PROBLEMY EKOROZWOJU/ PROBLEMS OF SUSTAINABLE DEVELOPMENT
SUBMITTED: 22.09.2024, ACCEPTED: 25.11.2024, PUBLISHED ON-LINE: 10.01.2025
2025, 20(1): 143-158
DOI: 10.35784/preko.6609

Estimating the Role of Globalization, Technological Development and Household Consumption on Ecological Footprint in Visegrad Countries

Oszacowanie roli globalizacji, rozwoju technologicznego i poziomu konsumpcji gospodarstw domowych na ślad ekologiczny w krajach Grupy Wyszehradzkiej

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Abstract
Environmental quality is a crucial topic both for developed and developing countries. In particular, along with globalization, developing countries strive to catch up with developed countries. However, the globalization process in developing countries may also cause environmental effects. Hence, the current paper aims to analyze the impact of globalization, technological development (TD), and household consumption on the ecological footprint (EF) in Visegrad countries (V4), Czechia, Hungary, Poland, and Slovakia over the period 1996-2021 through controlling economic growth, renewable energy consumption, and CO_2 emissions. In order to achieve this aim, we perform the augment mean group (AMG) estimator that takes into consideration cross-sectional dependence (CSD). The empirical findings reveal that globalization, renewable energy consumption, and CO_2 emissions significantly positively affect EF. However, economic growth (EG) has an insignificantly positive, and TD and household consumption have insignificantly negative impacts on EF in the whole panel. In addition, the country-specific results provide mixed results. For example, EG has a significantly positive effect on EF in Slovakia and Hungary and an insignificantly positive effect on EF in Poland and Czechia. Globalization significantly positively influences EF in Czechia and Slovakia and insignificantly positively affects EF in Poland and Hungary. Technological development (TD) has significantly negative effects on EF in Poland, Czechia, and Slovakia and positive effects in Hungary. Household consumption has a negative significant effect on EF in Hungary, an insignificant negative effect in Slovakia, and a positive insignificant effect in Poland and Czechia. Moreover, renewable energy consumption positively affects EF in Czechia and Hungary and has insignificantly positive effects in Poland and Slovakia. Finally, CO_2 emission has a significantly positive influence on EF in Poland, Czechia, and Slovakia and an insignificantly positive influence in Hungary. Consequently, empirical findings can help policymakers develop new policies for combating environmental degradation by considering the role of globalization, technological improvement, and CO_2 emissions.

Keywords: ecological footprint, environmental degradation, environmental quality, globalization, technological development, household consumption, CO_2 emissions

Streszczenie

Jakość środowiska jest kluczowym tematem zarówno dla krajów rozwiniętych, jak i rozwijających się. Wraz z globalizacją kraje rozwijające się dążą do dogonienia krajów rozwiniętych. Jednak proces globalizacji w krajach rozwijających się może również powodować skutki dla środowiska. Dlatego też niniejszy artykuł ma na celu analizę wpływu globalizacji, rozwoju technologicznego (TD) i konsumpcji gospodarstw domowych na ślad ekologiczny (EF) w krajach Grupy Wyszehradzkiej (V4), Czechach, na Węgrzech, w Polsce i na Słowacji w latach 1996-2021 poprzez kontrolowanie wzrostu gospodarczego, zużycia energii odnawialnej i emisji CO_2. Aby osiągnąć ten cel, wykorzystujemy estymator średniej rozszerzonej (AMG), który uwzględnia zależność przekrojową (CSD). Wyniki empiryczne pokazują, że globalizacja, zużycie energii odnawialnej i emisje CO_2 znacząco pozytywnie wpływają na EF. Jednak wzrost gospodarczy (EG) jest nieznacznie dodatni, a TD i konsumpcja gospodarstw domowych mają nieznacznie negatywny wpływ na EF w całym panelu. Ponadto wyniki dla poszczególnych krajów dostarczają zróżnicowanych rezultatów. Na przykład EG ma znacząco pozytywny wpływ na EF na Słowacji i Węgrzech oraz nieistotnie pozytywny wpływ na EF w Polsce i Czechach. Globalizacja znacząco pozytywnie wpływa na EF w Czechach i na Słowacji oraz ma nieistotnie pozytywny wpływ na EF w Polsce i na Węgrzech. Rozwój technologiczny (TD) ma znacząco negatywny wpływ na EF w Polsce, Czechach i Słowacji oraz pozytywny na Węgrzech. Konsumpcja gospodarstw domowych ma negatywny znaczący wpływ na EF na Węgrzech, nieistotny negatywny wpływ na Słowacji oraz pozytywny nieistotny wpływ w Polsce i Czechach. Ponadto zużycie energii odnawialnej pozytywnie wpływa na EF w Czechach i na Węgrzech oraz ma nieistotnie pozytywny wpływ w Polsce i na Słowacji. Wreszcie emisja CO_2 ma znacząco pozytywny wpływ na EF w Polsce, Czechach i na Słowacji oraz nieistotnie pozytywny wpływ na Węgrzech. W związku z tym ustalenia empiryczne mogą pomóc decydentom w opracowaniu nowych polityk zwalczania degradacji środowiska poprzez uwzględnienie roli globalizacji, udoskonalenia technologicznego i emisji CO_2.

Słowa kluczowe: ślad ekologiczny, degradacja środowiska, jakość środowiska, globalizacja, rozwój technologiczny, konsumpcja gospodarstw domowych, emisja CO_2

1. Introduction

Climate change and factors exaggerating environmental degradation are some of the important priorities of global society. It is a fact that the world is facing a massive amount of energy consumption that causes environmental degradation. In the last thirty years, various research fields have emerged on the factors affecting environmental quality. According to the World Meteorological Organization (2024) report, 2023 was the warmest year, with a 1.45 ± 0.12 °C above pre-industrial level. Carbon dioxide (CO_2), methane, and nitrous oxide concentrations have reached record levels in 2022 and 2023. Despite the country's engagement in the Kyoto Protocol and the Paris Agreement to reduce emissions to a targeted level, the levels are still alarmingly high. Particularly, the CO_2 emissions from gaseous fuel consumption have risen from 977.330 million (kt) to 7.322.550 million (kt) over seven times from 1960 to 2016. During the same period, CO_2 emissions from liquid fuel consumption have risen from 3.027.083 million (kt) to 10.809.210 million (kt) more than 3.5 times (World Bank, 2024). Although greenhouse emissions, including CO_2, methane, and nitrous oxide, are the main contributors to climate change, they do not entirely reflect anthropogenic pressure on ecosystems and environmental degradation (Ahmed et al., 2019; Kirikkaleli et al., 2023; Aytun et al., 2024). Hence, ecological footprint (EF) is preferred as a more comprehensive indicator for measuring environmental degradation. As verified by several studies, there are several factors influencing environmental quality. Among these factors, globalization is becoming more prominent in developing countries. In this context, it is possible to find out the nexus between globalization and environmental degradation. In particular, the effects of economic globalization on environmental degradation may have two opposite sides. For example, economic activities enlarge along with globalization, and industries' energy consumption rises. Hence, economic globalization negatively affects environmental quality (Ahmed et al., 2019). On the contrary, economic globalization may cause a shifting economic structure from industrial economies to an environmentally friendly service sector, which enhances environmental quality (Kirikkaleli et al., 2021; Rehman et al., 2021). In addition, technological development (TD) plays a crucial role in mitigating environmental degradation. The relevant literature explains the mitigating effect of TD on environmental degradation in various ways. Firstly, it is expected that TD improves energy efficiency, and using more technology reduces energy consumption and diminishes environmental degradation caused by energy consumption. Secondly, TD promotes using renewable energy and reduces dependency on non-renewable energy, which damages the environment (Raza et al., 2023; Aytun et al., 2024). Moreover, it is not solely accepted that TD promotes environmental quality. In addition, it is not universally accepted that TD contributes to environmental quality. Although TD improves energy efficiency, its marginal effect is diminishing, and since the scale of the economy enlarges, it raises demand for investment in natural sources. Besides, the improving effects of TD on environmental quality are more related to the coordination capability between technological investment and technological capabilities rather than the direct effect of technological investment (Chen & Lee, 2020). In summary, the relationship between TD and environmental quality is not straightforward. Indeed, several factors affect environmental quality; household consumption is another critical factor. The association between household consumption and environmental degradation emerges thanks to direct and indirect ways. The direct effect occurs from the consumption of energy sources such as electricity, natural gas, and gasoline. The indirect effect is caused by the production of goods and services consumed by households (Sohag et al., 2015; Liu et al., 2021). Since EG rises in the V4 countries, it is indispensable that household consumption rises as well. According to the World Bank (2024) data, household consumption was $54.5 billion, with a constant 2015 price in 1995, and increased to 94.60 $billion in 2023 in Czechia. From 1995-2023, household consumption increased from $47.72 billion, $133.23 billion, and $25.26 billion to $80.38 billion, $357.9 billion, and $57.62 billion in Hungary, Poland, and Slovakia, respectively.

Due to the controversial and mixed empirical results, additional investigations are needed. Therefore, the current paper aims to analyze the impact of globalization, technological development, and household consumption on EF for a panel sample of Visegrad countries (or V4), including Czechia, Hungary, Poland, and Slovakia, by utilizing a dataset spanning 1996 and 2021. There are two main motivations behind selecting the V4 countries as the sample for examining. Firstly, all V4 countries experienced a high level of liberalization following the collapse of the Soviet Union.

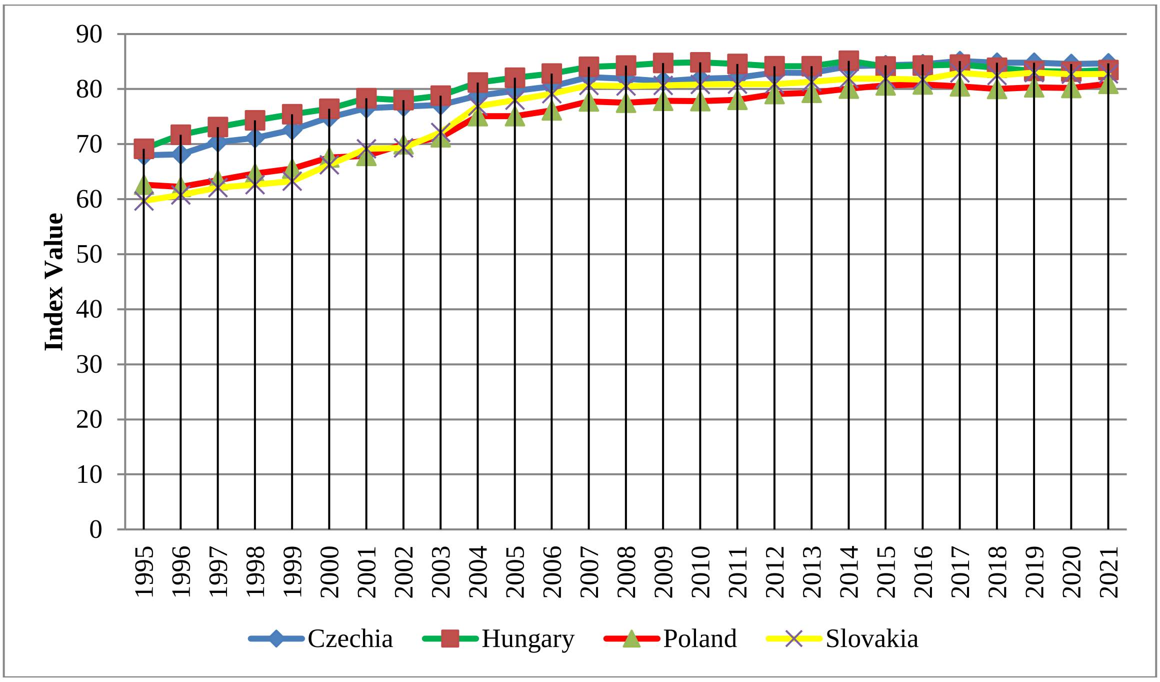

Figure 1. KOF overall globalization index in the V4 countries, source: (Gygli et al., 2019)

It is easily depicted in Fig. 1 that all the V4 countries have become a part of globalization. They adopted liberalization in terms of trade, foreign investment, and capital flow. According to the World Bank (2024), the share of trade over GDP indicating trade openness has risen from 83.5%, 78.4%, 43.72%, and 108.55% to 138.9%, 157.3%, 109.54%, and 181.52% in Czechia, Hungary, Poland, and Slovakia, respectively from 1995 to 2023. Moreover, the share of foreign direct investment (FDI) net inflow also has risen from 4.27%, 10.35%, 2.57%, and 0.91% to 4.57%, 17.39%, 5.30%, 2.29% in Czechia, Hungary, Poland, and Slovakia, respectively from 1995 to 2021 (World Bank, 2024). Furthermore, the integration of the V4 countries into the world is not limited to trade and investment; social and political integration also increases progressively. Hence, as illustrated in Fig. 1, the overall globalization index covering economic, social, and political dimensions has increased over 1995-2021. For example, the overall globalization index has increased from 68, 69, 63, and 60 to 85, 83, 81, and 83, spanning the period 1996-2021 in Czechia, Hungary, Poland, and Slovakia, respectively.

Secondly, another feature of the V4 countries is their solid EG path during the last three decades. Fig. 2 depicts that GDP per capita has increased in all countries during that period. The GDP per capita was $11.219 in 1995 and raised to $19.800 in 2023 in Czechia. Further, it increased from $7.676, $5.628, and $7.542 to $16.286, $17.270, and $19.217 from 1995 to 2023 in Hungary, Poland, and Slovakia, respectively. Therefore, it is possible to describe the V4 countries as emerging countries. Integration into the world production process through globalization makes it possible to consume more energy and develop new technologies to compete internationally. Hence, it is logical to think about how economic growth, globalization, and TD affect environmental quality in the V4 countries. Thus, investigating the relationship between economic growth, globalization, and technology in the V4 countries may provide new insights for emerging countries.

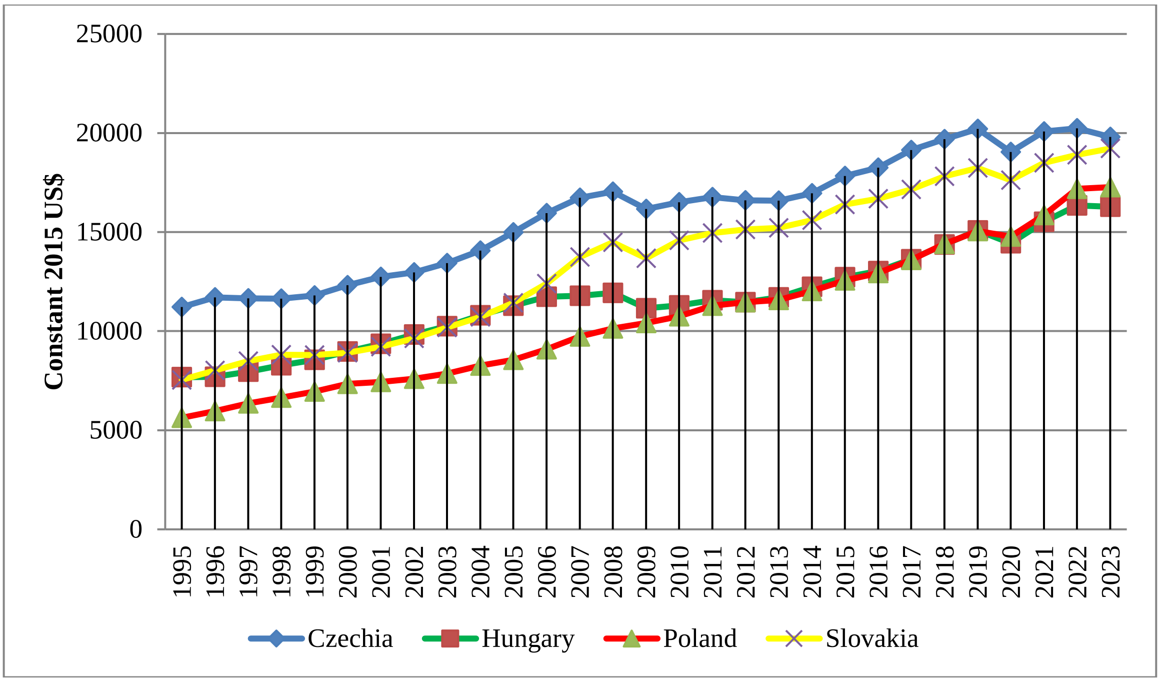

Figure 2. GDP per capita in the V4 countries, source: (World Bank, 2024)

The current paper makes three contributions to the existing literature. First, to the best of our knowledge, this is the first paper investigating the association between globalization, EF, and TD for the panel sample of the V4 countries. Second, we perform the augmented mean group (AMG) estimator, which considers cross-sectional dependence (CSD). Third, we utilized the overall globalization index instead of single indicators such as trade openness or financial investment. The KOF overall globalization index is a broad measurement covering globalization's economic, social, and political dimensions (Gygli et al., 2019).
The rest of the paper consists of five sections. Section 2 explains the relationship between sustainable development goals (SDGs), environmental degradation, and household consumption. Section 3 summarizes the empirical literature review. Section 4 describes the data, model, and methodology. Section 5 provides empirical outcomes and discussions. Section 6 provides concluding remarks with policy recommendations.

2. The importance of Sustainable Development Goals (SDGs) for a sustainable future

In the ever-evolving global development arena, the SDGs have emerged as a comprehensive framework for fostering a sustainable future. Established by the United Nations in 2015, these 17 goals address societal, environmental, and economic challenges. The overarching aim is to cultivate a more equitable and resilient world for current and future generations (Cheng et al., 2021; Elias et al., 2023; Stanojevic, 2020). The SDGs are a comprehensive set of 17 interconnected goals designed to address the world's most pressing challenges urgently. These range from poverty and inequality to environmental degradation and climate change. Adopted in 2015 by all 193 UN member states, these goals are set to be achieved by 2030 (Fei et al., 2021). The significance of the SDGs cannot be overstated, as they represent a global consensus on the need for a more sustainable and equitable future. The goals cover a broad range of issues, from ending poverty and hunger to ensuring access to clean water and sanitation and from promoting gender equality to building resilient infrastructure (Kleespies & Dierkes, 2022). The holistic approach taken by the SDGs is crucial, as it recognizes the interdependence of social, economic, and environmental factors in achieving sustainable development (Kaymaz et al., 2022).
Implementing the SDGs has been complex and multifaceted, with countries worldwide facing unique challenges and opportunities (Caiado et al., 2018). Emerging research has revealed the potentially intricate and even conflicting relationships between the different SDGs, where pursuing one goal may inadvertently undermine the achievement of another (Pradhan et al., 2017; Kaymaz et al., 2022). This underscores the need for a more nuanced understanding of the SDGs and the development of integrated policy approaches that simultaneously address multiple goals. The key strength of the SDGs lies in their development through international and interdisciplinary cooperation, recognizing the global nature of the challenges they seek to address (Kaymaz et al., 2022).
It should be emphasized that the COVID-19 crisis poses important challenges to realizing the SDGs in terms of most parts of the targets (Cengiz & Manga, 2023; OHCHR, 2024). Successfully achieving the SDGs necessitates a collective effort from all stakeholders, alongside a commitment to addressing the interconnected nature of these goals and identifying synergies among them. The urgency for a sustainable and resilient future has become in-

creasingly critical in the post-pandemic era. As the world confronts the economic, social, and environmental repercussions of the COVID-19 crisis, the SDGs offer a guiding framework for a more inclusive, equitable, and sustainable recovery. By striving towards the ambitious targets set by the SDGs, the global community can create a more prosperous, equitable, and environmentally aware world for all (Cheng et al., 2021; Kalinauskaite et al., 2021).

Historically, sustainability issues have primarily been addressed by public authorities and institutions. However, there has been a significant increase in interest from the private sector in integrating sustainability principles into their business operations (Khizar et al., 2021). A crucial aspect of sustainable development is sustainable consumption, which involves using products and services to meet essential needs while minimizing the use of natural resources, harmful materials, and waste emissions. Contemporary production and consumption patterns have placed considerable pressure on the environment, threatening the planet's ability to absorb pollutants and disrupting ecological stability due to the accumulation of waste (Silva et al., 2019).

The relationship between household consumption and sustainable development is a complex and multifaceted topic that has been the subject of extensive research and debate in recent years (Lorek & Spangenberg, 2001). As the global population grows and the demand for resources increases, the relationship between household consumption and sustainable development has become a central focus for policymakers, researchers, and environmental advocates. Responsible production and consumption are not just critical, but they are the very backbone of sustainable development (Vázquez-Burguete et al., 2023). This approach aims to meet the present generation's basic needs while ensuring that future generations' needs are not compromised (Goi, 2017). As the Brundtland Report outlines, sustainable development aims to balance development objectives, health, environmental protection, and social equity. However, achieving this more sustainable development has proven to be more intricate and challenging than initially expected (Boischio et al., 2009). In recent decades, shifts in human consumption patterns, influenced by market forces and global population growth, have adversely affected people's well-being and contributed to environmental issues like global warming and increased pollution (Abeysekera et al., 2022).

One of the critical challenges in this area is the exponential growth of household consumption, which has led to increasing pressure on natural resources and the environment (Hirschnitz-Garbers et al., 2016). To address this challenge, policymakers and researchers have explored various strategies to promote more sustainable household consumption, such as incentivizing energy-efficient appliances, encouraging the adoption of renewable energy sources, and promoting a circular economy. The literature suggests that a combination of policy instruments, including regulations, economic incentives, and information campaigns, can effectively influence consumer decision-making and promote more sustainable consumption (Haider et al., 2022; Vázquez-Burguete et al., 2023).

Besides, science, technology, and innovation are pivotal in promoting the SDGs. Innovative solutions and technologies can tackle significant challenges, enhance efficiency, and expedite progress toward these objectives (Grainger-Brown & Malekpour, 2019). For example, advancements in water treatment technologies are crucial for achieving the Clean Water and Sanitation goal (SDG 6). At the same time, developing renewable energy sources is essential for realizing the goal of Affordable and Clean Energy (SDG 7) (Delanka-Pedige et al., 2020; Muñoz et al., 2021).

The V4 countries have significantly addressed environmental challenges and promoted sustainable development. These countries have implemented various policies and initiatives to encourage sustainable consumption and production, including promoting eco-friendly packaging and reducing waste generation (Kozik, 2020). However, the region still faces challenges in adopting a more integrated and comprehensive approach to sustainable development. Patterns of production and consumption in the V4 countries have put substantial pressure on the environment, creating risks of compromising the absorption capacity of the planet and threatening ecological stability. Hence, they have tried to address these challenges, with the countries adopting national strategies and policies to promote sustainable development (Sulich & Sołoducho-Pelc, 2021).

3. Empirical literature review

The existing literature contains a wide variety of studies investigating the determinants of environmental degradation. Hence, we categorized the literature review under five headings in line with the variables used in the empirical model. Table 1 provides a summary of the literature review.

Table 1. Literature summary, source: authors' compilation.

Study	Sample	Period	Findings
Studies on the nexus between EG and EF			
Acar & Aşıcı (2017)	Türkiye	1961-2008	There is an inverted U-shaped relationship between production footprint and EG.
Khoi et al. (2021)	Singapore	1978-2016	EG positively influences EF.
Beşe & Friday (2022)	Türkiye	1970-2016	EG has a significant impact on EF.
Boukhelkhal (2022)	Algeria	1980-2017	EG increases EF.

Humbatova et al. (2024)	Azerbaijan, Hungary	2007-2022 (Azerbaijan) 2000-2021 (Hungary)	Although EG increases EF in Azerbaijan, it decreases EF in Hungary.
Rabbi & Abdullah (2024)	V4 countries	2010-2022	A complex nonlinear association exists between EG and EF.
Sun et al. (2022)	G-11 countries	1990-2020	EG causes EF.
Zhang et al. (2022)	E5 countries	1990-2019	EG increases EF.
Baz et al. (2020)	Pakistan	1971-2014	There is an asymmetric relationship between EG and EF.
Li et al. (2022)	China	1985-2018	There is an inverted U-shaped relationship between EG and EF. CO_2 increases EF.
Studies on the nexus between globalization and EF			
Amegavi et al. (2022)	Ghana	1984-2016	Economic globalization has a reducing effect on environmental quality.
Gyamfi et al. (2023)	E7 countries	1990-2019	Globalization exacerbates EF.
Thach & Ngoc (2023)	RCEP countries	1995-2016	EG and globalization positively affect EF.
Shayanmehr et al. (2023)	Top REN consuming countries	1994-2018	Globalization has a negative impact on EF.
Ansari et al. (2020)	GCC countries	1991-2017	Globalization increases EF.
Adebayo & Kirikkaleli (2021)	Japan	1990Q1- 2015Q4	Globalization, EG, and TD raise CO_2 while REN decreases.
Ahmed et al. (2019)	Malaysia	1971-2014	Globalization has no significant effect on EF. But causes to ECF.
Ansari et al. (2021)	Top REN consuming countries	1991-2016	Globalization and REN reduce EF.
Ibrahiem & Hanafy (2020)	Egypt	1971-2014	Globalization reduces EF.
Kirikkaleli et al. (2021)	Turkey	1985-2017	Globalization exaggerates EF.
Ulucak et al. (2020)	15 emerging economies	1974-2016	Financial globalization reduces EF.
Awosusi et al. (2022)	BRICS countries	1990-2017	Globalization decreases EF.
Studies on the nexus between TD and EF			
Lv et al. (2022)	China	2000-2019	Green technology reduces EF.
Yu & Guo (2022)	South Asia	1990-2018	Ecological innovation reduces EF.
Guan et al. (2022)	G-10 countries	1995-2019	Globalization and EG significantly cause EF, while technological innovation reduces the environmental burden.
Qiu & Wan (2023)	BRICS	1995-2019	Green technology decreases EF.
Raihan et al. (2024)	Poland	1990-2018	Technological innovation reduces EF.
Aydın et al. (2023)	G-7 countries	1990-2018	Nanotechnological innovations have a negative effect on EF in the USA, but they positively impact EF in Italy and the United Kingdom.
Studies on household consumption and environmental degradation			
Sohag et al. (2015)	Malaysia	1971-2010	There is an inverted U-shaped association between household consumption and CO_2.
Guo (2017)	China	1995-2010	Household consumption positively affects CO_2.
Liu et al. (2021)	China	1995-2017	Household consumption positively affects CO_2.
Studies on the nexus between REN and EF			
Balsalobre-Lorente et al. (2019)	MINT countries	1990-2013	There is a negative association between EF and REN.
Nketiah et al. (2022)	West African Countries	1995-2016	EF → REN
Li et al. (2023)	130 countries	1992-2019	REN negatively affects EF.
Joof et al. (2024)	USA	1980-2018	REN positively affects EF.
Mohamed et al. (2024)	Malaysia	1985-2020	REN for electricity generation positively affects EF.
Hasan et al. (2024)	Major oil-consuming countries	1996-2022	REN negatively affects EF.
Qing et al. (2024)	Six South Asian countries	1990-2020	REN negatively affects EF.
Bulut (2020)	Türkiye	1970-2016	EF is negatively related to REN.
Alola et al. (2021)	China	1971-2016	REN has a positive effect on EF.

Murshed et al. (2022)	South Asia	1995-2015	REN has a negative effect on EF.
Rahmane et al. (2021)	Algeria	1990-2017	REN, CO_2, and energy use positively affect EF.

Note: ECF: ecological carbon footprint; REN: renewable energy; → causality direction.

4. Data, model, and methodology

4.1. Data

The study's objective is to estimate the impact of globalization, technological development, and household consumption on EF for the V4 countries Czechia, Hungary, Poland, and Slovakia for the period 1996-2021. Table 2 lists the variables and data sources.

Table 2. Data and variable descriptions, source: authors' compilation.

Variable	Definition	Measure	Source
EF	Ecological Footprint	Ecological Footprint per person	Global Footprint Network (2024)
GDP	Economic growth	GDP per capita constant ($2015 price)	World Bank (2024)
CONS	Households consumption	Households and NPISHs Final consumption expenditure (constant 2015 US$)	World Bank (2024)
TEC	Technological development	Total number of patent applications (residents+nonresidents)	World Bank (2024)
KOF	Globalization	Overall index	Gygli et al. (2019)
REN	Renewable energy consumption	Energy consumption from renewables per capita (kWh - equivalent)	Our World in Data (2024)
CO_2	CO_2 emissions	CO_2 emissions, metric tons per capita	World Bank (2024)

4.2. Empirical model

In order to reveal the long-run relationship between ecological footprint, globalization, technological development, economic growth, household consumption, and renewable energy, and CO_2 emissions[1], we constructed an empirical model as follows:

$$\mathrm{EF_{it}} = \mathrm{f(GDP_{it}, KOF_{it}, TEC_{it}, CONS_{it}, REN_{it}, CO2_{it})} \quad (1)$$

We converted the Eq. [1] to full-natural logarithmic form and stated in Eq. (2):

$$\mathrm{lnEF_{it}} = \alpha_0 + \alpha_1 \mathrm{lnGDP_{it}} + \alpha_2 \mathrm{lnKOF_{it}} + \alpha_3 \mathrm{lnTEC_{it}} + \alpha_4 \mathrm{lnCONS_{it}} + \alpha_5 \mathrm{lnREN_{it}} + \alpha_6 \mathrm{lnCO2_{it}} + \varepsilon_{it} \quad (2)$$

where α_1, α_2, α_3, α_4, α_5, and α_6 represents long-term coefficients for lnGDP, lnKOF, lnTEC, lnCONS, lnREN, and $lnCO_2$ respectively. Furthermore, *i* donates to cross-section, *t* refers to the time, and is ε_{it} the error term.

4.3. Empirical methodology

There are four empirical stages for empirical methodology in the current study. In the first stage, we provide descriptive statistics of variables and a correlation matrix. In the second stage, we utilized Breusch & Pagan's (1980) LM test, Pesaran's (2004) scaled LM and CD tests, and Baltagi et al. (2012) bias-corrected scaled LM to check the presence of the CSD. Moreover, we adopted Pesaran & Yamagata's (2008) Delta ($\tilde{\Delta}$) and Delta $(\tilde{\Delta})_{adj}$ to test slope homogeneity in the model. In the third stage, we employ Pesaran's (2007) CIPS unit root test to examine the features of variables that consider the CSD. In the last stage, the AMG estimator is utilized to determine the long-run relationship between variables.

4.3.1. CSD Tests

If the data set is composed of a small number of cross-sections (N) and a large time dimension (T), then the Breusch & Pagan (1980) LM test can be suitable. However, this test is not appropriate when N is larger. In this case, the scaled LM test of Pesaran (2004) is applicable. However, if the N>T, it is not strong enough to correct size distortion. Pesaran's (2004) CD test can be employed instead of the scaled LM test in this case. Moreover, Baltagi et al. (2012) proposed the bias-corrected scaled LM test that can be applied for large N and small T (Tugcu, 2018). The Breusch & Pagan's (1980) LM test can be computed as follows (Murshed et al., 2021):

[1] Data for CO_2 emissions end in 2020. To estimate with balanced data, we used an average value for the period included for CO_2 emissions for 2021.

$$LM = \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} T_{ij}\hat{\rho}_{ij}^{2} \rightarrow X^{2}\frac{N(N-1)}{N} \tag{3}$$

where $\hat{\rho}_{ij}^{2}$ denotes the residual correlation obtained from the OLS equation, in addition, Pesaran's (2004) CD and CD_{LM} statistics can be specified as follows (Kostakis & Arauzo-Carod, 2023):

$$CD = \sqrt{\frac{2T}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}[\hat{\rho}_{ij},\ N(0,1)] \tag{4}$$

$$CD_{LM} = \left(\frac{1}{N(N-1)}\right)^{1/2}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(t\hat{\rho}_{ij}^{2}\right),\ N(0,1) \tag{5}$$

Furthermore, another crucial step is checking slope heterogeneity in panel econometrics. Therefore, we perform the Pesaran & Yamagata's (2008) Delta ($\tilde{\Delta}$) and Delta $(\tilde{\Delta})_{adj}$ tests to control the slope heterogeneity in the model. The Delta ($\tilde{\Delta}$) test statistics can be computed as follows (Dritsaki & Dritsaki, 2024):

$$\tilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\tilde{S}-k}{\sqrt{2k}}\right) \tag{6}$$

In Eq. [6], $\tilde{S}$ denotes the Swamy (1970) test statistics as depicted in the following equation (Kızılkaya et al., 2024):

$$\tilde{S} = \sum_{i=1}^{N}(\hat{\beta}_i - \tilde{\beta}_{WFE})'\frac{x_i' M_\tau x_i}{\hat{\sigma}_i^2}(\hat{\beta}_i - \tilde{\beta}_{WFE}) \tag{7}$$

where M_τ is the identity matrix, $\hat{\beta}$ and $\tilde{\beta}_{WFE}$ heterogenous coefficients and weighted coefficients of fixed estimators, respectively (Dritsaki & Dritsaki, 2024; Kızılkaya et al., 2024). Moreover, in the case of normally distributed error terms, the Delta $(\tilde{\Delta})_{adj}$ test statistics can be written as given (Dritsaki & Dritsaki, 2024):

$$\tilde{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}\tilde{S} - E(\tilde{z}_{iT})}{\sqrt{Var(\tilde{z}_{iT})}}\right) \tag{8}$$

In Eq. [8], $E(\tilde{z}_{iT}) = k$ and $Var(\tilde{z}_{iT}) = \frac{zk(T-k-1)}{T+1}$

4.3.2. Panel unit root test

In order to reveal the features of variables used in the model, it is one of the crucial stages in the estimation strategy. More importantly, in the case of the existence of the CSD, using the second-generation panel unit root tests is appropriate to detect the properties of the variables. For this purpose, we utilized Pesaran's (2007) cross-sectional augmented IPS (CIPS) unit test. This test can be calculated through cross-sectionally augmented Dickey-Fuller (CADF) as follows (Kızılkaya et al., 2024):

$$\Delta y_{i,t} = \alpha_i + \gamma_i y_{i,t-1} + \delta_i \bar{y}_{t-1} + \sum_{j=0}^{m}\varphi_{ij}\Delta\bar{y}_{t-j} + \sum_{j=1}^{n}\omega_{ij}\Delta y_{i,t-j} + u_{it} \tag{9}$$

where α_i is the constant term, the difference operator represents with Δ, $y_{i,t-j}$ is the time lag, and $\bar{y}_{t-j}$ is the average of the lagged level for cross-sections (Kızılkaya et al., 2024; Dritsaki & Dritsaki, 2024). Hence, the CIPS test can be calculated as follows (Dritsaki & Dritsaki, 2024):

$$CIPS(N,T) = \frac{1}{N}\sum_{i=1}^{N} CADF_i \tag{10}$$

4.3.3. Long-run estimation

The most traditional estimation techniques may ignore the CSD. However, in the globalized world, countries can be affected by each other. Hence, applying the appropriate estimation method is essential in the presence of the CSD. Therefore, we perform the AMG estimator of Eberhardt & Bond (2009), which takes into account the CSD. Also, there are other superiors of the AMG that it is applied to non-stationary variables and consider slope heterogeneity and endogeneity (Bekele et al., 2024).

The AMG estimator has dummy variables, and the first difference OLS equation (Pata et al., 2024; Bekele et al., 2024) is conducted as expressed in the following equation (Bekele et al., 2024):

$$\Delta y_{it} = \alpha_i + \delta_i \Delta X_{it} + \sum_{t=1}^{T}\vartheta_t D_t + \gamma_i f_t + u_{it} \tag{11}$$

In Eq. (11), δ_i is the country-specific slope parameter, D_t is the dummy variables, f_t denotes the unobserved common factor with heterogeneous factor, α_i is the constant term, u_{it} is the error term, and Δ is the first-difference operator (Bekele et al., 2024). The AMG estimator is written as follows based on panel-averaged group-specific parameters (Bekele et al., 2024; Pata et al., 2024):

$$\hat{\delta}_{AMG} = N^{-1} \sum_{i=1}^{N} \hat{\delta}_i \tag{12}$$

5. Empirical results and discussion

In order to observe the general characteristics of the series, descriptive statistics and correlation matrix are in Table 3 and Table 4, respectively.
Table 3 documents the descriptive statistics of the variables. According to the results, lnREN has the highest standard deviation, with 1.145, followed by lnTEC with 1.125, lnCONS with 0.680, and $lnCO_2$ with 0.295. The median values for lnEF, lnGDP, lnKOF, lnTEC, lnCONS, lnREN, and $lnCO_2$ are 1.50, 9.41, 4.38, 7.11, 24.89, 7.27, and 2.02 respectively.
The correlation matrix in Table 4 shows a strong relationship between lnEF and lnGDP and a negative relationship between lnTEC and lnGDP, lnCONS and lnGDP, lnTEC and lnKOF, and lnREN and lnTEC, $lnCO_2$ and lnKOF, and lnREN and lnCONS.

Table 3. Descriptive statistics of the variables, source: authors' compilation.

	lnEF	lnGDP	lnKOF	lnTEC	lnCONS	lnREN	$lnCO_2$
Mean	1.533134	9.410144	4.355257	7.219688	25.12341	6.962778	1.992887
Median	1.508799	9.415143	4.388238	7.112120	24.89230	7.279578	2.024526
Maximum	1.975108	9.913756	4.442651	8.954157	26.56109	8.242626	2.522180
Minimum	1.119699	8.694186	4.110874	5.068904	24.02756	4.148418	1.415247
Std. Dev.	0.171145	0.291644	0.086167	1.125546	0.680525	1.145318	0.295962
Skewness	0.318684	-0.342988	-1.269545	-0.165098	0.675884	-1.014954	0.062501
Kurtosis	2.621704	2.329434	3.696034	1.787462	2.397439	3.018447	2.131296
Jarque-Bera	2.380500	3.987627	30.03627	6.843537	9.491548	17.85709	3.337846
Probability	0.304145	0.136175	0.000000	0.032655	0.008688	0.000133	0.188450
Sum	159.4460	978.6550	452.9467	750.8475	2612.835	724.1289	207.2603
Sum Sq. Dev.	3.016925	8.760762	0.764757	130.4860	47.70074	135.1106	9.022119
Observations	104	104	104	104	104	104	104

Table 4. Correlation matrix, source: authors' compilation.

	lnEF	lnGDP	lnKOF	lnTEC	lnCONS	lnREN	$lnCO_2$
lnEF	1						
lnGDP	0.4128	1					
lnKOF	0.0629	0.7836	1				
lnTEC	0.0771	-0.6257	-0.5455	1			
lnCONS	0.1761	-0.0504	0.0840	0.5384	1		
lnREN	0.2070	0.7274	0.3926	-0.6269	-0.1324	1	
$lnCO_2$	0.8726	0.1372	-0.2549	0.3713	0.2776	0.0795	1

Table 5. CSD and slope homogeneity test results, source: authors' compilation.

CSD Tests							
	lnEF	**lnGDP**	**lnKOF**	**lnTEC**	**lnCONS**	**lnREN**	**$lnCO_2$**
Breusch-Pagan LM	24.94535 [0.000]	148.2941 [0.000]	148.0067 [0.000]	102.2606 [0.000]	138.2482 [0.000]	126.2943 [0.000]	75.31667 [0.000]
Pesaran scaled LM	5.469051 [0.000]	41.07678 [0.000]	40.99381 [0.000]	27.78803 [0.000]	38.17677 [0.000]	34.72598 [0.000]	20.01000 [0.000]
Bias-corrected scaled LM	5.389051 [0.000]	40.99678 [0.000]	40.91381 [0.000]	27.70803 [0.000]	38.09677 [0.000]	34.64598 [0.000]	19.93000 [0.000]
Pesaran CD	4.145060 [0.000]	12.17671 [0.000]	12.16466 [0.000]	9.989289 [0.000]	11.74265 [0.000]	11.20382 [0.000]	8.289929 [0.000]
Slope Homogeneity Tests							
	Statistics			**p-value**			
Delta ($\tilde{\Delta}$)	-0.828			0.408			
Delta ($\tilde{\Delta}$)$_{adj}$	-0.995			0.320			

Note: [] represents probability value.

Table 5 reports the CSD and slope homogeneity test results. It is indicated that the null hypothesis of no CSD is rejected at a 1% significance level in all CSD tests. Hence, it means that any shocks or unexpected situations in any V4 countries may spread to each other. Moreover, Delta ($\tilde{\Delta}$) and Delta ($\tilde{\Delta}$)$_{adj}$ test results showed that the null hypothesis of slope coefficient is homogen cannot be rejected. Therefore, it proves that slope homogeneity exists among cross-sections. Following the determination of the CSD, it is important to apply second-generation panel unit root tests that are robust to the CSD. For this purpose, we perform the CIPS unit root test, and the results are documented in Table 6.

Table 6. CIPS unit root test results, source: authors' compilation.

Variables	Specification	CIPS	
		Level	1st difference
lnEF	Constant	-1.957	-5.673
	Constant&Trend	-2.843	-5.768
lnGDP	Constant	-1.766	-3.452
	Constant&Trend	-2.084	-3.245
lnKOF	Constant	-2.309	-5.565
	Constant&Trend	-3.594	-5.641
lnTEC	Constant	-3.306	-
	Constant&Trend	-3.419	-
lnCONS	Constant	-2.316	-3.438
	Constant&Trend	-1.500	-3.294
lnREN	Constant	-2.421	-3.405
	Constant&Trend	-1.543	-3.322
$lnCO_2$	Constant	-2.335	-4.838
	Constant&Trend	-2.463	-4.826

Note: Critical values for constant: -2.21 (10%), -2.33 (5%), and -2.57 (1%).
Critical values for constant&trend: -2.73 (10%), -2.86 (5%), and -3.1 (1%).

The CIPS unit root test results documented that lnEF, lnGDP, lnKOF, lnCONS, lnREN, and $lnCO_2$ contain a unit root process at the level. However, they become stationary after taking the first difference. In contrast, lnTEC is stationary at the level in both the constant and constant&trend models.

Table 7. AMG estimation results, source: authors' compilation.

Countries	Constant term	lnGDP	lnKOF	lnTEC	lnCONS	lnREN	$lnCO_2$
Poland	-6.155 [0.405]	0.134 [0.738]	0.251 [0.250]	-0.068*** [0.006]	0.198 [0.635]	0.017 [0.441]	0.409*** [0.007]
Czechia	-17.144** [0.030]	0.070 [0.865]	1.474*** [0.000]	-0.062*** [0.003]	0.461 [0.310]	0.073** [0.050]	0.261** [0.043]
Slovakia	-11.800*** [0.009]	1.220*** [0.000]	0.631** [0.012]	-0.036* [0.099]	-0.035 [0.893]	0.022 [0.749]	0.308** [0.024]
Hungary	8.311 [0.175]	3.093*** [0.000]	0.087 [0.851]	0.068** [0.040]	-1.474*** [0.000]	0.090** [0.024]	0.086 [0.699]
Panel	-6.697 [0.222]	1.130 [0.109]	0.611** [0.048]	-0.024 [0.435]	-0.212 [0.623]	0.051*** [0.005]	0.266*** [0.000]

Note: Asteriks *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively. Also, [] represents probability value.

The AMG estimation results for the long-run relationship indicate that globalization, renewable energy consumption, and CO_2 emissions positively affect EF in the whole panel. However, the coefficients of economic growth, technological development, and household consumption are statistically insignificant in the whole panel. Moreover, the country-specific results show that EG positively impacts EF in Slovakia and Hungary, indicating that an increase of 1% in EG fosters EF by 1.220% and 3.093% in Slovakia and Hungary, respectively. The empirical findings on the positive effect of EG on EF is in line with study of Khoi et al. (2021), Alola et al. (2021), Beşe & Friday (2022), Boukhelkhal (2022), Humbatova et al. (2024), Thach & Ngoc (2023), Guan et al. (2022), and Khan & Idrees (2023). The positive association between EG and EF indicates that as EG rises, it enlarges the scale of economic activities and creates pressure on the environment. Hence, EG negatively affects environmental quality. Likewise, globalization positively influences EF in Czechia and Slovakia. For example, a rise of 1% in globalization increases EF by 1.474% and 0.631% in Czechia and Slovakia, respectively. Our empirical findings on globalization are consistent with studies of Amegavi et al. (2022), Gyamfi et al. (2023), Ansari et al. (2020), and Kirikkaleli et al. (2021). The positive effect of globalization on EF indicates that along with globalization, economic activities enlarge and increase demand for non-renewable energy sources. In particular, since renewable energy sources are limited in the V4 countries, inevitable globalization may push to use more on-renewable energy sources that harm environmental quality.

TD has a negative effect on EF in Poland, Czechia, and Slovakia. From this perspective, it is obtained that a rise of 1% in TD reduces EF by 0.068%, 0.062%, and 0.036% in Poland, Czechia, and Slovakia, respectively. This result is in line with the study of Qiu & Wan (2023), Raihan et al. (2024), Mensah et al. (2018), Guan et al. (2022), and Khan et al. (2020). The reducing effect of TD is in line with some arguments-for instance, TD incentivizes productivity, decreasing non-renewable energy consumption. Moreover, TD can mitigate the transition towards renewable energy sources that decrease environmental degradation. In contrast, it positively influences EF in Hungary. A rise of 1% in TD raises EF by 0.068% in Hungary. The possible reason for the negative effect could be increased technological development, which may increase energy efficiency and reduce dependency on non-renewable energy sources that cause environmental degradation. Moreover, the positive influence of TD on EF in Hungary is consistent with the findings of Cheng et al. (2019), Gu & Wang (2018), Adebayo & Kirikkaleli (2021), and Aydın et al. (2023). As mentioned above, an increase solely in technological innovation does not directly increase energy efficiency and promote environmental quality. Technological development's positive impact on environmental quality relies on the coordination capability between technological investment and technological capabilities. As countries move away from aligning technological investment with society, achieving the goals of promoting environmental quality becomes challenging.

Household consumption is statistically significant only in Hungary, and it shows that a 1% rise in household consumption decreases EF by 1.474%. The negative effect of household consumption's environment is consistent with the study by Guo (2017) for the sample of China and Sohag et al. (2015) for Malaysia, the inverted U-shaped between household consumption and CO_2 emissions. Household consumption patterns and behaviours can cause this result to evolve into environment-friendly commodities, and households replace non-renewable energy sources with renewable energy. For example, people prefer to use solar energy and natural gas.

Besides, renewable energy consumption positively affects the EF in Czechia and Hungary. For instance, an increase of 1% in renewable energy consumption incentives EF by 0.073% and 0.090% in Czechia and Hungary, respectively. Finally, CO_2 emissions increase EF in Poland**,** Czechia, and Slovakia. This means that an increase of 1% in CO_2 emissions increases EF by 0.409%, 0.261%, and 0.308% in Poland, Czechia, and Slovakia, respectively. The effect of CO_2 emissions on EF is consistent with the study of Li et al. (2022) and Rahmane et al. (2021). This result indicates that during economic activities, non-renewable energy sources that damage the environment feed the rise of CO_2 emissions. Hence, along with economic expansion, non-renewable energy sources raise CO_2 emissions and EF (Rahmane et al., 2021).

In the case of the V4 countries, it is possible to discuss the development of the SDGs. Firstly, among the investigated variables, it is clear that CO_2 emissions and renewable energy harm the environmental quality in the V4 countries. CO_2 emissions have arisen along with economic development and industrialization. Because the V4 countries still depend on non-renewable energy sources, including oil, coal, and natural gas (Rabbi & Abdullah, 2024). The share of energy consumption data (Our World in Data, 2024) indicates that the share of energy consumption from coal decreased from 89.14% to 36.58% from 1965 to 2023 in Poland. However, in the same period, Poland's share of oil and gas increased from 8.30% and 2.21% to 34.14% and 17.13%, respectively. Moreover, a small quantity of development occurred in renewable energy sources in Poland during the same period. For example, the share of hydropower, solar, wind power, and other renewables have risen from 0.34%, 0.00%, 0.00%, and 0.01% to 0.54%, 2.65%, 5.48%, and 2.30%, respectively. A similar trend has emerged in Czechia, Slovakia, and Hungary. For example, the share of energy consumption from coal declined from 87.64%, 65.74%, and 68.59% to 30.89%, 14.29%, and 3.99% from 1965 to 2023 in Czechia, Slovakia, and Hungary, respectively. In contrast, the share of oil increased from 10.04%, 25.32%, and 23.93% to 27.40%, 26.97%, and 36.98%, and the share of gas jumped from 0.92%, 2.79%, and 7.35% to 15.82%, 22.49%, and 32.36% from 1965-2023 in Czechia, Slovakia, and Hungary, respectively. Besides, only slight improvements have appeared in hydropower, solar, and wind in the V4 countries. The share of hydropower has increased from 1.41%, 6.15%, and 0.12% to 1.44%, 6.60%, and 0.23%, the share of solar has risen from 0.00%, 0.00%, and 0.00% to 1.34%, 0.84%, and 6.71%, and the share of wind has increased from 0.00%, 0.00%, and 0.00% to 0.43%, 0.01%, and 0.66% during the same period in Czechia, Slovakia, and Hungary, respectively. In addition, the share of energy consumption from nuclear has increased from 0.00%, 0.00%, and 0.00% to 17.90%, 24.49%, and 15.69% during 1965-2023 in Czechia, Slovakia, and Hungary, respectively. In Poland, its share is still 0.00%. Therefore, among renewable energy sources, only nuclear energy has increased significantly, but its contribution to society and the economy in terms of transition to renewable energy is arguable in the V4 countries.

Furthermore, another remarkable inference on the nexus between TD and EF in terms of the SDGs is that TD improves the environmental quality by reducing EF in the V4 countries except Hungary. This point should be analyzed from the two sides. On the first side, TD enhances environmental quality, whereas renewable energy consumption worsens it. This indicates that the coordination capacity between technological innovation and the energy sector could be stronger in the V4 countries. On the second side, despite the improvement of technological innovation in the V4 countries, it may not accelerate the transition to renewable energy in these countries. It shows us that the link between TD and the energy sector should be empowered, and integration between the two fields is required.

Finally, household consumption has an insignificant effect on EF except in Hungary. Overall, this signals that people may not consider the environmental effect of consumption. In other words, households may ignore whether consumption affects the environment. Hence, it is crucial to focus on raising people's awareness of consumption patterns that affect the environment and climate change. Moreover, the V4 countries have experienced remarkable progress in terms of integration into the world in the last three decades. However, the polluting effect of globalization still remains a challenging issue for these countries. While multinational companies' investments in the host economy may contribute to economic growth, policymakers should consider the negative externalities of all aspects of globalization.

6. Conclusions and policy implications

This paper analyzes the impact of globalization, technological development, and household consumption on EF in the V4 countries, Czechia, Hungary, Poland, and Slovakia, from 1996 to 2021, by employing the AMG estimator. The empirical findings reveal that globalization, renewable energy consumption, and CO_2 emissions significantly positively affect EF. However, EG is insignificantly positive, and TD and household consumption have insignificantly negative impacts on EF in the whole panel. In addition, the country results provide mixed results. For example, EG has a significantly positive effect on EF in Slovakia and Hungary and an insignificantly positive effect on EF in Poland and Czechia. Globalization significantly positively influences EF in Czechia and Slovakia and insignificantly positively affects EF in Poland and Hungary. TD has significantly negative effects on EF in Poland, Czechia, and Slovakia, as well as positive effects in Hungary. Household consumption has a negative significant effect on EF in Hungary, an insignificant negative effect in Slovakia, and a positive insignificant effect in Poland and Czechia. Moreover, renewable energy consumption positively affects EF in Czechia and Hungary and has insignificantly positive effects in Poland and Slovakia. Finally, CO_2 emission has a significantly positive influence on EF in Poland, Czechia, and Slovakia and an insignificantly positive influence in Hungary.

The V4 countries have experienced a realizing EG in the last three decades. Following the collapse of the Soviet Union, the integration into the world economy accelerated in these countries, and they suffered to become a part of a globalized world. However, along with globalization, it is essential to consider sustainable development. Hence, in line with empirical findings, we offer some policy implications for policy-makers as follows:

- Although EG is important for all countries, policymakers should consider its environmental effect and promote green economic growth.
- Some policies should incentivize the flow of technology and green technology transfers. For instance, firms related to green technology can be supported through tax exemption. More importantly, coordination between foreign and domestic firms in adopting technology-based production systems is important.
- Although TD can be raised, its environmental contribution requires coordination capacity. Although technological improvement has emerged in the V4 countries, the connection between technology and energy markets should be strengthened to facilitate sustainable development.
- Household consumption should be directed to energy-saving patterns.
- Finally, policymakers should incentivize the usage of renewable energy sources and environmentally friendly technologies.

Limitations of the study and projection for future studies

Although the current paper deepens the relationship between EF, globalization, technological development, and household consumption, it has some limitations. Firstly, the period was restricted as of 2021 due to the globalization index, the number of patents as a proxy for TD, and CO_2 emissions. Hence, it can re-examine when the data is updated. Secondly, we use EF as an indicator of environmental degradation. In recent literature, the load capacity factor (LCF) is preferred as a new measurement of environmental degradation. Hence, future studies can consider the LCF in the analysis.

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