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Exploring the nexus between shadow economy, institutional quality, green energy transition, and ecological footprint in G-7 economies: implications for sustainable development

Maria Shabir[1] · Asif Javed[2] · Muhammad Aqib Khursheed[3] · Shabbir Ahmad[4] · Saif Ullah[5]

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Abstract
The Shadow economy (SE) poses significant ecological challenges by operating informally, often bypassing environmental standards. Conversely, institutional quality (IQ) enforces compliance with environmental regulations. Similarly, adopting renewable energy sources (RES) provides sustainable alternatives to fossil fuels. Therefore, the study aims to investigate how SE creates unsustainable development by increasing ecological footprint (EFP) and how better IQ and adoption in RES reduce EFP towards sustainability. The Method of Moments Quantile Regression (MMQR) is applied to data for the G-7 countries, covering the period from 1996 to 2020. Findings reveal that SE plays a dominant role in increasing EFP, while improvements in IQ and enhancement of RES lead to a notable reduction in EFP. The study recommends policies to curb informal economic activities and enhance institutional quality alongside more significant investments in green energy to foster sustainable development. The study contributes to the existing literature by offering an extensive analysis that emphasizes the importance of IQ and RES in reducing EFP, utilizing a novel methodological approach and the latest comprehensive data.

Keywords Shadow economy · Institutional quality · Renewable energy · Ecological footprint · MMQR

Extended author information available on the last page of the article

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List of Abbreviations

SE IQ RES	Shadow Economy Institutional Quality Renewable Energy Sources
GLO FDI EFP	Globalization Financial Development Index Ecological Footprints
GDP SDG IEA	Gross Domestic Product Sustainable Development Goal International
GFN GHA WDI	Energy Agency Global Footprint Network Global Hectares World
MIMIC ICRG	Development Indicators Multiple Indicators, Multiple Causes model
EKC MMQR	International Country Risk Guide Environmental Kuznets Curve
CIPS CSD	Method of Moments Quantile Regression Cross-Sectional Im-Pesa-
CADF 2SLS	ran-Shin cross-sectional dependency Augmented Dickey-Fuller Two-
D-OLS FE-OLS	Stage Least Squares Dynamic Ordinary Least Squares Fixed Effects
FM-OLS SCH	Fully Modified Ordinary Least Squares Slope heterogeneity common
CST CSD VIF	stochastic trends Cross-sectional dependency Variance inflation factor
OECD	Organization for Economic Co-operation and Development

1 Introduction

Over the last century, there has been a significant increase in research activities related to environmental degradation (Ahmad et al. 2024a, b). We are currently living in an era of advancement, where higher industrial growth enhances the working efficiency of other sectors and increases economic productivity. However, at the same time, it also harms environmental health (Lau et al. 2023). According to an International Energy Agency report (IEA), most of the world's economies rely on non-renewable energy resources, such as oil, coal, and gas, for energy production (IEA 2022; Yuan et al. 2022). The combustion of these energy sources increases the concentration of greenhouse gas emissions in the environment, leading to various economic, social, and ecological challenges, including floods, storms, droughts, and biodiversity loss. However, in existing literature, researchers have used several environmental indicators, like SO_2, CO_2 and EFP to gauge the ecological well-being of the societies (Smith et al. 2021).

To protect the ecological health of societies, the international community has called for coordinated action, as reflected in the United Nations Sustainable Development Goals. Among these, SDG 7 promotes the use of clean energy sources, while SDG 13 focuses on climate action (Azam & Haseeb 2021; Chen et al. 2022a; Khezri et al. 2022, Javed et al. 2023a). Environmental variations are a byproduct of greenhouse gas emissions, which hurt the Earth's climate. Figure 1 illustrates the EFP level in G-7 economies from 2000 to 2020. Among the G7 economies, the United States and Canada have a high EFP, primarily due to high electricity consumption, a heavy reliance on fossil fuels, and extensive industrial operations. In comparison, Italy, Germany, France, and the UK show steady yet modest declines, driven by efforts to improve energy efficiency and implement climate policies. Over time, EFP Variations may be associated with economic cycles, shifts in energy sources, and environmental strategies. Governmental policies, green energy supplies, ecological taxes, moderate lifestyle choices, and technological advancements are essential factors for reducing EFP. It is widely acknowledged that environmentally friendly energy sources are essential for facilitating sustainable development.

The policymakers, government officials, and local stakeholders must identify the drivers of environmental sustainability. One possible driver of EFP is the shadow economy

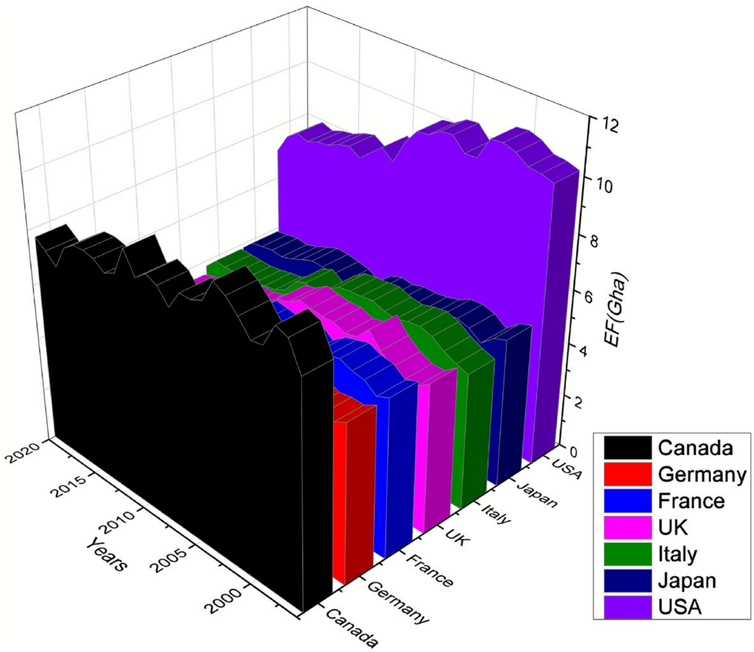

Fig. 1 Ecological footprint trend in G-7 economies. *Source*: Author's elaboration on Global Footprint Network data (GFN, 2023)

(SE). SE commonly arises when the business community deliberately avoids paying taxes. This action adversely affects the collection of government revenue, which directly reduces economic progress and indirectly increases the cost of production (Chen et al. 2018; Hardi et al. 2023). As the informal economy is not controlled and managed by professionals, and due to a lack of regulations, producers produce harmful products and emit carbon emissions (Eregha et al. 2023). The underground economy accounts for approximately 23% of global production losses. It poses a significant barrier to sustainable development. Political instability and corruption are the primary determinants of SE (Shahzad et al. 2021). Due to the lack of proper regulation and supervision, informal enterprises may employ outdated technologies or fail to comply with energy efficiency standards. Figure 2 displays Multiple Indicators and Multiple Causes (MIMIC) model estimates of the SE as a percentage of official GDP for G7 countries from 1995 to 2020. The x-axis indicates the years, and the y-axis displays the SE as a percentage of GDP.

Over this period, there is a sharp decline in the percentage of the SE from 1996 to 2010 in six economies, rather than in the USA. After 2010, the SE trend experienced a dramatic increase in all regions. However, the most dramatic rise was seen in the USA, at approximately 9.4%, Japan, at 11.3%, and Germany, at 16.4%, respectively. This rise was not accidental but explicitly related to two major global events: first, the *global financial crisis* of 2007–2009, and second, the Eurozone debt crisis between 2009 and 2012. The global financial crisis originated in the United States and quickly propagated through international banking and investment systems and adversely affected Europe and Asia. This crisis led to considerable reductions in economic activity, increased unemployment, enhanced inflation,

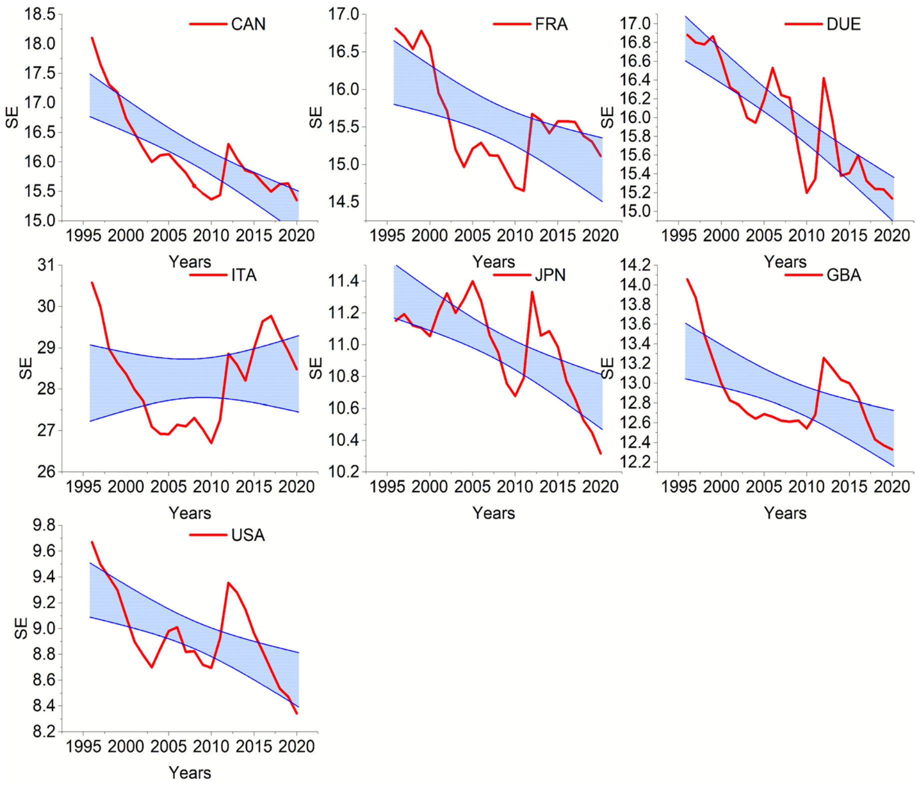

Fig. 2 Shadow economy trend in G-7 economies. *Source:* Author's elaboration on World Bank data (WDI, 2020)

and additionally, it decreased economic agent trust in formal institutions. As a consequence, a larger portion of the population and firms engaged in informal activities to generate income for survival. While the Eurozone crisis began in Europe, its repercussions were felt globally. The USA and Japan faced particular risk because of their extensive economic ties with Europe, including banking partnerships and export dependency (Waris et al. 2023). Existing literature on financial development highlights that instability in financial markets influences economic progress in various ways. Firstly, it slows down credit accessibility (Ullah et al. 2024a, b), which decreases income and the saving rate (Fengju et al. 2024), adversely affecting investor confidence, while high interest and tariff rates reduce global trade volume (Mawardi et al. 2024). As people lost steady jobs and firms faced demand drops, informal and cash-based work became a means of survival. In real world countries are not isolated within their borders; rather, they are interconnected via commerce, capital and human flows. As a consequence, prominent economic and financial shocks typically extend beyond their source area and adversely affect the global economies through spillover effects (events happened in one place but indirectly influence the other areas because of globalization and trade liberalization).

Moreover, institutional quality plays an integral role in shaping the country's environmental conditions. Through three dimensions such as accountability, transparency, and participation, institutional quality influences the countries' environmental regulations and reduces the ecological footprint. First, through accountability mechanisms, economic agents such as households, firms and authorities are responsible for their deeds. for example, carbon auditing assists in implementing climate policies (Qayyum et al. 2024). Secondly, through the important element of law, "transparency," IQ guarantees that environmental and resource utilization rules are the same for all economic agents. It discourages corruption and allows individuals to participate in eco-friendly activities like recycling, renewable energy adoption, and sustainable consumption. *Third,* by engaging citizens in decision-making processes, IQ promotes political stability which further protects the environmental quality (Waris et al. 2023; Adebayo et al. 2023). In their work for developing economies Yang et al. (2023) suggested that strict enforcement of environmental laws such as penalties, financial sanctions, and voluntary efforts help to address environmental damage. Li et al. 2023 concluded that IQ also influences property rights and strong property rights reduce the likelihood of resource overuse. Several recent investigations have examined the association between IQ and EFP, Jahanger et al. (2022), claimed that a strong IQ improves ecological well-being. Ozturk et al. (2023), Li et al. (2023) argued that effective government policies, a stable political situation, and control of corruption encourage the stakeholders to participate and invest in the renewable energy market. Moreover, a strong institutional framework fosters an atmosphere of transparency, trust, and equity, thereby discouraging individual participation in the SE (Karimi Alavijeh et al. 2023).

Figure 3 illustrates the IQ index of sample (G7) countries between two periods 1996–2010, and 2011–2020. Higher values (shown in dark blue) signify a more substantial degree of IQ, where scores in yellow/red denote weaker institutional frameworks. During the time-

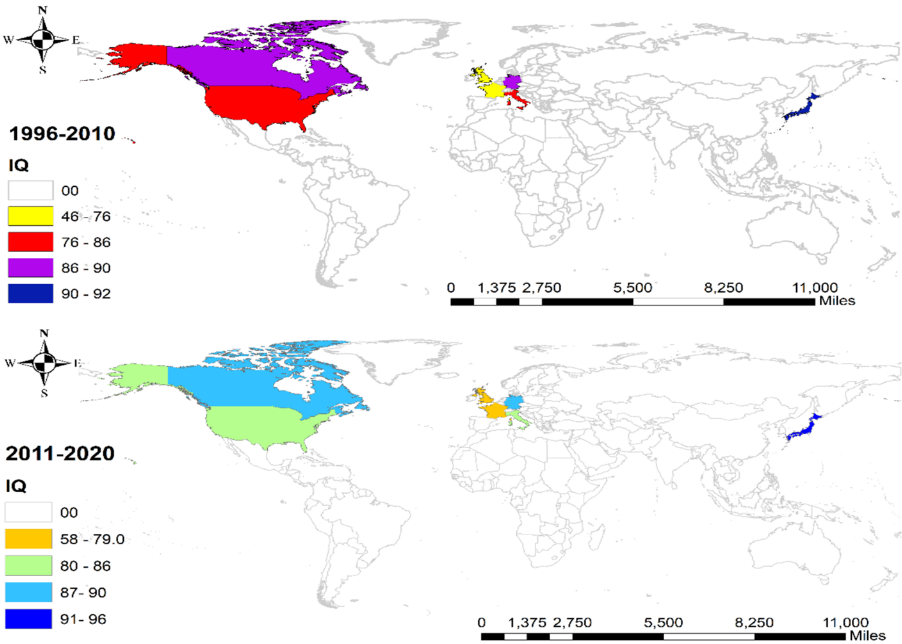

Fig. 3 Trend of institutional quality in G7 economies. *Source*: Author's elaboration on ICRG data (ICRG,2023)

frame of 1996–2010, Canada and Japan scored the highest IQ (90–92). This shows that they have an efficient governance system, which ensures effective decision making, and law enforcement. As a result, they are enjoying political stability. In contrast, the United States achieved somewhat lower scores (76–86), primarily because of political instability, lobbying influence, and difficulties in enforcing regulations**.** Prominent European nations showed notable differences: Germany and France fell into the 86–90 range, while Italy scored lower, from 46 to 76, pointing to longstanding issues of corruption, administrative inefficiency, and political unrest. Over the second decade (2011–2020), important transitions occurred. Canada''s score experienced a slight decline to 87–90. It might be because of the Keystone XL pipeline controversy (Terry 2012; Zhang et al. 2020). The United States experienced incremental improvement, indicative of financial reforms enacted after the 2007–2009 financial crisis (Jahanger et al. 2022). Germany and the UK maintained high scores (87–90), reflecting strong governance frameworks within the EU before Brexit (Shabani et al. 2024). Italy, on the other hand, continued to exhibit weaker institutional performance (58–79), influenced by persistent governance challenges and economic vulnerability. Overall, the G7 exhibits significant variation in institutional quality.

Since the Industrial Revolution, increasing energy demand has contributed to numerous environmental problems, highlighting the need for greater emphasis on clean renewable energy solutions. Recent concerns regarding population growth, oil price fluctuations, global warming, and climate change encourage the policymakers to find an alternative way of energy production and overcome energy shortage challenges (Coggin 2023). In the regard, Wenlong et al. (2023) and Özkan et al. (2023) suggested that the integration of renewable energy sources (RES) such as solar, wind, and hydropower in the electricity production offers significant economic and environmental advantages. As RES are superior to conventional sources because of their self-replenishment nature, they play an important role in achieving sustainable development. Renewable energy helps achieve SDG 7 by providing clean, affordable energy and supports SDG 13 by decreasing greenhouse gas emissions, contributing to environmental protection and sustainable, resilient development.

The energy economics literature highlights the economic significance of RES and argues that shifting to local renewable energy sources decreases reliance on imported fossil fuels, enhances energy security, reduces the trade deficit, and promotes long-term stability in electricity prices (Shabani et al. 2025, Raifu et al. 2025, Bhuiyan et al. 2022). Historically, economic growth correlates with higher energy use and increased GHG emissions, but renewable energy can help break this connection and support sustainable development (SD) (Shabani et al. 2024). From an ecological viewpoint, switching from fossil fuels to low-carbon energy significantly cuts greenhouse gas emissions and supports international efforts to combat climate change. Environmental scientists advise that the world's temperature should be limited to 1.5 °C above pre-industrial levels by 2040 to prevent ecological instability and societal distress (Wenlong et al. 2023; Özkan et al. 2023). Chen and Lee (2020), Khan et al. (2022), and Obobisa et al. (2022) stated that renewable energy provides an opportunity to support social and economic progress, improve energy access, ensure a secure energy supply, combat climate change, and reduce adverse environmental and health effects. Investing in renewable energy may lower vulnerability to supply disruptions and market swings through heightened competition and diversified energy options (Puntoon et al. 2022).

Based on the Environmental Kuznets Curve (EKC) framework, the initial stages of economic development are typically associated with higher utilization of fossil fuels, which directly increases environmental degradation and indirectly affects human and planetary health. Previous studies for China (Xia et al. 2025), Australia (Rai et al. 2025), the US (Işıkt al., 2024), European economies (Aslan et al. 2024), and Asian countries (Rather et al. 2024) revealed that reliance on non-renewable energy sources significantly enhances the GHG emissions and deteriorates ecological wellbeing (Shahbaz et al. 2020; Lau et al. 2023). On the other hand, renewable energy sources (RES) such as hydropower and nuclear power are commonly acknowledged as low-emission options. Unlike fossil fuels, they produce considerably fewer CO_2 emissions per unit of energy generated. Furthermore, RES promotes the decentralization of energy sources, which indirectly reduces energy poverty and directly enhances environmental quality (Zhong et al. 2021). Approximately 30% of the world population lives in G-7 economies, contributing 50% to the global GDP. G-7 economies comprise major industrialized nations with high living standards, robust infrastructure, and technological innovations. The G-7 countries have committed to increasing the proportion of renewable energy in their overall energy mix to 60% by 2030. Figure 4 illustrates the trends of utilization of renewable energy sources among the G-7 countries from 1996 to 2020. Overall, trends differ markedly between nations, influenced by distinct energy policies, technological progress, and resource availability. Italy and Germany demonstrate notable upward trajectories after 2005, likely due to strategic renewable energy initiatives. Germany demonstrated steady progress beginning in the early 2000s, largely due to the Energiewende, which prioritized solar and wind energy. Italy saw a significant rise after 2005, thanks to generous solar PV subsidies and EU renewable commitments. Due to its rich hydro resources, Canada maintains a high share over time. But 1999's renewable share declined due to two main reasons: first one,the rapid growth of Alberta's oil sands,

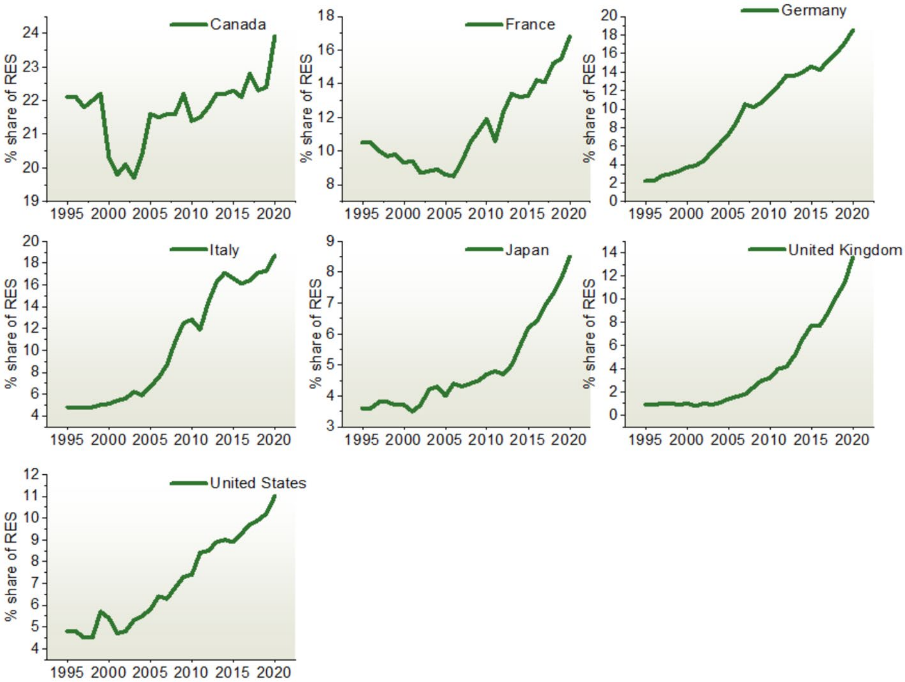

Fig. 4 Trends of RES in G-7 nations. *Source:* Author's elaboration on OECD data (OECD, 2023)

which boosted fossil fuel availability and lowered the renewables percentage (Giesy et al. 2010; Lazzaroni et al. 2016; Janzen et al. 2020).The second factor was related to lower water inflows, as low rainfall and snowpack in provinces like Quebec and British Columbia led to a decline in hydropower output (Burn et al. 2010; Cohen et al. 2015). Japan maintains a relatively small renewable energy share of around 4–5% until 2010, due to its heavy dependence on nuclear power and imported fossil fuels (Chen et al. 2014). After the Fukushima nuclear crisis in 2011 the trend of RES slightly declined. This temporary decrease can be attributed to disruptions in Japan's energy infrastructure, where the abrupt shutdown of nuclear plants resulted in increased reliance on fossil fuels. The shutdown of nearly all nuclear power plants forced Japanese government to reexamine its energy policies. However, in 2013, a feed-in tariff (FIT) scheme was introduced that ensured premium prices for renewable energy, particularly solar PV (Dong et al. 2017, Kimura et al. 2025). As a result, the RES trend rose, indicating the recovery and greater adoption of renewable energy sources in Japan. The UK exhibits accelerated growth starting in 2005, driven by offshore wind expansion and coal displacement. The US indicates a slow but steady rise, supported by state renewable energy mandates and federal tax credits.

This study observed that previous studies have largely examined the influence of formal economic activities on environmental sustainability (Hassan et al. 2024; Wang et al. 2024). In scientific literature, numerous parameters have been employed by researchers as environmental indicators such as CO_2, Methane (CH_4) and Nitrous oxide (N_2O) emissions (Razzaq et al. 2023; Degbedji et al. 2024). In which CO_2 emissions have been widely adopted compared to other variables. However, researchers have criticized CO_2 emissions and argued that it just carputer the emissions to the air and ignores the other sources of emissions. In this context, the EFP has been introduced as a degradation variable. It provides a more holistic assessment than CO_2 emissions as it captures the emissions from Cropland, Grazing land, Forest, build up land and Fishing grounds (Wenlong et al. 2023; Bekun et al. 2024; Makarov et al. 2024). Another gap we found is that earlier studies largely ignored the governance aspect of environmental degradation. IQ plays an important role in shaping countries' ecological conditions. Through the application of environmental regulations such as penalties, fines, and voluntary efforts it can overcome the primary sources of degradation. Numerous recent studies have examined the correlation between IQ and GHG emissions and observed the contradictory results. For instance, few studies (Xu et al. 2022; Mehmood et al. 2023) claimed that IQ-through strict regulations (He et al. 2022) and control of corruption (Hussain et al. 2023) declines the emissions and improves the environmental suitability. For OECD economies Jianguo et al. (2022) discovered that higher IQ levels lead to decreased CO_2 emissions. For emerging economies, Ahmed et al. (2022) applied the Cross-sectional autoregressive distributed lag model (CS-ARDL), and Augmented Mean Group (AMG), techniques and found that IQ negatively impacts EFP. In contrast, in their study of 47 emerging and developing countries, Le and Ozturk (2020) examined how institutional quality influences the environment and found that poor IQ correlates with higher levels CO_2 missions. Based on the above-mentioned contradictory results, we were interested to examine the influence of IQ on environmental degradation in G7 economies. G7 is an alliance of major industrialized countries across Asia, Europe, and North America.

In light of the foregoing discussion, no existing study has empirically investigated the combined impact of the shadow economy (SE), institutional quality (IQ), and renewable energy sources (RES) on the ecological footprint (EFP), while also accounting for globalization (GLO) and the financial development index (FDI) particularly within the context of G-7 countries. Understanding how these factors jointly influence the ecological footprint is therefore of critical importance. To address this research gap, the present study offers several key contributions to the existing body of literature. ***Firstly,*** the study examines the impact of informal economic activities commonly referred to as the shadow economy (SE) on environmental degradation, a dimension often overlooked in prior research. ***Secondly,*** it employs the Ecological Footprint (EFP) as a comprehensive indicator of environmental sustainability. Unlike traditional measures that capture a single aspect of environmental degradation, the EFP provides a multidimensional perspective on ecological pressures and resource use. *Thirdly*, while prior studies have largely focused on the effects of formal economic activities (e.g., GDP) on environmental degradation and the validation of the Environmental Kuznets Curve (EKC) hypothesis (see Sun et al. 2025; Dada et al. 2023; Zhao & Bashir, 2024), limited attention has been paid to the joint influence of SE, IQ, and RES on environmental outcomes. The absence of such integrative analysis has constrained both theoretical development and policy formulation. To bridge this gap, the current study introduces a unified theoretical framework that synthesizes the Environmental Kuznets Curve (EKC), Institutional Theory, the Porter Hypothesis, and the Laffer Curve Theory to explain how SE, IQ, and RES collectively shape environmental performance. By focusing on these key policy variables, the study deepens our understanding of how each factor independently and interactively influences environmental sustainability in G-7 economies. ***Fourthly,*** this study distinguishes itself methodologically by employing second-generation panel econometric techniques specifically designed to address major challenges in panel data analysis, such as cross-sectional dependence, slope heterogeneity, and non-stationarity. The empirical strategy incorporates advanced tests, including the CIPS and CADF unit root tests and the Westerlund cointegration test, alongside robust estimators such as FMOLS, DOLS, FE-OLS, and the Method of Moments Quantile Regression (MMQR). The MMQR technique, in particular, allows for heterogeneity and nonlinearity across different quantiles, making it possible to derive more nuanced policy implications tailored to varying levels of ecological footprint pressure among G-7 nations. Finally, while prior econometric analyses have often been limited to examining long-run associations, this study extends the inquiry by exploring causal linkages among variables using the Dumitrescu and Hurlin (2012) panel Granger causality approach. This additional step provides insights into the directionality of relationships, offering a more comprehensive understanding of the dynamic interactions between SE, IQ, RES, and environmental sustainability.

The remainder of this study is organized as follows. Section 2 illustrates the theoretical and empirical literature on SE. Variables, data, and methodological description are covered in Sect. 3. Section 4 demonstrates the findings and discussion. The conclusion and policy implications are stated in Sect. 5.

2 Literature review

2.1 Nexus between shadow economy and ecological footprint

Recently, SE and EFP have gained significant attention in academia and policymaking. Several studies have employed different methodologies, selected various regions, and discovered a heterogeneous relationship between SE and EFP. For instance, Hardi et al. (2024) examine the relationship between the SE and EFP in Indonesia from 1995 to 2020, revealing that unregulated economic activities substantially intensify environmental degradation, mainly through heightened energy demand and inadequate policy regulation. Likewise, Olanrewaju et al. (2025) highlight that the SE, driven by unregulated energy consumption, harms environmental sustainability in high-income EU countries. Their study emphasizes addressing informal economic activities to achieve climate goals. Similarly, using the time series data of Turkey from 1961 to 2014, Köksal et al. (2020) stated that the SE of Turkey is one of the major factors responsible for poor environmental conditions. The outcomes of the ARDL model indicate that SE activities increase the EFP and exacerbate climate change issues. In alignment with this, Lobont et al. (2025) explore the relationship between the SE and ecological sustainability, revealing that informal economic activities can significantly hinder efforts toward climate goals and sustainable ecological practices. Building on this evidence, Ortiz et al. (2022) examined the environmental consequences of the SE capital across 101 countries from 1995 to 2018. Using a spatial panel data model, they found that the SE significantly contributes to environmental degradation by facilitating unregulated economic activities and weakening ecological oversight. Consistently, Huynh (2020) investigates the link between the SE and air pollution in developing Asian countries over the period 2002–2015. Employing the GMM method, the study finds that the SE has a significant contribution to environmental degradation. On the other hand, SE also has indirect effects on environmental sustainability such as, Butt et al. (2024) examine the interplay between the SE, IQ, and environmental degradation, highlighting that stronger institutions can mitigate the adverse environmental impacts of informal economic activities in ASEAN-9 countries, thereby contributing to environmental sustainability. In contrast, Dada et al. (2023) used the MMQR on panel data from 29 African countries for the period 2000–2017. They found a negative relationship between the SE and EFP that varies across quantiles, possibly due to lower industrial emissions and resource use. Their results suggest that the SE exerts a neutral and mitigating effect on environmental degradation, challenging the uniformly negative narrative presented by earlier studies.

Moreover, in prior literature, some studies have used the term "informal economy" to refer to SE, as Chu (2022) examines the influence of the informal economy on EFP in 27 OECD countries from 1995 to 2015. Employing the Panel Quantile Regression, the results indicate that expansion of the informal economy in OECD countries contributes to a higher EFP, as unregulated activities frequently violate environmental regulations and increase environmental degradation. Similarly, Li et al. (2024) explored the complex interplay between the SE, natural resource income, and economic globalization and find that the expansion of informal economic activities can significantly increase carbon emissions and pose challenges to achieving environmental sustainability. Likewise, Chen et al. (2018) examine the effect of the informal economy on environmental quality in China and conclude that the informal economy increases illegal activities, such as illegal mining and natural resource extraction, which in turn lead to increased resource utilization and environmental contamination, ultimately resulting in extreme weather conditions. Echoing this finding, Khurshid et al. (2024) investigate the dynamic relationship between the SE, corruption, and environmental sustainability in South Asian economies, highlighting that increased reliance on REN can mitigate the adverse environmental impacts associated with informal economic activities. Finally, Dada et al. (2022) provide comprehensive evidence on the nexus between the informal economy and EFP across African countries using panel data from 1990 to 2018. Their findings reveal that the informal economy exacerbates environmental degradation by circumventing environmental regulations and contributing to unsustainable resource use. This study reinforces the argument that unregulated economic activities pose a significant threat to environmental sustainability. Building upon the prior literature, the study formulated the following hypothesis.

H1 *The SE is significantly positively related to EFP in G7 countries.*

2.2 Nexus between institutional quality and ecological footprint

IQ has emerged as a crucial determinant of environmental sustainability, particularly in shaping EFP. Given this, numerous empirical studies have examined the linkage between IQ and EFP, yielding varied outcomes based on country context, governance structures, and development level. For instance, Sun et al. (2025) analyze the impact of IQ on EFP in G20 countries from 2000 to 2021. Using the MMQR, it was found that institutional strength improves the efficiency of greenery and financial innovations in increasing both sustainability and economic success. Similarly, Azimi & Rahman (2023) found that IQ is critical in mitigating the adverse effects of external shocks on the EFP in G-20 countries. Their findings suggest that stronger institutional frameworks can help stabilize environmental outcomes, even during periods of external economic or ecological stress. Furthermore, IQ also improves energy efficiency and decreases EFP. Addai et al. (2024) investigate the interaction between renewable energy, IQ, and EFP in 11 countries for the period 1990–2022, concluding that a strong IQ significantly improves the efficacy of renewable energy in mitigating environmental degradation. Consistently, Azam et al. (2021), using the system generalized method of moments approach for a panel of 66 developing economies, found that weak IQ significantly undermines the regulatory oversight of energy production and consumption. Their findings suggest that poor governance facilitates the overuse of fossil fuel-based energy sources, leading to increased greenhouse gas emissions and a substantial decline in environmental quality. In the context of developing economies, Sabir et al. (2020) examined the role of political institutions in moderating the relationship between foreign direct investment and environmental degradation in South Asian countries. Utilizing panel data from 1984 to 2017, their findings reveal that stronger political institutions can significantly mitigate the negative environmental impacts of FDI. This suggests that IQ plays a pivotal role in shaping environmentally sustainable investment outcomes, especially in regions where regulatory frameworks are often weak or inconsistently enforced. Likewise, Mohamed et al. (2025) analyze the impact of IQ and EFP for Somalia from 1990 to 2020. Using the ARDL method, they found that stronger IQ contributes to long-term reductions in Somalia's ecological footprint, underscoring its essential role in promoting environmental sustainability.

An alternative perspective argues that a strong IQ is crucial for advancing REN and achieving sustainable development goals. A well-functioning institution is crucial for implementing the right tactics and systems to combat CO_2 emissions driven by human activities and climate change. Building on this strand of research, Jianguo et al. (2022) analyzed the relationship between IQ, economic growth, and CO_2 emissions in OECD economies from 1990 to 2016. Their results reveal a significant and widespread influence of IQ on reducing CO_2 emissions and promoting environmental sustainability. Furthermore, they suggested that when institutions adhere to the principles of accountability, equity, and environmental protection protocols, as well as the imposition of environmental taxes, they reduce the EFP and enhance the environmental strength of the economies. Moreover, Abid (2016) investigated the influence of economic, financial, and institutional determinants on environmental degradation in sub-Saharan African countries from 1996 to 2010, using the GMM method. The study found that weak IQ exacerbates environmental degradation by limiting the enforcement of environmental regulations and undermining the effectiveness of sustainable development policies. This evidence highlights the crucial role that institutional strength plays in mitigating emissions and promoting environmental sustainability in developing regions. Similarly, Godil et al. (2020) employed the Quantile Autoregressive Distributed Lag model to examine the dynamic nonlinear effects of IQ on environmental degradation in Pakistan. Their findings reveal that the impact of IQ on environmental degradation varies across different emission levels. Notably, strong institutional frameworks help mitigate environmental degradation more effectively at higher quantiles, highlighting the asymmetric and threshold-dependent nature of governance in influencing environmental quality. Finally, Gyamfi et al. (2024) evaluate the various impacts of IQ and globalization on environmental pollution in open and closed economies in GCC countries from 1990 to 2010. By employing the CS-ARDL method, they demonstrated that strong institutions are crucial for mitigating ecological degradation, particularly in countries with higher levels of global integration.

IQ plays a vital mediating role in achieving environmental sustainability, as Almulhim et al. (2025) examined the combined influence of IQ and REN on CO_2 for BRICS countries from 1996 to 2020. Using the MMQR, the study highlights that strong IQ plays a pivotal role in reducing CO_2 emissions, suggesting that effective governance and institutional frameworks are essential for achieving long-term environmental sustainability, particularly when combined with renewable energy adoption. Similarly, Zheng et al. (2024) analyze the mechanisms influencing IQ and education on CO_2 for E7 countries during the period 1995–2020. Their MMQR results indicate that enhanced IQ, alongside higher education, significantly contributes to achieving carbon neutrality in emerging economies, reinforcing its importance for environmental sustainability. Complementing this, Butt et al. (2024) highlights that effective governance and robust institutional mechanisms are instrumental in mitigating the environmental damage caused by the shadow economy in ASEAN-9 nations, further reinforcing the critical role of IQ in supporting environmental sustainability. Based on insights from existing research, this study posits the following hypothesis.

H2 *IQ is significantly negatively correlated with EFP in G7 countries.*

2.3 Nexus between renewable energy sources and ecological footprint

The transition toward a green economy has emerged as a critical strategy for mitigating environmental degradation, with an increasing body of literature emphasizing its significant role in reducing EFP and fostering long-term sustainability. For instance, Zhao and Bashir (2024) examined the impact of energy efficiency, natural resource utilization, and the digital economy on EFP in OECD countries from 2002 to 2020. Using the MMQR, the findings demonstrated that renewable energy plays a crucial role in mitigating environmental degradation. Similarly, Sharif et al. (2024) investigated the relationship between renewable energy and EFP in countries with the highest levels of environmental degradation from 1990 to 2018. Employing MMQR, the study uncovered that renewable energy plays a crucial role in reducing EFP across all levels of environmental degradation. This suggests that renewable energy contributes consistently and significantly to environmental sustainability, regardless of a country's existing level of ecological degradation. Furthermore, Liu et al. (2025) investigated the dynamic relationship between renewable energy consumption and EFP in the BRICS nations. The study highlights that increased reliance on renewable energy sources significantly contributes to reducing ecological degradation. Their findings emphasize that integrating clean energy can mitigate economic growth losses due to environmental harm, suggesting that renewable energy is a vital policy tool for promoting sustainable development in emerging economies. In a similar vein, Appiah et al. (2023) analyze the impact of environmental policy and renewable energy on EFP in 29 OECD countries from 1990 to 2020. Employing CS-ARDL, the study revealed that renewable energy significantly reduces the EFP, suggesting that a transition towards cleaner energy sources is essential for achieving environmental sustainability. The study emphasizes the importance of aligning renewable energy policies with innovation-driven strategies to mitigate EFP effectively. Similarly, Khurshid et al. (2024) highlight the positive impact of renewable energy consumption on environmental sustainability, demonstrating that increased use of green energy significantly mitigates environmental degradation in South Asian economies. Consistently, Almulhim et al. (2025) found that renewable energy consumption significantly reduces consumption-based CO_2 emissions, highlighting its crucial role in mitigating environmental degradation.

According to Burke and Stephens (2017), the concept of energy democracy gained popularity following the 2008 financial crisis. At that time, world economies faced economic and energy challenges, prompting them to consider transitioning from exhaustible to non-exhaustible energy resources to meet their economic needs. Their findings highlight the importance of inclusive, decentralized, and participatory energy systems in facilitating a transition from fossil fuels to renewable energy sources. Similarly, Olanrewaju et al. (2025) examine how the shadow economy undermines green energy efforts and environmental sustainability in high-income EU nations. Their findings suggest that informal energy use hinders progress toward sustainable energy transitions and climate objectives. Furthermore, Campos & Marín-gonzález (2020) found that citizen engagement in energy production can overcome environmental, social, and economic challenges. Healy and Barry (2017) stated that GE promotes energy accessibility and reduces energy poverty. Many people in the southern part of the world lack access to energy, and the current energy system operates under a monopolistic framework. This system prioritizes the interests of the elite class instead of addressing energy and environmental issues. Selseng et al. (2022) examined the strength of GE about the environment and found that these democratic qualities play a meaningful role in mitigating ecological challenges. Expanding on this idea, Javed et al. (2024a, b) investigate the effects of energy efficiency on environmental performance in the leading 10 manufacturing countries for 1990–2019. Their findings from the CS-ARDL model emphasize the significance of these elements in promoting environmental sustainability and facilitating the transition to low-carbon economies within the context of sustainable development. Accordingly, the study proposes the following hypothesis.

H3 *RES has a negative and significant impact on EFP in G7 countries.*

2.4 Literature gap

The existing body of literature serves as a vital source of knowledge; however, despite these contributions, several important gaps remain unaddressed that require further empirical investigation. First, prior research has predominantly analysed environmental outcomes using isolated determinants such as the SE, IQ, and RES without considering their joint influence on EFP. This fragmented approach has limited the understanding of how these variables interact dynamically within advanced economies. Moreover, most existing studies have relied on conventional environmental indicators such as CO_2 emissions, thereby overlooking the EFP as a more comprehensive and multidimensional measure of environmental sustainability (Jianguo et al. 2022; Godil et al. 2020). Second, the empirical literature has disproportionately focused on developing and emerging economies, including G20 nations (Sun et al. 2025), African economies (Dada et al. 2023), GCC countries (Zhao and Bashir, 2024), and Indonesia (Hardi et al. 2024), while evidence from the G7 context remains scarce. Given that G7 economies possess mature institutional frameworks, ongoing energy transitions, and complex patterns of informal activity, examining these dynamics within advanced economies is both timely and essential. Third, while previous studies acknowledge the role of formal economic activities such as financial development, education, and technological progress in influencing environmental outcomes, the environmental implications of informal economic activities remain largely overlooked. This omission is particularly significant because the SE can exacerbate environmental degradation through unregulated production, weak enforcement, and resource exploitation; it may also hold potential for green formalization if integrated within institutional reforms. Fourth, despite growing recognition of the influence of institutional governance, few studies have explored how the IQ and RES influence the SE–EFP nexus. The absence of such integrative analysis limits both theoretical understanding and policy design. Therefore, this study introduces a unified theoretical framework that combines the Environmental Kuznets Curve (EKC), Institutional Theory, the Porter Hypothesis, and the Laffer Curve Theory to explain how institutional integrity, economic formalization, renewable energy sources jointly shape environmental outcomes. This theoretical synthesis offers a multi-dimensional explanation of environmental performance, showing how stronger institutions enhance regulatory enforcement, how formalization improves compliance incentives, and how green technological progress transforms the growth environment relationship. Finally, from a methodological standpoint, most previous studies have relied on mean-based estimators that fail to capture the nonlinearities and heterogeneity across the distribution of environmental performance. This limitation can obscure policy-relevant variations among countries positioned at different stages of environmental pressure and lead to oversimplified conclusions. To address this, the present study employs the MMQR approach, which provides a deeper understanding of how the SE, IQ, and RES influence EFP across various quantiles. This enables a more comprehensive examination of heterogeneous effects, which reflect differences in environmental conditions and institutional contexts among G7 economies. Furthermore, while much of the existing literature has neglected the issue of endogeneity, this study recognizes that the high degree of economic and institutional integration within G7 countries may give rise to reciprocal relationships among SE, IQ, GE, and EFP. To ensure robustness and mitigate potential endogeneity bias, the study conducts appropriate diagnostic tests and employs the Two-Stage Least Squares (2SLS) estimation technique as an additional robustness check. This integrated econometric strategy strengthens the validity of the empirical findings and enhances the credibility of the study's policy implications.

3 Theoretical background, data, and methods

3.1 Theoretical framework

Traditional classical and neoclassical economic models by Ricardo (1821), Romer (1990), Lucas (1988), Barro (1990), and Solow (1956) claimed that labor, capital, and technological progress are the key drivers of long-term growth. Subsequently, Grossman and Krueger (1991) proposed the Environmental Kuznets Curve (EKC). It shows a nonlinear link between economic development and environmental degradation. Likewise, the Schumpeterian theory (Schumpeter, 1983) highlights that innovation and technological advancement drive growth and reduce environmental damage. These frameworks, extensively confirmed through empirical testing (Jianguo et al. 2022; Ross et al. 2024; Ullah et al. 2024a, b; Sun et al. 2025), found that productivity improvement enhances long-run economic growth and decreases the cost of production. Economic growth is generally viewed as a function of consumer spending, capital formation, and government expenditures key constituents of aggregate demand. However, this model typically does not incorporate the shadow economy, even though it influences actual economic performance. Despite these advancements, a considerable portion of the literature has overlooked the determinants of the informal (shadow) economy. The theoretical foundation of this study is based on welfare economic theories by Coase Theorem (1960); public economic taxation theory by Arthur Laffer (1974), institutional quality theory by Davis et al. (1970), and modern ecological theory by Hajer (2017).

The classical and neo classical growth theories do not address the effect of informal economic activities on the environment. The informal economy is known as the grey economy or shadow economy. It highlights the economic activities that are not officially recorded or taxed Unrecorded activities often pass regulatory standards, such as environmental legislation, leading to the use of outdated equipment, improper waste disposal, or open burning, which heightens EFP. Figure 5 graphically illustrates the Laffer curve theory, which depicts an inverted U-shaped relationship between the tax rate and government tax revenue.

The X-axis of the diagram shows the tax rate in % of GDP, and the Y-axis shows the tax revenue (TR). At the *initial stage,* when the government levies taxes on production and consumption, it increases the government's revenue. After collecting tax revenue, the government increases public spending on various developmental and non-developmental projects, such as infrastructure, industrial expansion, and energy initiatives, which can lead to higher carbon emissions. In the second *stage*, the tax rate is optimum, neither too low nor too high. Since taxation is not excessive, most businesses and individuals are encouraged to operate within the law. Formal economic activities are regulated by environmental policies, leading to a decline in environmental damage. At the *third stage*, when the government raises the tax rate, it reduces the government revenue and promotes shadow activities in the economy. SE further creates a market failure situation. This occurs because markets frequently fail to account for the environmental damage caused by economic activities, resulting in a decrease in investment in clean energy solutions (Randall 1983).

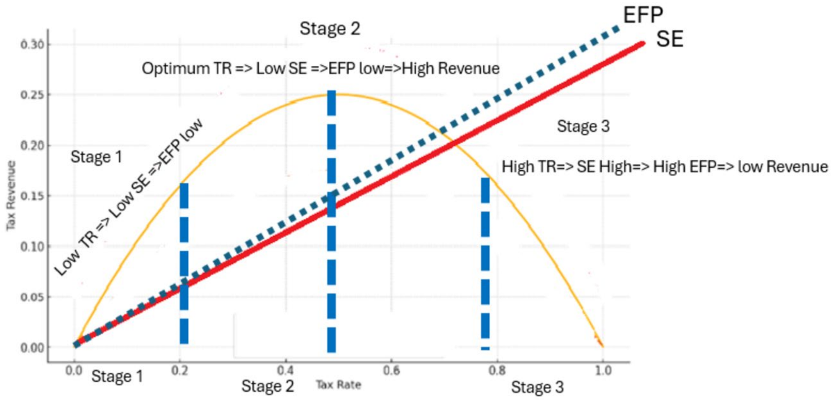

Fig. 5 Graphical representation of the Laffer curve and SE. *Source*: Author's elaboration

Institutional theory explains how governance standards, such as anti-corruption measures, influence EFP (Davis et al. 1970; Common, 1937; Mauro 1995; Meyer & Rowan 1977). In line with this theory, Benatti et al. (2024) argued that strong institutional framework plays a crucial role in shaping a country's environmental well-being. In their research work, Rachid et al. (2025) found that improving the bureaucratic system and controlling corruption are the most effective ways to reduce environmental degradation. In numerous ways, IQ helps economies to achieve sustainable development goals by 2050. Firstly, a strong institutional framework encourages the development and adoption of eco-friendly technologies through the enforcement of stringent environmental regulations, taxes, and subsidies (Dam et al. 2024). Secondly, effective institutions support transparency, prevent corruption, and involve communities in environmental planning (Hasan et al. 2024; Emmanuel et al. 2023). Thirdly, it encourages businesspeople to participate in the formal economy and enables them to adhere to environmental standards, thereby enhancing environmental sustainability (Sun et al. 2023).

Environmental theories suggest that advancements in research and development related to green technological innovations are essential for enhancing environmental standards. According to the Porter theory, stricter environmental regulations encourage the use of renewable energy sources and reduce the EFP (Porter & Linde, 1995). For instance, Gong et al. (2023) suggested that integrating green energy sources into the total energy mix reduces the per-unit cost of electricity production and improves environmental sustainability (Zambrano-Monserrate et al. 2024). This theoretical foundation provides a complete basis for examining the impact of SE, IQ, RES, GLO, and FDI factors on EFP.

Based on the above theoretical background, we derive the following empirical model.

$$EFP_{it} = f\left(SE_{it}, IQ_{it}, RES_{it}, GLO_{it}, FDI_{it}\right) \tag{1}$$

The regression form of the model is portrayed as follows:

$$\ln EFP_{it} = a_0 + \beta_1 \ln SE_{it}^{\prime\Upsilon_{1i}} + \beta_2 IQ_{it}^{\prime\Upsilon_{2i}} + \beta_3 RES_{it}^{\prime\Upsilon_{3i}} + \beta_4 \ln GLO_{it}^{\prime\Upsilon_{4i}} + \beta_5 \ln FDI_{it}^{\prime\Upsilon_{5i}} + \mu_{it} \tag{2}$$

Here, EFP_{it} denotes ecological footprint, a_0 is an intercept while β_1, β_2, β_3, β_4, β_5 Are the slope coefficients of the (SE_{it}) shadow economy, institutional quality (IQ_{it}), green energy (RES) globalization (GLO_{it}), and financial development index (FDI_{it}), and μ_{it} Show the error term. Subordinates "i" and "t" represent the number of cross sections (G-7) and time (1996 to 2020). We took the natural log of the variables, except for IQ and RES, and overcame the issue of data skewness.

3.2 Data

The current study examines the empirical influence of shadow economy (SE), institutional quality (IQ), renewable energy sources (RES), Globalization (GLO), and financial development index (FDI) on ecological footprint (EFP) in G-7 countries.[1] For empirical analyses, this study uses balanced panel data set of sampled countries from 1996 to 2020. The data on EFP is gathered from the Global Footprint Network and quantified in Global hectares per person (GHA per person). Data on the SE are collected from the World Development Indicators and calculated using multiple indicators, multiple causes model-based (MIMIC) estimates of informal output (% of official GDP). The IQ index is based on six diverse factors: government stability, corruption control, military influence in politics, law enforcement, democratic accountability, and bureaucratic efficiency. It ranges from 0 to 100 and is derived from the ICRG. For the compatibility of other variables, we divided them into 100. A higher value indicates strong institutional quality, and a lower value shows poor institutional quality. RES will serve as a proxy for the energy transition, (% contribution of renewables to total primary energy supply) as sources obtained from the OECD database. For control variables, GLO data was extracted from the Swiss Economic Institute website. It is an index that ranges from 0 to 100. The data on the FDI index was gathered from the International Monetary Fund (IMF). The definitions, measurement units, expected signs, and data sources are presented in Table 1.

3.3 Estimation strategy

This study utilizes the subsequent empirical methodologies (see Fig. 6): The first Step involves examining the existence of cross-sectional dependency (CSD) in the panel data. This is done by employing the bias-adjusted LM test created by Pesaran et al. (2008) and the general CD and scaled CDLM tests presented by Pesaran (2004). Second, in addition to the coefficient of determination (CD), the presence of country-specific qualities leads to variations in the slope, indicating that these countries differ in terms of the specific characteristics being studied. Therefore, the slope coefficients homogeneity (SCH) approach developed by Pesaran and Yamagata (2008) confirms the presence of different slopes in the models. Third, the stationarity of the parameters was assessed using two advanced second-generation stationarity approaches established by Pesaran (2007), that is, Cross-Sectional Im-Pesaran-Shin (CIPS) and Cross-Sectional Augmented Dickey-Fuller (CADF) tests. Fourth, the advanced bootstrap Westerlund (2007) panel cointegration methodologies are used to establish the cointegration connection in this research. If the variables exhibit cointegration, utilizing the suitable estimation technique is imperative. Fifth, this study employs the Fully Modified Ordinary Least Squares (FM-OLS) method, as developed by Pedroni

[1] Canada, France, Germany, Italy, Japan, the United Kingdom and the United States.

Table 1 Variable descriptions

Variables	Symbol	Meas. units	Data sources	Exp. sig
Ecological footprint	EFP	GHA per person	Global footprint Network[a]	N/A
Shadow economy	SE	MIMIC	WDI[b]	+
Institutional quality	IQ	Index (0–100)	ICRG	−,+
Renewable energy sources	RES	% of contribution of renewables to total primary energy supply	OECD	−,+
Globalization	GLO	The index ranges from 0–100	Swiss Economic Institute[c]	+,−
Financial development index	FDI	Comprises sub-indices of a financial institution and financial market indices	IMF	+,−

[a]https://www.footprintnetwork.org/

[b]https://data.worldbank.org/

[c]https://kof.ethz.ch/

(2001), the Dynamic Ordinary Least Squares (D-OLS) approach proposed by Stock and Watson (1993), the Fixed Effects (FE-OLS) method, and the Method of Moments Quantile Regression (MMQR) approach. In the *final Step*, the panel Granger causality test is utilized to determine the direction of causality among the variables being investigated (Dumitrescu & Hurlin 2012).

3.3.1 Slope heterogeneity

SCH is an additional perspective problem in panel samples and should be accurately identified to evade biased estimates. However, in this study, Pesaran and Yamagata (2008) are employed to determine the sloping nature of the parameter. The SCH test's null hypothesis follows: "slope-coefficients are not heterogeneous across cross-sectional units." The following equation of the test presents the statistics:

$$\hat{\Omega}_{SLP-HTY} = (N)^{\frac{1}{2}} \cdot (2K)^{\frac{1}{2}} \cdot \left(\frac{1}{N}.\widehat{H} - g\right) \tag{3}$$

$$\hat{\hat{\Omega}}_{SLP-HTY} = (N)^{\frac{1}{2}} \cdot \left(\frac{2g.(T-g-1)}{T+1}\right)^{-\frac{1}{2}} \cdot \left(\frac{1}{N}.\widehat{H} - 2g\right) \tag{4}$$

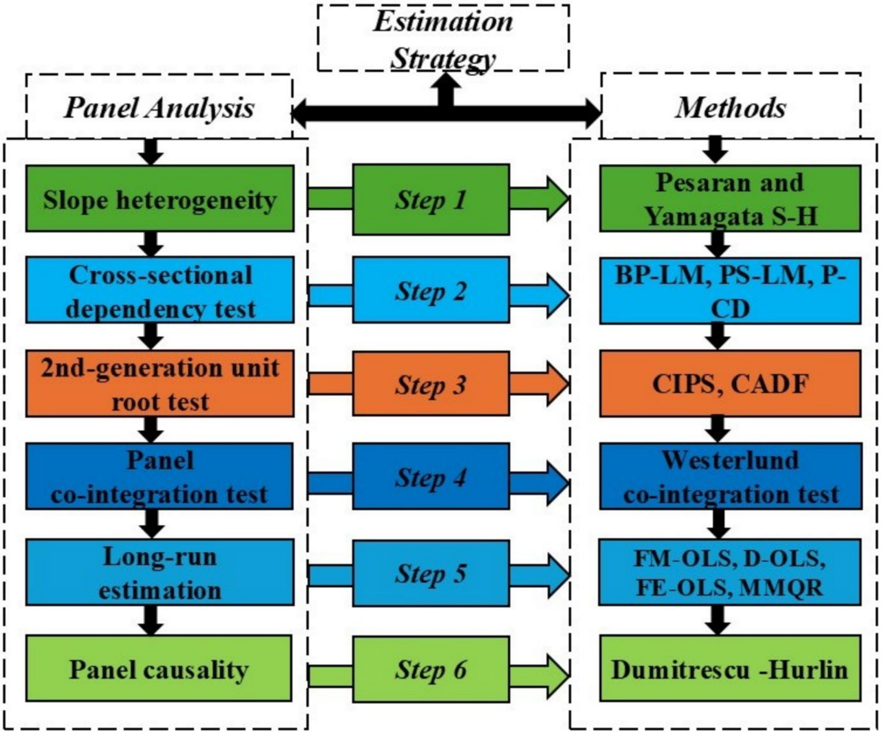

Fig. 6 Flow chart of estimation strategy. *Source*: Author's elaboration

Equations (3) and (4) identify omega ($\widehat{\Omega}$ tilde and adjusted omega tilde ($\widehat{\widehat{\Omega}}$) where N, $\widehat{H}$, l, and T state to cross-section, explanatory variables, and time appropriately.

3.3.2 Cross-sectional dependency

The most critical issue with panel data is the conditional serial dependence (CSD) of the residuals. Due to globalization, economies are financially integrated and dependent on one another, resulting in common stochastic trends (CST) in panel data (Tufail et al. 2022). As a result, incorrect and biased conclusions are reached. Therefore, we employ various CSD tests such as the Pesaran CSD test (Pesaran 2004), Breusch-Pagan LM test (Breusch & Pagan 1980), Pesaran Scaled LM test (Pesaran 2004), and Bias-Corrected Scale LM (Baltagi et al. 2012; Javed et al. 2024a) to determine the presence of CSD. The following summarizes the standard equation used in CSD tests.

$$CSD = \sqrt{\frac{2T}{N\left(N-1\right)}\sum_{i=1}^{N-1}\sum_{j=1+i}^{N}\widehat{\rho}_{ij}} \rightarrow N\left(O,1\right) \tag{5}$$

where T shows the period, N represents the pair-wise parameters, and $\hat{\rho}_{ij}$ Determines the cross-section correlation of errors.

3.3.3 Unit root/Stationarity

The next Step in our investigation is to examine the order of integration using a stationarity test to achieve the stationarity feature of the variables. For this purpose, we employed the proposed cross-sectionally augmented CIPS and CADF tests, as first-generation panel unit root tests (such as LLC, CIPS, and Fisher ADF) can produce erroneous results in the presence of common stochastic trends (CSD) (Levin et al. 2002; Choi 2001). Second-generation CIPS and CADF testing is beneficial because it allows CSD to reduce the possibility of false positive outcomes (Pesaran 2007). The CIPS test has the following equational form:

$$\nabla X_{it} = \vartheta_i + \vartheta EFP_{it-1} + \vartheta_i \overline{X}_{it-1} + \sum_{i=0}^{p} \vartheta_{il} \nabla \overline{X}_{it-1} + \sum_{i=0}^{p} \vartheta_{il} \nabla X_{it-1} + \varepsilon_{it} \quad (6)$$

$\overline{X}$ = cross-section average while

$$X_{it} = \vartheta_{SE} \overline{SE}_{it} + \vartheta_{IQ} \overline{IQ}_{it} + \vartheta_{GE} \overline{GE}_{it} + \vartheta_{GLO} \overline{GLO}_{it} + \vartheta_{FDI} \overline{FDI}_{it} \quad (7)$$

They can also be obtained from the test statistics of CIPS:

$$\widehat{CIPS}_{Unitroot\_test} = N^{-1} \sum_{i=1}^{n} CDF_i \quad (8)$$

3.3.4 Panel cointegration

Due to the presence of CSD, data heterogeneity, and non-stationarity, cointegration detection requires a heterogeneous estimation strategy (Pedroni 2004; Larsson et al. 2001). Cointegration tests verify the validity of the long-term relationship between the variables. However, this study employed the Westerlund (2007) cointegration test to detect panel cointegration. This test examines the CSD problem in panel data and yields accurate cointegration estimates based on the null hypothesis of "no cointegration". For instance, Westerlund panel cointegration has the advantage of accommodating different structural breaks in the panel series and identifying the location of the structural break endogenously using Bai and Perron's (2003) method. This test is based on the following four statistics: two-group statistics (Gt, Ga) and two-panel statistics (Pt, Pa):

$$G_t = N^{-1} \sum_{i=1}^{N} \frac{\vartheta_i}{SE(\vartheta_i)} \quad (9)$$

$$G_a = N^{-1} \sum_{i=1}^{N} \frac{T\vartheta_i}{SE(\vartheta_{ij})} \quad (10)$$

$$P_t = \frac{\hat{\vartheta}_i}{SE(\hat{\vartheta}_i)} \tag{11}$$

$$P_a = T\hat{\vartheta} \tag{12}$$

3.3.5 Method of moment quantile regression

In the present study, we utilized the MMQR, as presented by Machado and Silva (2019), to examine the distributional and heterogeneous variances among various quantiles of our dependent variable, EFP, and independent variables (SE, IQ, RES, GLO, and FDI). However, Kao et al. (2001) previously developed the D-OLS to compare FM-OLS and FE-OLS estimations in constrained samples unbiasedly. The D-OLS methodology utilizes a Monte Carlo simulation to address endogeneity by integrating lagged differences. The FE-OLS estimator is augmented with standard errors proposed by Driscoll and Kraay (1998). These can be utilized to meticulously evaluate each cross-sectional dependence and autocorrelation up to a specific lag time. Due to the limitations of the previously mentioned panel techniques, the panel quantile regression (PQR) estimator was utilized to analyze heterogeneity and distributional effects across each quantile (Sarkodie & Strezov 2019). Koenker and Bassett (1978) pioneered this concept, which is frequently utilized to determine the conditional median of several response quantiles. PQR demonstrates increased sensitivity to outliers in estimations and clarifies the tenuous relationship between the conditional means of two variables (Abid et al. 2025; Binder & Coad 2011).

Nevertheless, the MMQR technique is an enhanced version of PQR that incorporates fixed effects (Anwar et al. 2021; Usman et al. 2025). Moreover, MMQR has distinct advantages; it outperforms traditional quantile regression due to its superior ability to handle unobserved heterogeneity. It can also analyze the conditional heterogeneous covariance effect between our primary and explanatory variables while accommodating individual fixed effects. The MMQR surpasses other models, including the conventional quantile regression model, due to its ability to manage the covariance effect in the general distribution. This strategy enables the individual impact to influence the entire distribution, rather than merely altering the means among the others (Canay 2011; Koenker 2004). This method is effective when the model includes endogenous independent variables and is integrated with individual effects. This estimation enhances the examination of trends across the key dependent variable of interest's lower, middle, and higher-order quantiles. The MMQR applied methodology has several advantages, including its resilience to outliers and its ability to accommodate conditional heterogeneous covariance effects (Chau et al. 2022).

In contrast to moving means, MMQR exhibits greater resilience to outliers and disregards the potential for underlying heterogeneity in the panel, hence accommodating the influence of conditional heterogeneous covariance on the overall distribution. Finally, the MMQR can address endogeneity problems and produce accurate results, even in the presence of a dataset's lack of linearity and normality. The model of estimation employed is as follows.

Conditional Quantile $\mathcal{Q}_y\left(\delta \middle| \overbrace{X}_{it}\right)$:

$$\breve{\dot{Y}}_{it} = \acute{\alpha}_i + \overbrace{X}_{it} + \phi\left(\tilde{\eta}_{\rm i} + \acute{\check{Z}}_{\rm it}\xi\right)\acute{\breve{U}}_{it} \tag{13}$$

where the probability, $\phi\left\{\tilde{\eta}_{\rm i} + \acute{\check{Z}}_{\rm it}\xi > 0\right\} = 1$, and the parameters $(\acute{\alpha}_i, \tilde{\eta}_i\ i{=}1, 2, 3$ up to n describes the discrete i fixed-effects, whereas $\acute{\check{Z}}$ represents the k-vector of recognized modules of $\overbrace{X}$, and are distinguishable alterations with j as follows:

$$\acute{\check{Z}}_j = \acute{\check{Z}}_j\left(\overbrace{X'}\right), j = 1, 2, \ldots, k \tag{14}$$

$\overbrace{X}_{it}$ and $\acute{\breve{U}}$ are identically dispersed beyond individuals and time periods (t). Machado and Silva (2019) state that standardized momentum conditions $\acute{\breve{U}}'_{it}$ are orthogonal to $\overbrace{X}_{it}$. Thus, Eq. 10 suggests the following:

$$\mathcal{Q}_y\left(\delta\left|\overbrace{X}_{it}\right.\right) = \left(\acute{\alpha}_i + \tilde{\eta}_i q\left(\delta\right)\right) + \overbrace{X}_{it}\phi + \acute{\check{Z}}_{it}\xi q\left(\delta\right) \tag{15}$$

From the above equation, $\overbrace{X}_{it}$ is a vector of descriptive interest variables represented as each observed variable's natural logarithm (SE, IQ, RES, GLO, and FDI). $\mathcal{Q}_y\left(\delta\left|\overbrace{X}_{it}\right.\right)$

Represent the quantile–distribution of $\breve{\dot{Y}}$; EFP, which is restrictive on the position of the explanatory variable $\overbrace{X}_{it}$. $\acute{\alpha}_i\ (\delta) \equiv \acute{\alpha}_i$ q (δ); the scalar to reveal the quantile δ' fixed effects for across individual i. q (δ) designates a sample quantile. This is evaluated by resolving optimization as follows.

$$Min_q = \sum_i \sum t\varpi o'\left(RIT - \lambda_i + \acute{\check{Z}}_{it}\gamma\right)q \tag{16}$$

where $\varpi' o\left(\overbrace{R}\right) = (\delta - 1)\overbrace{R}\hat{I}\left\{\overbrace{R} \leq 0\right\} + \mathrm{T}\overbrace{R}\hat{I}\left\{\overbrace{R} > 0\right.$ Represents the checked function.

3.3.6 Granger causality

The subsequent steps to determine a long-term link between the variables entail employing causal analysis to delineate the direction of the association. This study will employ the Wald statistics-based causality test established by Dumitrescu and Hurlin (2012). The primary benefit of this test is its consideration of dependencies and heterogeneity among nations. It can also be executed when the time dimension (T) is either greater or less than the cross-sectional dimension (N). The analysis is conducted utilizing two stable series. If the series utilized in the investigation is unstable, the inconsistency must be identified and rectified. Dumitrescu and Hurlin (2012) define the null and alternative hypotheses in panel causality analysis as follows:

$H_0 = \beta_i = 0 \forall_i = 1, \ldots, N$ There is no causal relationship from x to y

$$H_1 = \beta_i = 0\forall_i = 1, \ldots, N_1$$

$$\beta_i \neq 0\forall_i = N_1 + 1, N_1 + 2$$

In some cross-sections, there is a causal relationship from x to y. Individual Wald statistics for each cross-section are produced first to test the null hypothesis proposed by Dumitrescu and Hurlin (2012). For each cross-section, these statistics show the causal link. The Wald statistics are valid for the panel and are then calculated by averaging the individual Wald statistics.

$$W_{N,T}^{Hnc} = \frac{1}{N}\sum_{i=1}^{N} W_{i,T} \tag{17}$$

When the time dimension is more than the cross-section dimension, Dumitrescu and Hurlin (2012) recommend using the (T>N) test statistic, and when the time dimension is less than the cross-section dimension, they recommend using the (TN) test statistic. The standardized test statistics in this study is presented below because T>N in this investigation.

If T>N

$$Z_{N,T}^{Hnc} = \sqrt{\frac{N}{2K}\left(W_{N,T}^{Hnc} - K\right)} \rightarrow N(0,1) \tag{18}$$

Dumitrescu and Hurlin (2012) employ a Monte Carlo simulation to compute the test statistics and associated probability values.

4 Results and discussion

4.1 Descriptive statistics

Descriptive statistics information of the sampled variables is presented in Table 2. EFP has a mean value of 1.793 (s.d. = 0.275), while SE and IQ indicate mean values of 2.682% (s.d. = 0.339%) and 3.313(s.d = 0.339), respectively. There is less variability in the dataset, as the standard deviation values are lower than the mean values. However, EFP and SE

Table 2 Descriptive statistics

	EFP	SE	IQ	RES	GLO	FDI
Mean	1.79	2.68	3.21	8.64	4.39	2.20
Median	1.73	2.72	3.31	6.63	4.40	1.75
Max	2.39	3.42	4.18	19.54	4.49	12.73
Min	1.24	2.12	1.57	0.79	4.12	− 4.51
S. d	0.27	0.33	0.61	5.38	0.07	2.27
Skewness	0.55	0.52	− 1.07	0.54	− 1.22	1.87
Kurtosis	2.33	2.81	3.80	1.94	4.76	8.47
JB	12.22	8.37	38.40	16.22	66.59	31.35
Prob	0.00	0.01	0.00	0.00	0.00	0.00

show a leptokurtic distribution, while all other variables (IQ, RES, GLO, and FDI) also demonstrate leptokurtic distributions. Lastly, based on the Jarque–Bera test statistics, we reject the null hypothesis of 'data is normally distributed' at the 1% level of significance and identify issues of data abnormality. To address the challenge of data abnormality, we use second-generation methods. Further, Fig. 7 presents the box plot summary statistics of the six variables for G-7 countries from 1996 to 2020. It captures the central tendency, variability, and distribution shape of the data. In each box plot, the top line represents the maximum value of the series, while the bottom line indicates the minimum value. The box also displays the average of each series with a square marker and the median with a circle. In addition, Fig. 8 illustrates the bivariate analysis of six sampled variables, where the dependent variable (EFP) is positively correlated with SE. IQ, RES, FDI, and GLO are negatively associated with EFP. This study did not find a multicollinearity issue among the study variables. Multicollinearity among the independent variables was assessed using the variance inflation factor (VIF) analysis. Since all VIF values are below 2.00, with an average VIF of 1.40, the level of multicollinearity is considered low. Typically, a VIF value exceeding 10 indicates a potential issue (O'brien 2007; Maftoon et al. 2025). Therefore, the results suggest that multicollinearity is not a major concern in this analysis, implying that the estimated coefficients of the independent variables are likely to be stable and reliable (see Table 3). Finally, Fig. 9 shows a Scatter plot of variables. The results of the kurtosis and the skewness disclosed the nonlinearity attributes of the series. Thus, using a linear technique will produce a misleading result. The current study, in this case, used the panel non-linear Method of Moments Quantiles Regression (MMQR) approach.

4.2 Results of slope heterogeneity

Table 4 presents the statistical outcomes of slope heterogeneity test (Pesaran and Yamagata 2008). Based on the prob. values of (delta = 6.30) and ($\tilde{\Delta}$ Adjusted statistics (p = 7.43) allowed us to reject the null hypothesis at 1% level of significance and conclude that there is a difference between the series.

4.3 Results of CSD tests

Table 5 shows the empirical outcomes of the CDS tests Pesaran scale LM. Pesaran, (2007) and Baltagi et al. (2012) for the chosen G7 nations. CSD is one of the most significant problems in panel data analysis. Due to globalization, industrialization, and the integration of financial and economic systems, economies are interdepended on each other. But the first-generation traditional econometrics models assume that nations are cross-sectionally independent and generate biased outcomes. Based on the CSD tests statistics we reject the null hypothesis of "Cross-sectional units are independent" at 1% level of significance and confirmed the presence of CSD in G7 economies.

4.4 Results of panel unit root tests

After the identification of CSD in the dataset, the next step in panel data analysis is the examination of panel unit roots. This study employs second-generation panel unit root tests, specifically the CADF and CIPS tests (Pesaran 2007). The results of the CADF and CIPS

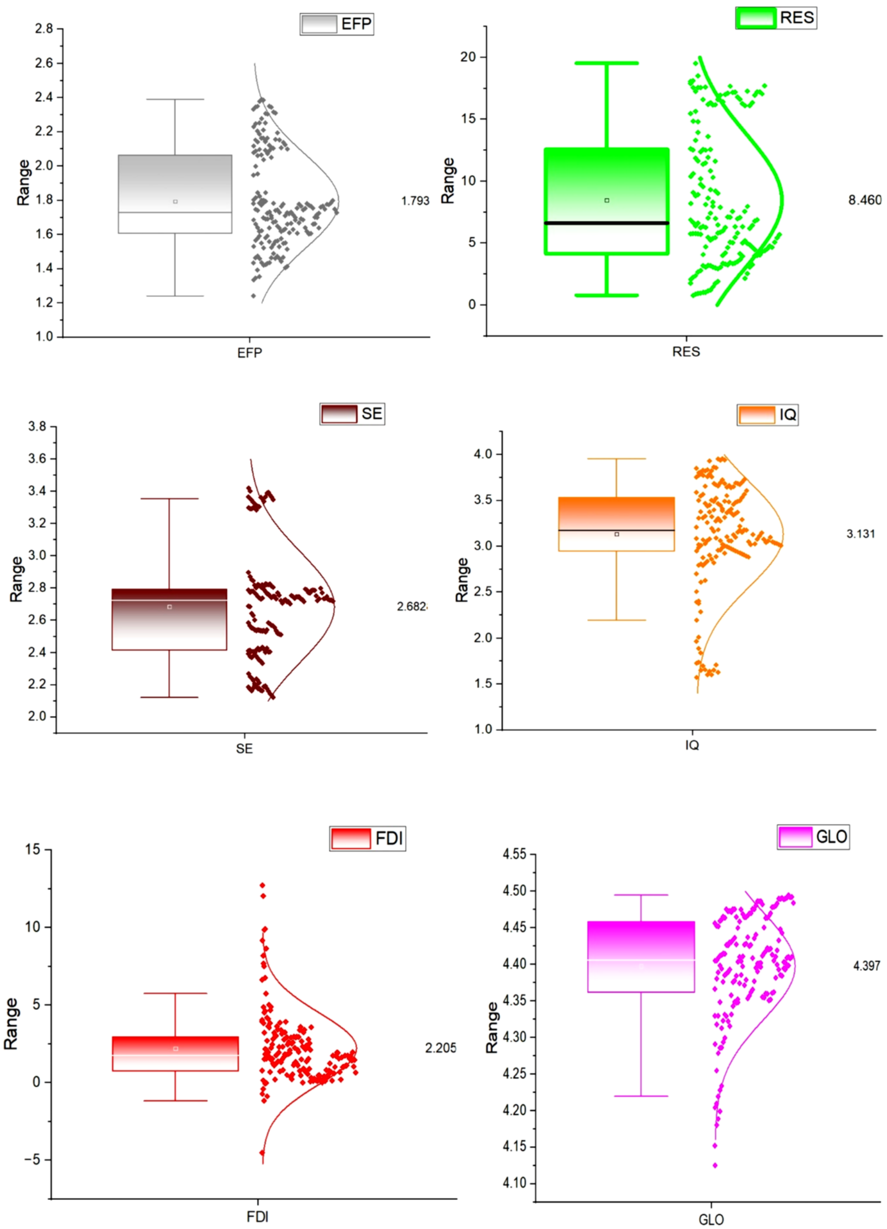

Fig. 7 Box-plot summary of variables. *Source:* Author's elaboration

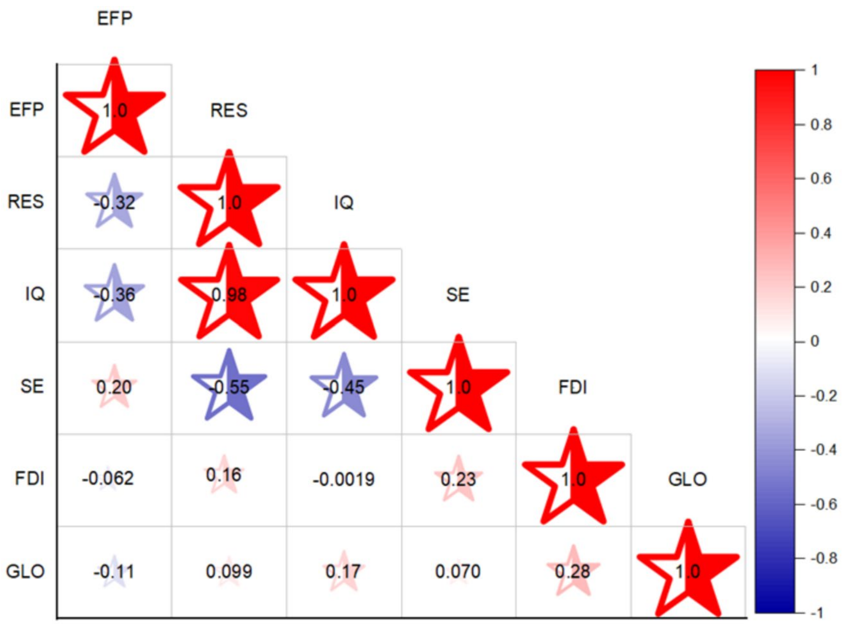

Fig. 8 Correlation matrix. *Source*: Author's elaboration

Table 3 Variance inflation factor (VIF) test

Variables	VIF	1/VIF
SE	1.78	0.562
IQ	1.52	0.658
RES	1.36	0.735
GLO	1.19	0.841
FDI	1.14	0.875
Mean VIF	1.40	

tests are summarized in Table 6. Outcomes presented in the table show that all study variables are stationary at the I (1) level. We reject the null hypothesis of 'series has a unit root' at the 10% level of significance and conclude that the mean, variance, and covariance of the study variables are constant over time (absence of unit root).

4.5 Results of the bootstrap westerlund test

When we find that variables are stationary at the first difference, we further check the long-run association among variables. For this purpose, this study employed an advanced bootstrap Westerlund cointegration test (Westerlund 2007). Error correction-based cointegration test. During the presence of CSD and slope heterogeneity (SHG), the traditional cointegration tests, such as the Johansen cointegration test and Kao test (Kao 1999), produce biased outcomes and provide incorrect information regarding the long-run association among the sample variables. The estimated results of the Westerlund cointegration test are reported in Table 7. The estimated results suggest that the null hypothesis "*the absence of long-term*

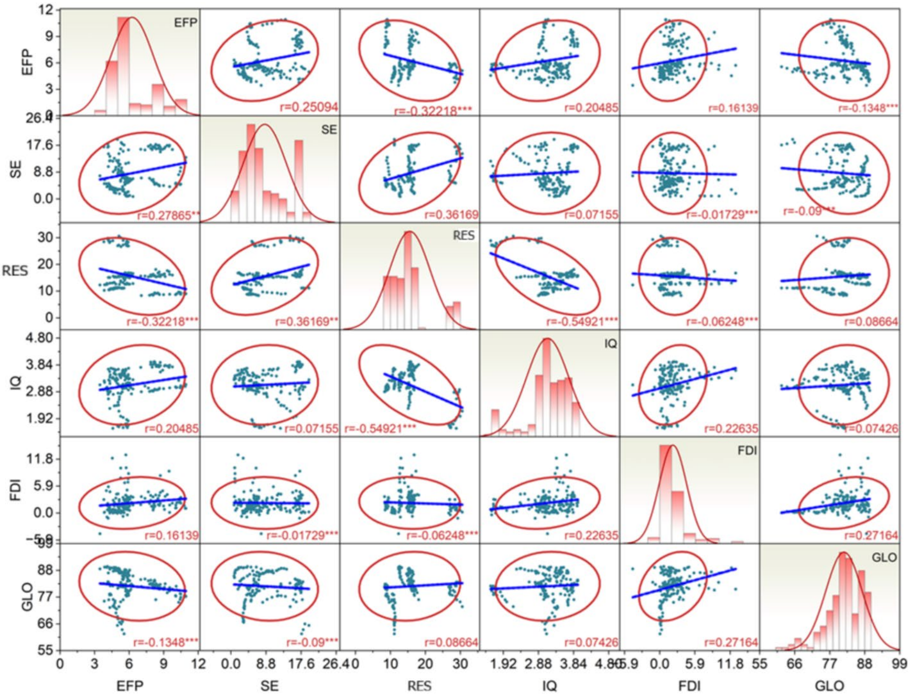

Fig. 9 Scatter plot of variables. *Source*: Author's elaboration

Table 4 Slope heterogeneity test results

Test	Statistic	*P*-value
$\tilde{\Delta}$	6.30	0.00***
$\tilde{\Delta}$ adjusted	7.43	0.00***

*** indicates a significant level of 1%

Table 5 Outcomes of cross-sectional dependence

Tests	EFP	SE	IQ	GE	GLO	FDI
Breusch-Pagan LM	240.56***	100.27***	113.33***	156.79***	35.90**	158.08***
Pesaran-Scaled LM	32.79***	11.15***	13.16***	19.87***	1.21	20.07***
Pesaran CD	15.12***	7.58***	0.56	10.94***	4.39***	12.01***

** and *** indicate the rejection of the null hypothesis at a 5% and 10% significance level

cointegration" is rejected in favor of the alternative hypothesis "*the existence of long-term cointegration*" at 1% level of significance. The study findings confirm the presence of long-term relationship between SE, IQ, RES, GLO, FDI and EFP in G-7 countries.

4.6 Panel mean estimations

This study investigates the long-term effects of SE, IQ, RES, FDI, and GLO on EFP by three distinct long-term Panel Mean estimation methods: FM-OLS, D-OLS, and FE-OLS. Table

Table 6 Results of CIPS and CADF

Variables	CIPS		CADF	
	I (0)	I (1)	I (0)	I (1)
EFP	− 3.05	− 5.60*	− 2.99	− 3.82*
SE	− 124	− 3.70*	− 1.43	− 2.47*
IQ	− 1.33	− 4.66*	− 2.13	− 3.69*
RES	− 1.64	− 4.19*	− 2.98	− 2.62*
GLO	− 1.45	− 4.64*	− 2.09	− 3.13*
FDI	− 1.98	− 3.67*	− 1.43	4.038

* indicate significance at 10%; Critical values are: 5% = − 2.45, 1% = − 2.67

Table 7 Westerlund cointegration outcomes

Stats	Value	Z-value	*p*-value	Robust *p*-value
Gt	− 15.22	− 14.23	0.00	0.00
Ga	− 20.35	− 22.34	0.00	0.00
Pt	− 29–36	− 29.37	0.00	0.00
Pa	− 40.12	− 35–84	0.00	0.00

Pt, Pa, panel cointegration, and Gt, Ga, cointegration for each country

Table 8 Long-run Mean results

Variables	FM-OLS	D-OLS	FE-OLS
	Coefficient	Coefficient	Coefficient
SE	0.77***	1.33***	0.29***
IQ	− 0.19**	− 0.20***	− 0.01**
RES	− 0.50***	− 0.31**	− 0.17***
FDI	− 0.16**	− 0.04***	− 0.07***
GLO	− 1.96***	− 1.03***	0.12*

*** and ** denote the 1% and 5% significance levels, respectively

8 shows the empirical results of all three models. The estimated results demonstrate that SE has a substantial positive influence on EFP across all models, with statistical significance at a 1% level. This indicates that an escalation in SE activities within the sample countries exacerbates environmental degradation, thereby diminishing environmental sustainability in G-7 nations. This positive association indicates that, when other factors are held constant, a 1% increase in shadow activities results in a decrease in environmental sustainability by around 0.774 (FM-OLS), 1.33 (D-OLS), and 0.29 (FE-OLS), respectively. These study findings are consistent with those of Butt et al. (2025) for ASEAN economies and Faisal et al. (2025) for BRICS-T economies, which employed the FMOLS and DOLS models, and found that SE activities hurt environmental sustainability. Secondly, IQ has a significant negative impact on the EFP in all three models at the 1% and 5% significance levels. Effective governance and robust institutions that promote environmental protection policies mitigate ecological degradation by reducing EFP, thereby enhancing environmental sustainability in G-7 economies. The negative significant impact of IQ on EFP indicates that a 1% increase in IQ results in a decrease in EFP by 0.19(FM-OLS), 0.20(D-OLS), and 0.01 (FE-OLS), respectively. These results align with prior studies conducted by Dam et al. (2024) for OECD economies and Mohamed et al. (2025) for Somalia.

The empirical coefficients of RES indicate that a 1% increase in RES consumption results in a reduction in EFP by 0.50 (FM-OLS), 0.31 (D-OLS), and 0.17 (FE-OLS), respectively. The adverse correlation between RES and EFP suggests that the utilization of RES in G-7 nations enhances ecological sustainability. The study's results align with those of Murshed et al. (2022), Ahmad et al. (2024a, b), Javed et al. (2024a, b), and Rahadian et al. (2025), who reported a negative association between green energy utilization and environmental degradation.

The analysis of financial development index (FDI) reveals a significant adverse impact on environmental degradation across all long-term mean estimation models. Specifically, controlling for other variables, a 1% increase in FDI leads to a rise in the EFP by 0.16 (FM-OLS), 0.04 (D-OLS), and 0.07 (FE-OLS), respectively. The current findings corroborate earlier research by Saqib et al. (2024), Bergougui (2024), Keswani et al. (2025), and Ullah et al. (2025), which employed advanced econometric models and claimed that financial development improves environmental sustainability and reduces the EFP. The empirical results also show a negative relationship between GLO and EFP across all models. A 1% increase in globalization activity is associated with a decrease in EFP by 1.96 (FM-OLS), 1.03 (D-OLS), and 0.12 (FE-OLS), respectively. The evidence aligns with previous findings (Karimli et al. 2024; Pata et al. 2024; Sibt-e-Ali et al. 2024), which suggest that globalization reduces the EFP by promoting efficient resource management and disseminating eco-friendly technologies.

4.7 Long-run heterogeneous estimation using the MMQR model

After examining the interrelationships among the variables using three distinct long-term estimation methods, the study proceeds to assess the heterogeneous effects of SE, IQ, RES, FDI, and GLO on EFP across various quantiles (ranging from the 10th to the 90th percentile). This is done using the MMQR, a novel approach. Table 9 presents the results of the MMQR analysis, showing how SE, IQ, RES, FDI, and GLO impact ecological sustainability differently across quantiles. To clarify these results, the quantile distribution is divided into three groups: lower quantiles ($\tau = 0.10$ to 0.30), middle quantiles ($\tau = 0.40$ to 0.60), and upper quantiles ($\tau = 0.70$ to 0.90). The effects, however, vary across all quantiles, as illustrated in Fig. 10.

The empirical findings obtained by MMQR demonstrate that the SE has a statically significant and positive effect on the EFP across all quantiles (10th to 90th). This strong degree of association indicates that as shadow economic activities such as illegal forestry, unlicensed mining, unofficial manufacturing, and black-marketing sales, significantly raise environmental pressures. Further, illegal deforestation reduces forests and endangers biodiversity, while unregulated extraction contaminates soil and water bodies, harming ecosystems (Dada et al. 2021). Additionally, informal manufacturing enterprises often rely on outdated equipment's cheap and polluting technologies that produce significant amounts of green greenhouse gases emission and destroy environmental sustainability. Informal economic activities work beyond the scope of regulatory authorities. The relationship is corroborated by prior research by Dada et al. (2021, 2022) and Köksal et al. (2020), Khurshid et al. (2024), who argued that poor organizational strategies and unlawful practices can lead to the evasion of legal standards, and tax avoidance thereby threatening ecological stability. Furthermore, Hardi et al. (2024) argued that due to lack of government intervention and poor environmental standers SE increases the EFP.

Moreover, this study observed a significant negative correlation between IQ and EFP across all quantiles (10th to 90th). This degree of association shows that a 1% improvement

Table 9 MMQR outcomes

			Lower quantiles			Middle quantiles			Upper quantiles		
Var	Location	Scale	(0.10)	(0.20)	(0.30)	(0.40)	(0.50)	(0.60)	(0.70)	(0.80)	(0.90)
SE	0.74**	− 0.33***	1.28***	1.07***	0.98***	0.86***	0.73***	0.61***	0.47**	0.36*	0.20
	(0.2)	(0.12)	(0.33)	(0.27)	(0.25)	(0.22)	(0.21)	(0.2)	(0.2)	(0.21)	(0.23)
IQ	− 0.08***	− 0.01	− 0.06	− 0.07**	− 0.07**	− 0.07***	− 0.08***	− 0.08***	− 0.09***	− 0.09***	− 0.1***
	(0.02)	(0.01)	(0.04)	(0.03)	(0.03)	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)
RES	− 0.01***	0.003**	− 0.01***	− 0.01***	− 0.01***	− 0.01***	− 0.01***	− 0.01***	− 0.01***	− 0.01**	− 0.004
	(0.002)	(0.001)	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)
FDI	− 0.01	− 0.003	− 0.005	− 0.01	− 0.01	− 0.01	− 0.01	− 0.01	− 0.01	− 0.01	− 0.01
	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
GLO	− 0.01***	− 0.04	− 0.005***	− 0.005***	− 0.01***	− 0.01***	− 0.01***	− 0.01***	− 0.01***	− 0.01***	− 0.01***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)

*** and ** denote the 1% and 5% significance levels, respectively in the functioning of institutions leads to a decrease in the EFP by (− 0.6 to − 1.0%) from the lower to upper quantiles. It suggests that the elimination of corruption and the promotion of transparency significantly improve environmental sustainability. Moreover, through the enforcement of sustainability laws, the government can overcome environmental stress. Furthermore, a higher degree of IQ helps decrease economic uncertainty and transaction costs, and ensures the implementation of clean energy regulations, ultimately decreasing EFP. The present study outcomes are lined with the existing literature (Uzar 2021; Amegavi et al. 2022; Azimi & Rahman 2023; Ayad et al. 2023; and Liao et al. 2023), who employ the Method of Moment Quantile Regression (MMQR) and panel models and claim that IQ declines EPF. For Asian economies, Rahman et al. (2022) applied Driscoll and Kraay's standard error technique and Panel Corrected Standard Error (PCSE) models and suggested that the transparency of the judiciary and anti-corruption policies significantly enhance environmental quality and reduce environmental degradation. For G20 economies (Azimi et al. 2023), used the second-generation econometric models and found a negative association between IQ and EFP. Based on their empirical model outcomes, they suggested that stringent institutional policies directly influence consumer and producer behavior and convince them to use environmentally friendly energy sources. In contrast, for MERCOSUR nations Qayyum et al. (2024) applied a CS-ARDL model and found a positive correlation between IQ and EFP. They claimed that political instability, weak accountability, and the self-priorities of government officials significantly influence the environmental sustainability of economies.

The empirical outcomes of the MMQR model indicate that RES hurts ecological sustainability across all quantiles, ranging from the lower to the upper quantiles (10th-90th). The computed coefficients indicate that an increase in gross emissions results in a decrease in EFP. In their research work (Usman et al. 2020; Javed et al. 2024b), they explain the economic and environmental advantages of RES. Firstly, it reduces the cost of imported oil and improves the country's balance of payment (BOP) account. Secondly, it produces energy from freely available energy sources, such as solar, wind, thermal, and hydro, and improves the environmental quality. Simultaneously, it conserves biodiversity and alleviates the ecological strain by decreasing EFP. The prior investigations by Lau et al. (2023) for 36 OECD economies, Ansari et al. (2021) for the top 22 green energy producing countries, Kahouli et al. (2022) for Saudi Arabia, Liu et al. (2023) for OECD economies, Jiakui et al. (2023 for China, and Shu et al. (2023) for G7 economies, and Javed et al. (2023a, b) found an inverse association between green energy sources utilization and EFP. Scholars suggest that substituting fossil energy with cleaner, modern alternatives can effectively restore ecological balance. Finally, the empirical results of study control variables FDI and GLO indicate a negative and substantial influence on EFP across all quantiles ranging from (10th to 90th). This association shows that a 1% increase in level of FDI lead to decline in the EFP by (− 0.05% to − 0.01%) from lower to upper quantiles. This suggests that efficient financial institutions provide necessary finance and capital to economic agents for investment in energy sources, increase the interest rate on carbon-intensive industrial activities, and decline EFP. In existing literature Leng et al. (2024) applied the MMQR model for seven abundant resources developing countries and found that FDI for green energy sources significantly declines the EFP and protects ecological health. Lastly, the empirical outcomes of GLO show that a 1% increase in the level of GLO lead to a decrease in the EFP by (− 0.05% to − 0.01%) from lower to upper quantiles. By spreading the use of clean energy technolo-

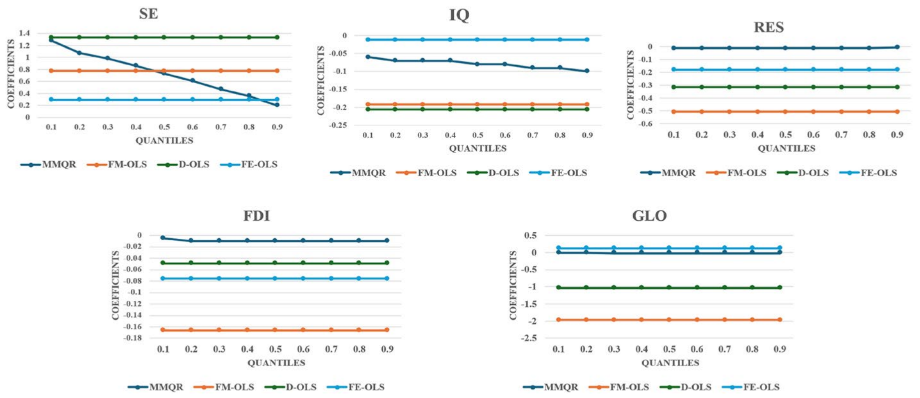

Fig. 10 MMQR outcomes. *Source*: Author's elaboration

Table 10 Summary of MMQR outcomes

Var	Lower (τ = from 0.10 to 0.30)	Middle (τ = from 0.40 to 0.60)	Upper quantiles (τ = from 0.70 to 0.90)
SE	+	+	+
IQ	−	−	−
RES	−	−	−
FDI	−	−	−
GLO	−	−	−

The − and + signs represent significant negative and positive relationships between the response and explanatory variables, respectively

gies, and energy efficient appliances, GLO deteriorates the EFP and protects the ecological quality of nations. A research study by Karimli et al. (2024) for 35 European economies and Pata et al. (2024) for BRICS economies argued that GLO decline the EFP. They suggested that globalization can exert pressure on nations to implement stricter environmental regulations and protect their economic and environmental welfare. Table 10 and Fig. 11 provide a statistical summary of the MMQR estimates for all the variables analyzed in the study (Table 11).

4.8 Robustness analysis

To ensure the robustness of the MMQR results, a Two-Stage Least Squares (2SLS) estimation was performed to address potential endogeneity issues in SE and IQ. Based on the theoretical perspective and the confirmation of bidirectional causality identified through the Granger causality tests, SE and IQ were treated as potentially endogenous variables. This argument was further supported by the Durbin–Wu–Hausman test (Nakamura & Nakamura 1981; Baum et al. 2007), which strongly rejected the null hypothesis of exogeneity (*P*-value = 0.014). Consequently, SE and IQ were instrumented using the one-period lagged values of all five explanatory variables (L.SE, L.IQ, L.RES, L.GLO, and L.FDI). The validity of these instruments was confirmed by the Sargan–Hansen test (Arellano 2002; Chao et al. 2014 (see Table 12), which failed to reject the null hypothesis of instrument exogeneity. The 2SLS results, presented in Table 11, are consistent with the MMQR estimates

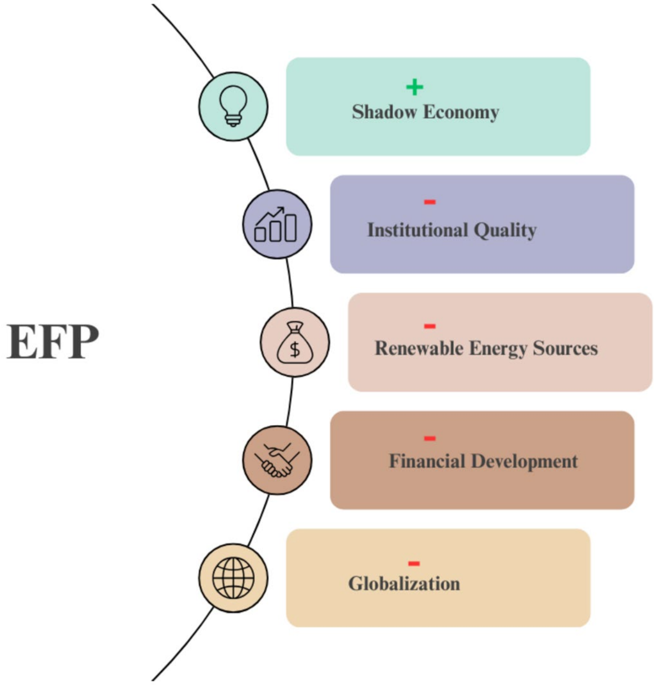

Fig. 11 FMOLS, DOLS, FE-OLS, and MMQR outcomes. *Source*: Author's elaboration

Table 11 2SLS results

Variables	Coefficient	Standard error	*P*-value
SE	0.170	0.045	0.000***
IQ	− 1.103	0.312	0.000***
RES	− 0.247	0.093	0.008***
GLO	− 0.664	0.351	0.059*
FDI	− 2.237	0.663	0.000***

*** and **, and * denote the 1% and 5%, and 10% significance levels, respectively

Table 12 Sargan-Hansen test of overidentifying restrictions

Test	Value	*P*-value
Sargan-Hansen	2.174	0.337

in both sign and statistical significance. Specifically, SE continues to exert a positive and statistically significant effect on EFP, IQ remains negatively associated with EFP, and RES continues to mitigate EFP. Moreover, GLO and FDI maintain their negative and significant relationships with EFP. Overall, the consistency of results across both the MMQR and 2SLS estimations underscores the robustness of the findings against distributional heterogeneity and potential endogeneity issues.

Table 13 Causality analysis

Null hypothesis	Wald-statistic	Z-value	*P*-value
SE≠EFP	2.51***	2.85	0.004
EFP≠SE	3.21***	4.14	0.000
IQ≠EFP	1.83	1.56	0.117
EFP≠IQ	11.19***	19.07	0.000
RES≠EFP	1.93*	1.73	0.083
EFP≠RES	16.15	28.35	0.000***
FDI≠EFP	2.05**	1.97	0.048
EFP≠FDI	0.90	− 0.17	0.862
GLO≠EFP	4.99***	7.46	0.000
EFO≠GLO	1.61	1.14	0.252

***, **, and * denote the 1%,5%, and 10% significance levels, respectively

4.9 Causality test

In the concluding phase of our study, we rigorously assess and validate the causal links between EFP and the explanatory factors. Although methodologies like FM-OLS, D-OLS, FE-OLS, and MMQR approaches produce precise estimates, they fail to consider the direction or causality of the interactions among the variables. To address this limitation, we applied the panel Granger causality method developed by Dumitrescu and Hurlin (2012), with the results summarized in Table 13. The Wald statistics and Z-scores were used to test the null hypothesis of no causal relationship. The results show that the Wald statistics and Z-scores are statistically significant for most causal relationships, thus rejecting the null hypothesis of no association between the variables. The analysis reveals both unidirectional and bidirectional causal relationships among the variables. Specifically, there is a unidirectional relationship between IQ and the EFP, RES and EFP, GLO and EFP, and FDI and EFP. Additionally, the analysis confirms a bidirectional causality between the SE and EFP. These causal linkages suggest that policy changes related to SE, IQ, RES, FDI, and GLO will have a significant impact on ecological sustainability in G-7 countries. Figure 12 visualizes these causal relationships.

5 Conclusion and policy implications

5.1 Conclusion

This study empirically examines the effects of SE, IQ, RES, FDI, and GLO on the EFP in G-7 countries from 1996 to 2020. Prior to the empirical analysis, a series of preparatory tests were conducted to assess the attributes of the panel data. The SCH test, developed by Pesaran and Yamagata (2008), was utilized to confirm the presence of a heterogeneous slope model, while the CSD test by Pesaran (2007) evaluated the existence of cross-sectional dependency. To determine the integration order of the variables, the second-generation stationarity test by Pesaran (2007) was employed. Additionally, the bootstrap Westerlund (2007) cointegration test was used to explore the long-term cointegration relationship between ecological sustainability and the independent variables. Based on the results from these initial assessments, the most suitable econometric model was developed to analyze the interrelationships among the variables. The research employs the MMQR alongside various long-run mean

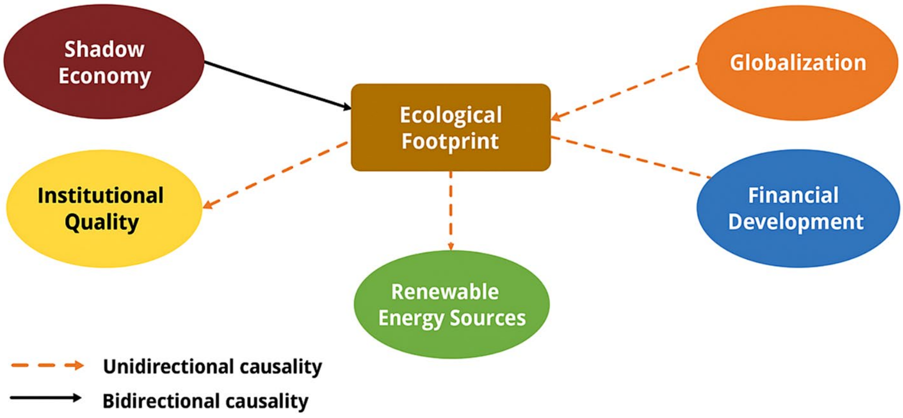

Fig. 12 Causality of explanatory variables with EFP. *Source*: Author's elaboration

estimation techniques, such as FM-OLS, D-OLS, and FE-OLS, to ensure robustness the current study employs 2SLS approach for endogeneity. The MMQR method offers a more nuanced understanding of the complex relationships between ecological sustainability and its drivers compared to traditional long-run mean approaches. To assess causal links among the variables, the Dumitrescu and Hurlin (2012) causality test was employed. The findings of the slope heterogeneity test confirmed the presence of slope heterogeneity in the model, while the CSD test indicated cross-sectional dependency in the panel. The stationarity test revealed varying integration orders among the variables, and the Westerlund (2007) cointegration test demonstrated a long-term relationship between the dependent and independent variables. The empirical findings indicate that the SE exerts a significant and positive impact on EFP across all models and quantiles, indicating that increased informal economic activity contributes to greater environmental degradation. This relationship holds consistently, reinforcing the environmental risks posed by unregulated economic practices. Further, institutional quality consistently shows a significant negative association with EFP, highlighting that robust governance, anti-corruption measures, and institutional transparency are crucial for improving environmental outcomes. Higher IQ levels help enforce environmental policies, reduce uncertainty, and enhance regulatory compliance. On the other hand, RES negatively correlates with EFP in both mean and quantile regressions, underlining its critical role in promoting ecological sustainability. Increased reliance on RES not only improves environmental quality but also supports long-term sustainability goals. Besides, some evidence suggests that FDI can increase EFP in the short term, the long-term findings from the MMQR regression analysis reveal a consistent negative effect across all the quantiles, suggesting that FDI especially when aligned with environmental standards can enhance environmental sustainability. Globalization contributes positively to environmental sustainability by reducing EFP across all models and quantiles. This may reflect the diffusion of green technologies, international environmental norms, and more efficient resource utilization associated with global economic integration. Finally, causality analysis confirms both unidirectional and bidirectional relationships among the variables. Notably, there is bidirectional causality between SE and EFP, while IQ, RES, FDI, and GLO all exhibit unidirectional causal effects on EFP. These findings imply that policy measures targeting these factors can directly and significantly influence environmental outcomes.

5.2 Policy implications

The findings of this study offer several theoretically grounded and empirical policy implications for achieving a sustainable environmental future. First, the MMQR results reveal that the SE emerged as a major driver of ecological deterioration, primarily due to unregulated activities that evade environmental compliance. Consistent with Institutional Theory, this highlights the need for institutional reforms that expand the state's regulatory capacity and formalize informal economic activities. Rather than merely "reducing informality, governments should focus on institutionally coherent mechanisms such as simplified registration processes, tax incentives for compliance, and digital governance systems that make formalization economically rational. From a Laffer Curve perspective, formalization broadens the tax base and creates fiscal space for green investment without imposing excessive burdens on firms. Italy's "Electronic Invoice System," for instance, demonstrates how fiscal transparency and digital monitoring can simultaneously reduce informality and environmental externalities. Second, Institutional quality plays a decisive role in environmental governance, as confirmed by the MMQR results, which show a significant negative relationship between IQ and EFP across middle and higher quantiles. Rooted in "Institutional Theory", strong and transparent institutions enhance rule enforcement, reduce corruption, and ensure consistent policy implementation. G7 countries should strengthen institutional capacity through bureaucratic modernization, judicial independence, and participatory policy frameworks. These measures not only improve environmental outcomes but also enhance them. Third, the transition toward RES should be framed through the Porter Hypothesis, which posits that stringent, well-designed environmental regulations drive innovation and competitiveness. The MMQR findings indicate that RES consistently reduces ecological pressure across quantiles, confirming its critical role in sustainable transformation. Policymakers should therefore provide predictable regulatory frameworks, innovation incentives, and carbon pricing mechanisms that encourage firms to adopt cleaner technologies. For instance, France's low-emission nuclear energy strategy and Germany's expansion of wind and solar energy illustrate how regulatory certainty, when paired with technological innovation, yields both economic and environmental benefits. Finally, drawing on the synergy between the EKC and Porter frameworks, green innovation should be seen as an engine of growth rather than a constraint. Integrating sustainability metrics into industrial and energy strategies will enable G7 economies to scale up green investments while maintaining competitiveness. This entails promoting hydrogen energy, offshore wind systems, and smart grid infrastructure through public–private partnerships and green finance instruments such as sustainability-linked bonds. Such initiatives can accelerate the decoupling of economic activity from environmental degradation, enabling G7 nations to reach their EKC "turning point" earlier and maintain long-term ecological balance.

5.3 Limitations and future study suggestions

Despite rigorous analysis, this study is subject to several limitations. First, the empirical findings are based on data from G-7 countries, using a time frame restricted to 1996–2020.

Consequently, the conclusions may not be generalizable to other regions, particularly to emerging or less developed economies. Second, the measurement of the shadow economy introduces potential biases. This study employs the Multiple Indicators Multiple Causes (MIMIC) model as a proxy to estimate the shadow economy. While widely used, this method involves several assumptions and complexities, which can result in either underestimation or overestimation. The latent nature of the shadow economy makes it inherently difficult to quantify with precision. Thus, future research should consider integrating alternative estimation techniques or composite indices, along with cross-validation across different datasets, to improve robustness and accuracy. Third, while this study investigates the influence of institutional quality (IQ) on environmental performance (EFP), it does not isolate the individual effects of specific IQ dimensions. Further research could dissect which components of institutional quality (e.g., rule of law, regulatory quality, control of corruption) have the strongest influence on EFP, enabling a more granular and policy-relevant understanding of their impact. Fourth, the present research used Method of Moments Quantile Regression estimation technique which effectively captures heterogeneous effects across the conditional distribution but does not account for short-run dynamics. To overcome this limitation, future studies should consider advanced econometric models such as the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) and the Pooled Mean Group ARDL (PMG-ARDL), which facilitate the analysis of both short- and long-run relationships. Finally, to strengthen the external validity of the results, future research should apply the model to other economic blocs such as BRICS, MENA, OECD, EU, E-7, and G-20. Additionally, comparative studies between developed and developing economies would provide deeper insights into structural and institutional differences and their implications for environmental performance.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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Authors and Affiliations

Maria Shabir[1] · **Asif Javed**[2] · **Muhammad Aqib Khursheed**[3] · **Shabbir Ahmad**[4] · **Saif Ullah**[5]

✉ Asif Javed
asif.javed@unich.it

Maria Shabir
mshabir@ogs.it

Muhammad Aqib Khursheed
muhammad.khursheed@unich.it

Shabbir Ahmad
s.ahmad@uq.edu.au

Saif Ullah
sullah.ms18igis@igis.nust.edu.pk

[1] National Institute of Oceanography and Applied Geophysics - OGS , Trieste The Laboratory on Quantitative Sustainability, Trieste, Italy

[2] Dipartimento di Economia, Universita degli Studi Gabriele d' Annunzio Chieti Pescara, Pescara, Italy

[3] Department of Business Economics , University of Gabriele d'Annunzio Chieti Pescara, Pescara, Italy

[4] The University of Queensland, Brisbane, Australia

[5] National University of Sciences and Technology, Islamabad, Pakistan