. Empirical findings have discovered that REC has no significant impact on CO_2 emissions in the long term. Similarly, Pata and Caglar (2021) examined the impact of REC on EF for China with annual data for the period 1980–2016 using Augmented ARDL, FMOLS, DOLS, CCR and Toda-Yamamoto causality methods. According to the empirical results of the study, the effect of REC on EF is found to be insignificant in the long run. Furthermore, unidirectional causality is found from REC to EF.

2.4. The impacts of real income on environmental degradation

The relationship between GDP and environmental degradation is complex and has been the subject of much debate among economists, environmentalists and policymakers. The use of energy is inevitable for economic development and activities. This means that energy consumption is a necessary element of economic development, with GHG emissions that can affect environmental quality (Adedoyin et al., 2021). On the one hand, economic growth and rising incomes can lead to improvements in environmental quality, as people and governments have the resources to invest in pollution control and environmental management. Moreover, as people become more affluent, they tend to demand a cleaner and healthier environment, which can lead to greater investment in environmental protection and restoration. On the other hand, economic growth and rising incomes can also lead to increased environmental degradation, as higher levels of consumption and production often lead to greater demand for natural resources and energy, which can contribute to climate change, deforestation and other forms of environmental degradation (Acaravci and Ozturk, 2010).

Economic growth, which includes production and consumption activities, shows the economic progress of a country, but it can have both positive and negative environmental impacts (Jahanger et al., 2022a). This situation is also referred to in the literature as the 'environmental Kuznets curve' (EKC). The EKC hypothesis states that pollution increases with income up to a certain level of income or development, and then, as this level of income or development increases due to structural and technological effects, pollution does not increase but rather decreases. Inspired by this hypothesis, environmental economists such as Grossman and Krueger (1991, 1995), Selden and Song (1994), and Dinda (2004) developed the EKC hypothesis, which examines the relationship between environmental degradation and economic growth. This hypothesis has been studied by many researchers (Stern, 2017; Bekun et al., 2021; Pata et al., 2023). For example, Ganda (2019), Luo et al. (2021) and Adebayo et al. (2022) found that environmental pollution increases with the increase in GDP. The results of our analysis are consistent with these findings. On the other hand, Park et al. (2018) and Erdogan et al. (2023) found that GDP decreases environmental pollution. In addition, Chu (2022) and Khan et al. (2022) found mixed effects of GDP on environmental pollution in their studies.

There are many studies in the literature that examine the impact of technological development on environmental degradation. Some of these studies argue that technological development reduces environmental degradation (Luo et al., 2021; Liu et al., 2022; Chen et al., 2023), while others argue that it increases environmental degradation (Park et al., 2018; Celik and Alola, 2022; Dogan and Pata, 2022). However, many different parameters are used as indicators of technological development and as environmental indicators. It can be seen that the results of empirical analyses using these parameters differ from each other. In order to clear up this confusion in the literature, this study presents in Table 1 the studies that model technological development indicators separately and shows how the effect of technological development on environmental degradation is mixed (Ganda, 2019; Ma et al., 2022). Thus, the present study contributes to the extant literature on energy-environment and technological innovation in terms of scope by considering the E-7 bloc and method and subsequently proffers policy suggestions to related stakeholders.

3. Data, model description and methodology

3.1. Data description, and model construction

Studies in the literature use variables such as total greenhouse gases, CO_2 emissions, EF, carbon footprint, resource rent, nitrogen dioxide, sulphur dioxide, PM2.5 and PM10 as environmental degradation variables (Dam and Sarkodie, 2023; Dam et al., 2023b). In this study, EF was used as the environmental degradation variable.

Variables such as R&D expenditure, number of patents, information and communication technology (ICT) and technical cooperation grants are used as technology variables. In this study, the total number of patent applications was used as the technology variable. Several empirical papers have used the total number of patents as a proxy for technological innovation (Liu et al., 2022; Ma et al., 2022; Obobisa et al., 2022). This is because an increase in the number of patents indicates the diversity of R&D activities and technology resources in an economy (Jianguo et al., 2022).

In this study, the annual data of the E-7 countries for the period 1992–2018 have been used. Data on the variables EF, TI, NRR, GDP, REC and TO are presented in Table 2.

We converted all variables to natural logarithms in order to obtain reliable and consistent results in the analyses. The descriptive statistics used in the study are presented in Table 3.

In order to test whether there is a problem of multicollinearity between the dependent variable and the independent variables, a multicollinearity test was carried out. Table 4 shows the results of this test.

In Table 4, since VIF values are less than 5, it shows that there is no multicollinearity problem.

This study empirically examines the effect of the independent variables on the dependent variable for the E-7 countries. The mathematical function and econometric model of the empirical analysis are as follows (Eq. (1) and Eq. (2)):

$$lnEF_{it} = f\left(lnTI_{it}^{\beta_{1i}}, lnNRR_{it}^{\beta_{2i}}, lnGDP_{it}^{\beta_{3i}}, lnREC_{it}^{\beta_{4i}}, lnTO_{it}^{\beta_{5i}}\right) \tag{1}$$

$$ln\ EF_{it} = \alpha_0 + lnTI_{it}^{\beta_{1i}} + lnNRR_{it}^{\beta_{2i}} + lnGDP_{it}^{\beta_{3i}} + lnREC_{it}^{\beta_{4i}} + lnTO_{it}^{\beta_{5i}} + \varepsilon_{it} \tag{2}$$

In Eq. (2), α_0; constant term, β; coefficient of the independent variable, i; cross-section, t; time period and ε_{it}; error term.

3.2. Methodology process

Cross-sectional dependence (CSD) between geographical regions should be taken into account when making panel evaluations in econometric analyses. In this context, the CSD test is used to assess the interrelationship between sections in a panel. The CSD test is used in cases where the general period observations are T > N and T < N. For this reason, the CSD test was first performed in the study to check the stationarity of the series (Ullah et al., 2023). Estimates made with non-stationary series may be biased. If a shock occurring in one of the variables affects the other units, the problem of CSD between series arises. Therefore, in this case, 2nd generation unit root tests should be chosen instead of 1st generation unit root tests (Pesaran, 2007). In this study, we test for inter-series CSD using Pesaran's CD tests (Pesaran, 2021). Appropriate unit root tests were then selected according to the results of the CSD tests.

We used the PMG-ARDL approach to measure the relationship between the series. The PMG-ARDL estimator provides evidence on whether the series are cointegrated with I(0), I(1) or a mixture of both. In addition, we tested whether there is a causal relationship between the series or the direction of the causality. Fig. 1 shows the econometric methodology of the current study.

Table 2
Data description and sources.

Variables	Abbreviation	Description and Measurement	Source
Ecological footprint	$lnEF_{it}$	Ecological, footprint, gha per person	GFN
Technological innovation	$lnTI_{it}$	Total patents	OECD
Natural resource rents	$lnNRR_{it}$	Natural resources rents (% of GDP)	WDI
Real income	$lnGDP_{it}$	GDP per capita (constant 2015 US$)	✓
Renewable energy	$lnREC_{it}$	% of total final energy consumption	✓
Trade openness	$lnTO_{it}$	The ratio of total exports and imports to GDP	✓

Note: Global Footprint Network (GNF) and World Development Indicator (WDI).

Table 3
Descriptive statistics.

Variables	Mean	Median	Max.	Min.	Std. Dev.
lnEF	0.369	0.436	0.832	−0.107	0.233
lnTI	2.263	2.326	4.535	−0.522	0.879
lnNRR	0.476	0.532	1.342	−0.854	0.479
lnGDP	3.636	3.804	4.079	2.763	0.361
lnREC	1.276	1.377	1.757	0.502	0.385
lnTO	1.628	1.679	2.043	1.194	0.163

GDP is the variable with the highest mean among the series for which we used annual data for the period 1992–2018 in the E-7 countries. However, EF has the lowest mean, TI has the highest maximum, while EF has the lowest maximum. Looking at the minimum values of the series, EF, TI and NRR have negative values, while GDP, REC and TO have positive values.

Table 4
Test for multicollinearity.

Variable	1/VIF	VIF
lnTI	0.903	1.11
lnNRR	0.789	1.27
lnREC	0.390	2.56
lnGDP	0.566	1.77
lnTO	0.656	1.52

3.2.1. Panel estimators

We use a PMG-ARDL, FMOLS and DOLS estimator to examine the impact of TI, REC, NRR and TO on EF for a panel of E-7 countries. Pesaran et al. (1999, 2001) developed the PMG method to deal with heterogeneity in panel data in 1999 and the ARDL method to estimate non-stationary relationships in panel data in 2001. This method is an appropriate estimator to assess the short- and long-run relationship, as the unit root test results show that the series are stationary at different levels. The PMG-ARDL estimator plays an important role in providing evidence on the cointegration status, such as whether the series are integrated to degree 0 (I(0)), integrated to degree 1 (I(1)) or a combination of both (a mixture). The ARDL approach does not pre-test the variables. Given the characteristics of the cyclical components of the data, this feature alone renders the standard cointegration technique inappropriate, and even the unit root tests available to determine the order of integration are still highly controversial (Adedoyin and Zakari, 2020). The inability of the ARDL estimation method to control for bias in panel data models with individual effects due to bias arising from the relationship between the white noise term and the mean differenced independent variables is addressed by the PMG-ARDL approach (Pesaran and Yamagata, 2008). These methods have been widely used in the econometric literature. Pesaran and Yamagata (2008) combined PMG and ARDL methods to deal with heterogeneity in panel data. This method, called Pooled Mean Group - Autoregressive Distributed Lag

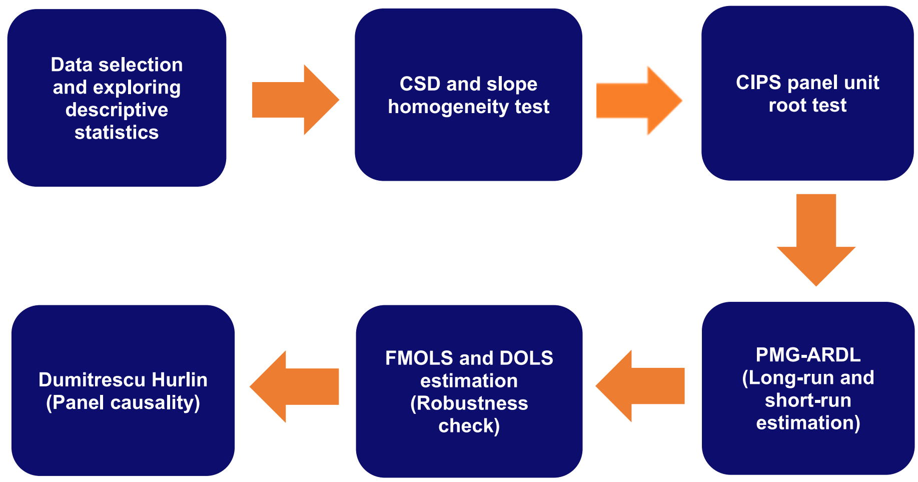

Fig. 1. Econometric framework.

PMG-ARDL, provides a more flexible, efficient and consistent approach than ARDL for estimating non-stationary relationships in panel data. The PMG-ARDL method is organised as in Eq. (3):

$$\Delta Y_{1it} = \alpha_{1i} + \beta_{1i} Y_{1it-1i} + \sum_{l=2}^{k} \beta_{1i} X_{1it-1} + \sum_{j=1}^{p-1} Y_{1ij} \Delta Y_{1it-j} + \sum_{j=0}^{p-1} \sum_{l=2}^{k} Y_{1ij} \Delta X_{1it-j} + \varepsilon_{1it} \quad (3)$$

Here, Y_1; dependent variable, X_1; independent variable, Δ; first difference operator, ε_{it}; error term. If the variables used in the model of the study are rearranged in Eq. (3):

$$\Delta lnEF_{it} = \alpha_{1i} + \beta_{1i} lnEF_{it-1i} + \beta_{2i} lnTI_{it-1} + \beta_{3i} lnNRR_{it-1} + \beta_{4i} lnREC_{it-1} + \beta_{5i} lnGDP_{it-1} + \beta_{6i} lnTO_{it-1} + \sum_{j=1}^{p} Y_{1i} \Delta lnEF_{it-j} + \sum_{i=0}^{q} Y_{2i} \Delta lnTI_{it-j} + \sum_{i=0}^{q} Y_{3i} \Delta lnNRR_{it-j} + \sum_{i=0}^{q} Y_{4i} \Delta lnREC_{it-j} + \sum_{i=0}^{q} Y_{5i} \Delta lnGDP_{it-j} + \sum_{i=0}^{q} Y_{6i} \Delta lnTO_{it-j} + \varepsilon_{1it} \quad (4)$$

In the study, the robustness of the estimation results of the ARDL method was checked by applying FMOLS and DOLS tests.

3.2.2. *Panel causality test*

Many studies have been carried out in the literature to test the causality between the series. The recently popular DHC test is used to assess the causality between two time series. This test can determine not only whether two series are causally related, but also the direction of causality. In other words, it can determine which series influences the other. This causality test, developed by Dumitrescu and Hurlin (2012), uses a version of the Granger (1969) test to determine the level of causality. This method, which is a more reliable variant of the Granger test, is used on panel data to examine possible causes and effects. The DHC test is used in this analysis. The DHC test is the essence of the Granger causality test as it is used for heterogeneous panel data sets with fixed coefficients (Ahmed et al., 2022). In this test, the Zbar test represents the normal distribution and the Wbar test represents the mean (Dumitrescu and Hurlin, 2012). The DHC test is expressed by the following equation:

$$Z_{it} = \alpha_i + \sum_{j=1}^{p} \beta_i^j Z_{it-j} + \sum_{j=1}^{p} \gamma_i^j T_{it-j} \quad (5)$$

Where j represents the lag length and β_i^j represents the autoregressive parameters.

The null hypothesis and the alternative hypothesis of this test are as follows:

$$H_0 : \beta_i^{(k)} = 0 \; for \; i \text{ No causality},$$

$$H_1 : \begin{matrix} \beta_i^{(k)} = 0, i = 1, 2, \ldots N_1 \\ \beta_i^{(k)} \neq 0, i = N_1 + 1, N_1 + 2, N_1, \ldots N \end{matrix} \text{ Unidirectional causality.}$$

4. Results and discussion

4.1. *Pre-estimation test results*

In panel data analysis, the first step is to check whether there is a CSD between the series using different tests. If there is a CSD between series, methods that take this into account should be used, otherwise the results may be biased and inconsistent (Pesaran, 2021). Therefore, we analyse the inter-series CSD using the CD test developed by Pesaran (2021). Table 5 presents the results of these tests.

The results shown in Table 5 support the CSD between the series. It is rejected at the 1 % significance level for all series and all three tests. This shows that any shock that occurs in the sample countries also affects the other countries.

4.2. *Stationary test results*

Following the results of the CSD test, it was decided to test for the unit root between series using the CIPS panel unit root test. Table 6

Table 5
The cross-sectional dependence test results.

Variables	CD-Test	Prob.
lnEF	4.598[a]	(0.000)
lnTI	22.124[a]	(0.000)
lnNRR	13.171[a]	(0.000)
lnGDP	21.878[a]	(0.000)
lnREC	15.703[a]	(0.000)
lnTO	2.996 [a]	(0.002)

[a] Indicate significance at the 1 %.

Table 6
CIPS unit root test results.

Variable	Without trend		Within trend	
	Level	Δ	Level	Δ
lnEF	−2.108	−4.679***	−2.472	−4.810***
lnTI	−4.091***	−5.762***	−4.124***	−5.952***
lnNRR	−1.614	−4.876***	−2.241	−4.852***
lnGDP	−1.323	−3.256***	−1.911	−3.510***
lnREC	−2.129	−4.436***	−2.824*	−4.506***
lnTO	−2.271*	−4.467***	−3.504***	−4.507***

***and * indicate significance at the 1 % and 10 % levels, respectively.

Table 7
PMG-ARDL estimation results.

Variables	Coefficients	t–statistics	Prob.
Long run results			
$lnTI_{it}$	−0.064***	−4.781	0.000
$lnNRR_{it}$	0.053***	4.259	0.000
$lnGDP_{it}$	0.249***	2.811	0.005
$lnREC_{it}$	−0.234***	−4.346	0.000
$lnTO_{it}$	−0.053	−1.518	0.131
Cons.	−0.039	−1.559	0.121
Short run results			
$\Delta lnTI_{it}$	0.040	1.211	0.227
$\Delta lnNRR_{it}$	0.009	1.628	0.105
$\Delta lnGDP_{it}$	0.251*	1.738	0.084
$\Delta lnREC_{it}$	−0.128	−1.400	0.163
$\Delta lnTO_{it}$	−0.129*	−1.700	0.091
ECT_{t-1}	−0.550***	0.048	0.000

***and *are defined significance at the 1 % and 10 % levels, respectively.

presents the results of this test.

As can be seen from the results of the unit root tests presented in Table 6, the series are stationary at different levels. That is, some of the series are stationary at I(0) while others are stationary at I(1). The fact that the series are stationary at different levels helps in the application of the PMG-ARDL method.

4.3. Panel estimator results

The PMG-ARDL approach was used to present the long- and short-term estimation results of the panel data analysis, and the results are presented in Table 7.

Table 7 shows that TI has a negative and statistically significant effect on EF in the long run. There is significant evidence that TI has a positive impact on environmental quality in the E-7 countries. Holding the other variables constant, the estimated long-run coefficient of TI is negative and significant at the 1 % level. This means that a 1 % increase in TI leads to a 0.06 % decrease in EF. There is evidence that TI minimally reduces pollution. This is not due to a lack of technological infrastructure in the E-7 developing countries, but rather to a minimal level of environmentally friendly technologies. Similar results have been found in the literature by Ahmad et al. (2020), Zeraibi et al. (2021), Abid et al. (2022), Sherif et al. (2022), and Usman et al. (2023). Furthermore, these studies emphasise the need for increased investment in TI. Similarly, Zuo et al. (2022) emphasised that TI for BRI countries will maintain the international capabilities of the sample countries and provide a long-term environmentally-oriented sustainable economy.

According to the long-term estimation results, the effect of NRR on EF is mixed, similar to the literature. According to the PMG-ARDL and FMOLS results, a 1 % increase in NRR increases EF by 0.053 and 0.347 respectively. However, according to DOLS results, a 1 % increase in NRR decreases EF by 0.171. For example, Hassan et al. (2019), Ahmed et al. (2020), Usman et al. (2022), and Hussain et al. (2023) concluded that an increase in NRR increases pollution. However, Balsalobre-Lorente et al. (2018) and Adebayo et al. (2022) found that NRR reduces environmental pollution. The negative impact of natural resources shows that natural resource wealth provides an economy that limits pollution by reducing the need to import traditional energy sources such as natural gas and oil. These results suggest that the E-7 countries form an inhomogeneous community in terms of natural resource wealth and environmental sustainability.

We observe that renewable energy has a strong impact on EF. Empirical evidence has shown that RECs reduce EF, i.e. increase environmental quality. Furthermore, a 1 % increase in REC use reduces EF by 0.23 %. Sahoo and Sethi (2021), Usman and Hammar (2021), Adebayo (2022) and Huang et al. (2022) found similar results to our study. These studies emphasise that REC reduces the negative impact on the environmental balance and that this energy should be promoted. Huang et al. (2022) also argue that increasing REC and TI is the key way to increase renewable energy capacity and environmental quality. Similarly, previous studies such as Dam and Sarkodie (2023) and Guloglu et al. (2023) provide parallel plausible explanations for why environmental sustainability increases with improvements in renewable energy investment.

In the fast-growing E-7 countries, economic growth leads to an increase in energy demand. Real income is positive and statistically significant in all three estimators. It was found that GDP increases the EF in both the long and the short run. In the long run, a 1 % increase in GDP increases the EF by 0.24 %. These results are consistent with those of Ulucak et al. (2020), Nwani and Adams (2021), Jahanger et al. (2022a), Zuo et al. (2022) and Adebayo et al. (2023b). In addition, it is also possible to come across studies in which real income leads to a full reduction in the pollution of the environment. Pata et al. (2023) analysed the effect of real income on CO_2 emissions in ASEAN countries using the PMG-ARDL method and found a negative relationship. In this study, where TO was used as a control variable, there was no positive but statistically significant effect on EF.

The PMG-ARDL demonstrates that increased use of renewable energy and technological innovation improve environmental performance by reducing environmental impacts, while economic growth and natural resource rents worsen environmental performance in the E-7 countries.

The short-run results show that the coefficient of the error correction term (ECT) is negative and significant, as expected. In this case, it can be seen that the shocks that occur in the E-7 countries in the short run converge in the long run. In the short run, GDP increases the EF, while the CTR reduces it. Furthermore, since the probability values of the other independent variables are not significant in the short term, we do not interpret their coefficients.

In the current study, the FMOLS and DOLS tests were used to test the consistency of the predicted outcome and to check robustness. The FMOLS and DOLS results are presented in Table 8.

FMOLS and DOLS results indicate that technological improvements

Table 8
FMOLS and DOLS robustness test results.

Variable	FMOLS	DOLS
$lnTI_{it}$	−0.517***	−0.403**
	−14.697	−2.028
	(0.000)	(0.047)
$lnNRR_{it}$	0.347***	−0.171**
	6.333	−1.940
	(0.000)	(0.057)
$lnGDP_{it}$	0.523***	1.892***
	48.309	2.882
	(0.000)	(0.005)
$lnREC_{it}$	−0.263***	−0.959
	−10.655	−1.418
	(0.000)	(0.162)
$lnTO_{it}$	0.087***	0.319**
	3.368	2.386
	(0.000)	(0.020)

***and ** define significance at the 1 % and 5 % levels, respectively.

reduce the EF. A 1 % increase in TI reduces EF by 0.40–0.51 %. These results are consistent with the PMG-ARDL results. According to the FMOLS results, NRR increases the EF at the 1 % significance level, while it decreases it at the 5 % significance level in the DOLS results. In the FMOLS estimation results, REC was found to have a negative and statistically significant effect on EF. The effect of GDP on EF is positive and highly significant according to both FMOLS and DOLS results. In the PMG-ARDL test consequence, while the effect of TO openness on EF was not significant, it was determined that it has a positive and significant effect in FMOLS and DOLS results.

4.4. Panel causality test results

Based on the Granger causality test, the DHC test can test for both linear and non-linear causal relationships. This test is used to detect causality between series. Table 9 shows the results of the DHC test.

Table 9 shows that there is a unidirectional causality from the TI series to the EF series. Technological progress and the adaptation of innovations to the environment contribute positively to environmental sustainability. Similar to the results obtained, Ganda (2022) found a unidirectional causality from TI to environmental degradation in the new BRICS countries. They also found a unidirectional causal relationship between NRR and EF. Aladejare (2022) found similar results to ours in the five richest African countries. Moreover, while a unidirectional causality was found between EF and trade openness, no causality was found between REC and EF. In contrast, a bidirectional causality was found between GDP and EF.

5. Conclusion and policy implications

5.1. Conclusion

The demand for fossil fuels is increasing due to the rate of economic growth in the E-7 countries and the increase in foreign trade capacity. This situation poses a daily challenge to the environmental sustainability of the developing E-7 countries. In this context, the main policy tool for many countries is to reduce fossil fuels and to pass on to future generations an environment compatible with the SDGs through the use of alternative energy. SDG-7 and SDG-8 are crucial for the E-7 countries to achieve environmental sustainability. To this end, the increased use of renewable energy should be supported.

The link between GDP, REC, TI, NRR and environmental sustainability that we have modelled in our study is critical to achieving the UN SDGs. Adopting a sustainable development approach, which balances economic growth with environmental protection and social equity, is essential to ensure a sustainable future for all. The study first examines the CSD among the series. Since the existence of CSD among the series was verified, the CIPS unit root test, one of the 2nd generation unit root tests, was applied to test the stationarity of the series. Since the series are stationary at different levels in the panel unit root test results, the PMG-ARDL method was chosen as the long- and short-run estimator. In the PMG-ARDL test results, it was found that the use of TI and REC reduces the EF in the long run. On the contrary, NRR and GDP were found to increase EF in the long term. In this study, the FMOLS and DOLS estimators were used to test the consistency of the PMG-ARDL estimation results. Similar results were obtained. The DHC test was used to determine the causality between the series. In the DHC test results, a unidirectional causality relationship was found from TI to EF, from EF to NRR and TO, while a bidirectional causality relationship was found between GDP and EF.

In particular, the SDG framework and indicators need to be conceptually and methodologically well-designed and tested before adoption (Hák et al., 2016). This study conceptually and methodologically addressed the determinants of ecological footprint in the context of the SDGs and analysed the impact of NRR, TI and REC. These findings suggest that future studies will focus on TI and REC in the context of the SDGs for all countries, especially European countries, in the context of zero waste targets.

5.2. Policy implications

Environmental pollution has reached alarming levels in our world, where technological development has peaked and natural resources are being over-consumed. In this context, it is very important for countries to focus on investments in renewable energy to combat pollution. This is consistent with the results of our empirical analysis in the E-7 countries. Taking into account the empirical findings, the study has some important implications for policymakers. In order to achieve the SDGs, E-7 countries need to take stronger and more stringent measures against environmental degradation. Considering that TI significantly reduces EF, E-7 countries should support TI and these technologies should be directed to more environmental research and development activities. In addition, TIs should be applied in the renewable energy sector in these countries and resources should be allocated in budget planning to fund technological developments in this area.

Considering that NR has a positive and significant effect on EF in E-7 countries, policies should be developed in these countries to limit the consumption of NR, to prioritise the consumption of clean resources and to help find new clean resources. To ensure the sustainability of NR, sustainability should be based on resource use and environmental measures should be further strengthened. Taking into account that REC reduces EF in E-7 countries, it is concluded that the contribution of REC to the achievement of SDG-7 by these countries is high. Therefore, it is important for these countries to increase the share of REC in total energy consumption. At this point, incentives and projects to increase economic growth and renewable energy production should be prioritised. Strengthening incentives for renewable energy and reviewing sanctions will help to increase the share of renewable energy in use. Developing countries, such as the E-7, are striving to reach optimal income levels and thus increase their economic growth rates. As such, it is suggested that developing countries such as the E-7 should be guided by the SDGs. As a result of the robustness check, the positive and significant effect of TO on EF suggests that E-7 countries trade in non-environmentally friendly imports. Developing countries such as the E-7 should adopt environmentally friendly foreign trade policies instead of importing polluting goods, especially fossil fuels.

Moreover, our findings suggest that renewable energy has a positive impact on sustainable environmental performance, hence the importance of comprehensive and sustainable environmental policies. In this context, E-7 governments can implement a green reform programme for sustainable growth in both the public and private sectors. Increased investment in green technology initiatives will help countries achieve the net zero carbon target.

Table 9
DHC test results.

No	H_0	W-Stat.	Zbar-Stat.	Prob.	Causality
1	$lnTI \neq lnEF$	8.033	6.188	6.E-10***	$lnTI \rightarrow lnEF$
2	$lnEF \neq lnTI$	2.561	0.360	0.718	None
3	$lnNRR \neq lnEF$	2.264	0.045	0.964	*None*
4	$lnEF \neq lnNRR$	5.276	3.252	0.001***	$lnEF \rightarrow lnNRR$
5	$lnGDP \neq lnEF$	7.540	5.662	1.E-08***	$lnGDP \rightarrow lnEF$
6	$lnEF \neq lnGDP$	5.850	3.863	0.000***	$lnEF \rightarrow lnGDP$
7	$lnREC \neq lnEF$	3.192	1.033	0.301	*None*
8	$lnEF \neq lnREC$	2.530	0.328	0.742	*None*
9	$lnTO \neq lnEF$	3.389	1.242	0.214	*None*
10	$lnEF \neq lnTO$	7.339	5.449	5.E-08	$lnEF \rightarrow lnTO$

***$p < 0.01$ denotes a statistical rejection level at 1 % and $\neq$ denotes no causality.

5.3. Future research suggestion

Despite the use of five important explanatory factors as determinants of the Ecological Footprint, this study has some limitations. First, this study does not take into account the income level or population diversity in the E-7 countries. The impact of the determinants of the Ecological Footprint may be different in high-income countries than in low-income countries. Alternatively, countries with similar populations could be grouped and modelled separately. Future studies should take these aspects into account. Second, this study uses the ecological footprint, an indicator of environmental pressure, as the dependent variable. Future research can use environmental sustainability variables (load capacity factor; inverted load capacity factor) instead of pollution variables and provide comprehensive policy recommendations. Third, the study showed that the effects of the determinants of ecological footprint are different depending on the econometric methods used. Future studies can discuss the determinants of Ecological Footprint using different econometric methods such as wavelet coherence, Fourier transforms and non-linear analysis. In this way, policies to reduce ecological footprint can contribute to the achievement of carbon neutrality and the realisation of SDG-7, SDG-8 and SDG-13.

Availability of data and materials

The data for this present study are sourced from WDI as outlined in the data section.

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Ethical approval

Authors mentioned in the manuscript have agreed for authorship read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.

Code availability

All codes for the analysis are available in STATA and E-views statistical software.

Consent to participate

Note Applicable.

Consent to publish

Applicable.

CRediT authorship contribution statement

Mehmet Metin Dam: Data curation, Conceptualization. **Funda Kaya:** Methodology, Investigation, Formal analysis. **Festus Victor Bekun:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141020.

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