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Factors affecting ecological footprint in Saudi Arabia: a panel data analysis

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The global environment has witnessed an increase in environmental risks over the last few decades due to the rising demand for energy to support economic development and urbanization. These environmental risks are exacerbated by the escalating human activity that depletes natural resources. Therefore, analyzing factors affecting Ecological Footprint (EFP), which include many variables such as urbanization, energy consumption, natural resources, economic growth, and technological innovation, is essential to achieve sustainable development. Urbanization is a key driver of economic growth. Achieving economic development requires the utilization of natural resources and energy which increase the EFP. Therefore, the focus on technological innovation is essential to reduce the EFP. Despite the critical environmental and economic implications of factors affecting EFP, studies on this area are lacking, especially across Middle Eastern countries, and present contradictory findings. Therefore, the main aim of this study is to investigate the effect of urbanization, energy consumption, natural resources, economic growth, and technological innovation on the EFP in Saudi Arabia. To this end, the study utilizes an autoregressive distributed lag (ARDL) model, which is considered the most suitable econometric approach when variables are stationary at I (0) or integrated of order I (1), based on data collected from various international sources for the period spanning from 1990 to 2022. In both the long run and the short run, empirical findings show that urbanization, natural resources, and technological innovation decrease the EFP, while energy consumption and economic growth increase the EFP. These results reveal that energy policies need to be addressed, and economic growth is unable to lower the EFP due to a lack of connection between economic policies and environmental goals. On the other hand, the study shows that urban policies and the management of natural resources are effectively linked to environmental goals. These findings have several significant policy implications for reducing the EFP. Suggestions include effectively linking economic policies to environmental goals by electrifying the economy. Additionally, several procedures should be considered, including replacing current carbon-based energy with renewable sources, reevaluating the pricing of the energy system, increasing taxes on carbon-based energy, and reassessing current energy laws and regulations.

KEYWORDS

ecological footprint, energy consumption, natural resources, urbanization, economic growth, technological innovation

1 Introduction

Environmental hazards have become the most significant challenge that hinders sustainable development globally. The increase in urbanization, economic expansion, and energy consumption is a key factor in environmental degradation. Urbanization is one of the major engines for economic development (Alnsour, 2014; Alnsour, 2016). Enhancing economic development requires the utilization of natural resources and energy, especially the extensive use of fossil fuels, which results in environmental degradation. As the process of urbanization continues, economic specialization will increase, leading to higher energy consumption and greater utilization of natural resources (Aldegheishem, 2023a; Aldegheishem, 2023b). Therefore, the increase in energy use is equivalent to an increase in the EFP, degrading environmental quality. Consequently, the protection of the environment requires assessing factors affecting EFP, including urbanization, energy use, economic development, natural resources, and technological innovation. However, the impact of these factors on the EFP remains unclear due to their variability across countries and the diversity of econometric models utilized to evaluate these relationships. Generally, many studies that have examined the impact of various factors on the EFP (e.g., Zhao et al., 2014; Sebri, 2016; Feng et al., 2017; Bello et al., 2018; Rashid et al., 2018; Nathaniel and Khan, 2020; Gupta et al., 2022; Sahoo and Sethi, 2022) have revealed that environmental degradation is continuing to increase worldwide.

Research on this topic in the context of the Middle East is lacking. Therefore, this paper extends previous literature by focusing on various factors, such as urbanization, energy use, economic growth, natural resources, and technological innovation that impact the EFP, targeting Saudi Arabia as one of the largest countries in the Middle East in terms of economic capabilities and geographic area. The study addresses the following major question: To what extent do urbanization, energy consumption, natural resources, economic growth, and technological innovation impact the EFP in Saudi Arabia? We selected Saudi Arabia for several reasons. Firstly, Saudi Arabia is the largest oil producer globally and holds the world's largest oil reserves (Kahouli et al., 2022). It ranks 4th globally in primary energy production, with 30 quadrillion Btu (U.S. Energy Information Administration (EIA), 2022). Furthermore, Saudi Arabia is one of the largest consumers of oil globally, ranking 5th in petroleum and other liquids consumption, consuming 3,649 thousand barrels per day (EIA, 2022). The country ranks 10th globally in terms of CO_2 emissions, and the energy sector is responsible for approximately 82.2% of these emissions (Samargandi, 2017; Kahia et al., 2021). Secondly, Saudi Arabia has implemented numerous initiatives aimed at environmental protection, reducing energy consumption over the next 2 decades, diversifying away from oil, and fostering the development of non-oil sectors (Aldegheishem, 2023a). During the COP21 conference in Paris, the Saudi government explored the potential elimination of fossil fuel subsidies and proposed implementing conditions such as a carbon tax in various provinces for several reasons (Samargandi, 2017). Thirdly, Saudi Arabia boasts the largest ICT market in the Middle East region (Kahouli et al., 2022). The Saudi government aims to develop advanced digital infrastructure and attract foreign investment to improve energy efficiency through clean technologies (Kahouli et al., 2022).

This topic is tremendously important for Saudi Arabia, where rapid urbanization and substantial economic development have accelerated the demand for natural resources. In 2022, Saudi Arabia's urbanization rate reached 84%, with a GDP of 1.11 trillion USD (World Bank, 2022). Recent studies (e.g., Raggad, 2018; Amer et al., 2022) indicate that economic development in Saudi Arabia is primarily reliant on fossil fuels, resulting in environmental degradation. The recent Environmental Performance Index (2022) has ranked Saudi Arabia 99th out of 180 countries in the air quality indicator. The greenhouse gas emissions (Mt CO_2eq/yr) in Saudi Arabia rose from 466.494 in 2005 to 810.512 in 2022 (Crippa et al., 2023). According to the Global Footprint Network (GFN) (2022), the EFP of Saudi Arabia is 5.7 global hectares per person, while the biocapacity in Saudi Arabia is only 0.7 global hectares per person. Sustainable development requires an EFP lower than the biocapacity; however, Saudi Arabia encountered an ecological deficit of 5% in 2022. Such an ecological deficit implies that the supply of services and goods provided by the ecosystem is lower than the demand for them. Despite the importance of this topic for Saudi Arabia due to Vision 2030's aim to achieve efficient use of natural resources, there is a significant lack of studies on the determinants of EFP. Investigating the impacts of urbanization, economic growth, energy consumption, natural resources, and technological innovation on the EFP in Saudi Arabia is essential to address challenges that contribute to environmental degradation.

This research contributes to the literature on environmental economics and energy in several ways. Firstly, it sheds light on the connection between urbanization, economic growth, energy consumption, natural resources, technological innovation, and the EFP in Saudi Arabia. This is significant considering that the country's economy heavily relies on energy and the implementation of various environmental standards. In this context, a body of literature from Saudi Arabia has predominantly examined the effects of economic growth, energy use, and energy prices on carbon emissions (e.g., Alkhathlan and Javid, 2015; Alshehry and Belloumi, 2015; Raggad, 2018; Alkhateeb et al., 2020; Agboola et al., 2021). Meanwhile, other studies have investigated the impact of renewable energy on environmental quality (Tlili, 2015; Kahia et al., 2021). However, these studies often fail to explain the connections that drive the interaction between different factors affecting environmental quality. Studies on the determinants of EFP are extremely scarce, despite the topic's significance for Saudi Arabia. In order to close this gap, this study examines the dynamic relationships between urbanization, economic growth, energy consumption, natural resources, technological innovation, and the EFP in Saudi Arabia for the period from 1990 to 2022. Secondly, unlike previous literature that focused on the CO_2 indicator, this study uses the EFP as a novel indicator of environmental quality. In Saudi Arabia, no previous study has integrated the variables used in this study, highlighting the significance of our empirical study in analyzing factors that have not been investigated before. Hence, this study addresses this gap, providing new valuable insights for the literature and policymakers. Additionally, the study utilizes the ARDL model, in which the causal relationships between indicators can be determined for both the long run and the short run. Finally, the study provides valuable insights for addressing environmental challenges and the difficulties related to the efficient utilization of natural resources and energy in Saudi Arabia, offering implications for relevant policy issues.

2 Literature review

It is well-established that there is an interaction between human beings, the environment, and the place. The increase in human activity is an unavoidable phenomenon that directly or indirectly causes environmental hazards and climate change (Magazzino, 2024). Assessing the influence of human activity on natural processes requires the use of footprint techniques, including ecological, environmental, carbon, nitrogen, land, and water footprints.

The EFP, as a comprehensive measure for assessing environmental sustainability and the impact of human activities, was introduced by Rees and Wackernagel (1996). It consists of six bio-productive land use classifications, including carbon footprint, grazing land, fishing grounds, cropland, forestland, and built-up land (GFN, 2023). Researchers such as Zafar et al. (2019), Ulucak and Bilgili (2018), Destek and Sinha (2020), Solarin et al. (2019), and Bello et al. (2018) have considered the EFP as a proxy for environmental quality. The EFP estimates the number of natural resources used by a population and the amount of pollution produced (Kongbuamai et al., 2021). In this way, the EFP serves as a measure of environmental sustainability and resource management. Therefore, it is utilized as a dependent variable in this study to assess environmental quality.

Literature shows several factors affecting the EFP, such as urbanization, energy consumption, economic growth, natural resources, and technological innovation. Urbanization is a significant driver of increased demand for natural resources, leading to environmental challenges. However, the literature provides contradictory findings. Studies conducted by Al-Mulali and Ozturk (2015), Danish and Wang (2019), Ahmed et al. (2020), and Nathaniel et al. (2020) illustrate that the EFP increases with urbanization, resulting in environmental challenges such as air pollution, soil pollution, water pollution, CO_2 emissions, and biodiversity reduction. On the other hand, empirical studies by Yang and Khan (2022), Ullah et al. (2023), Long et al. (2017), Nathaniel and Khan (2020), Nathaniel et al. (2020), Yasin et al. (2020), Ulucak and Khan (2020), and Arnaut and Dada (2023) have demonstrated that urbanization leads to a decrease in the EFP. They argue that urbanization correlates with increased purchasing power among urban residents, potentially driving demand for clean technologies and more optimal utilization of natural resources. The literature shows that urbanization can have either a positive or negative impact on the EFP. The consumption patterns of natural resources and clean technologies contribute to determining the relationship between urbanization and the EFP. This argument raises the question of whether the EFP is affected by factors other than clean technologies, such as the amount of natural resources and urbanization rates, which vary from country to country. Saudi Arabia has experienced a high rate of urbanization and possesses abundant natural resources.

Energy is a crucial input for economic development. The literature has extensively examined the relationship between the use of energy, whether renewable or non-renewable, and environmental degradation. Nathaniel and Khan (2020) demonstrated that non-renewable energy consumption increases the EFP, while renewable energy consumption reduces the EFP in ASEAN countries. Kahouli et al. (2022) stated that green energy (renewable energy and electric power consumption), among other factors, is negatively associated with the EFP in the long run in Saudi Arabia. Alola et al. (2019) highlighted that both nonrenewable energy and economic growth increase environmental degradation in 16 European countries in the long run, while renewable energy decreases ecological deterioration. Dogan et al. (2020) established that economic growth and renewable energy reduce environmental degradation in 28 OECD countries during the period 1990–2014. Similarly, Bashir et al. (2023) found that coal energy and economic growth increase the EFP in the long run and short run, while geothermal energy and technological innovation lower the EFP in the long run and short run in newly industrialized countries for the period 1990–2018. Can and Gozgor (2017) emphasized that energy consumption stimulates CO_2 emissions in France. Likewise, Destek and Sinha (2020) examined 24 OECD countries and concluded that renewable energy has a positive effect on the environment, while nonrenewable energy leads to environmental degradation through increased the EFP. A recent study by Arnaut and Dada (2023) on the United Arab Emirates demonstrated that both non-renewable energy consumption and economic growth stimulate the EFP in both the long run and the short run, while renewable energy reduces the EFP. As a result, energy use is a major driver of economic growth; however, its excessive use leads to environmental degradation. Energy consumption plays a crucial role in the relationship between economic growth and EFP. Increased energy demand for economic development leads to higher environmental degradation. Thus, it is important to examine the relationship between energy consumption, which is assessed in our empirical work by total primary energy consumption, and its effect on the EFP in Saudi Arabia.

The roots of the relationship between economic growth and environmental degradation refer to the Environmental Kuznets Curve (EKC) developed by Grossman et al. (1995). The EKC hypothesis suggests that the relationship between income and environmental degradation can be represented by an inverted U-shaped curve. Despite the EKC being widely used by economists, it has been criticized by other fields studying global climate change (Stern, 2017). However, the literature on the EKC hypothesis shows disagreement. For example, researchers such as Adzawla et al. (2019), Kasperowicz (2015), and Arouri et al. (2012) have confirmed it, while others such as Demissew and Kotosz (2020), Aye and Edoja (2017), Raggad (2018), and Abid (2016) have not confirmed it. This variability aligns with the perspective of Satterthwaite (2008), who argues that environmental challenges are contingent upon economic capabilities and can differ significantly across various regions. A significant body of literature has explored the relationship between economic growth and the EFP. Addai et al. (2022) highlighted a long-run, unidirectional causal relationship between economic growth and the EFP in Eastern Europe for the period 1998–2017. Çakmak and Acar (2022) emphasized that economic growth is positively and significantly linked to EFP in oil-producing countries such as Saudi Arabia, Russia, the United States, Kuwait, Canada, Nigeria, China, and Brazil during the period 1999–2017. Similarly, Eregha et al. (2023) found that economic growth stimulates the EFP in the Next-11 countries. Ikram et al. (2021) concluded that there is a bidirectional causal relationship between economic growth and the EFP in Japan in both the short run and long run. A more recent study by Ritu and Kaur (2024) on India for the period 1997–2020 revealed that economic growth is positively associated with EFP in the long run. Another study by Magazzino (2024) on China for the period 1960–2019 showed that economic growth increases the EFP. A study conducted recently by Neifar et al. (2023) in Morocco for the period 1980–2021 showed that economic growth increases the EFP. In conclusion, the varied outcomes observed in studies conducted in countries with diverse geographical and socio-economic characteristics highlight the intricate relationship between economic growth and the EFP. These findings suggest that economic growth can have both positive and negative impacts on the EFP, highlighting the need to analyze the relationship between economic growth and the EFP in Saudi Arabia. Despite Saudi Arabia experiencing strong economic growth with a GDP of 1.11 trillion USD (WDI, 2023), the total CO_2 emissions were estimated at 14.26 metric tons *per capita* in 2020 (WDI, 2023), indicating the existence of environmental challenges. Therefore, it is important to assess the relationship between economic growth and environmental quality to address related policy issues.

Natural resources are another factor affecting the EFP. According to Zhao et al. (2014), the mining and depletion of natural resources lead to environmental degradation and influence ecological systems by diminishing environmental quality, producing various types of pollution, desertification, landscape degradation, and climate change. The literature on the relationship between natural resources and the EFP shows disagreement. Hassan et al. (2019) found that natural resources increase the EFP in Pakistan. Zafar et al. (2019) found a unidirectional causal relationship between natural resources and the EFP in the United States for the period 1970–2015. Ahmed et al. (2020) found that natural resource rent increases the EFP in the long run in China. Ahmed et al. (2020) concluded that natural resources increase the EFP in the long run in 22 emerging economies for the period 1984–2016. On the contrary, other studies have shown that natural resources have a negative impact on the EFP. Danish and Khan (2022) highlighted that natural resource rent decreases the EFP in BRICS economies for the period from 1992 to 2016. The same results were confirmed by Nathaniel et al. (2021) for the same countries. Amer et al. (2022) found a negative connection between natural resources and the EFP in GCC countries for the period from 1995 to 2017. Khan et al. (2022) found that natural resources improve the environmental quality for the selected Organization for Economic Co-operation and Development (OECD) countries during the period 1990–2015. As a result, a significant debate surrounds the impact of natural resources on the EFP. Studies on the relationship between natural resources and the EFP are very limited in the context of Saudi Arabia, which motivates us to investigate this relationship further.

Many studies have evaluated the role of technological innovation in mitigating the EFP. Javed et al. (2023) assessed the impact of green technology innovation, among other variables, on the EFP in Italy for the period 1994–2019. The study found that green technology innovation improves the quality of the environment by reducing the EFP. Raza et al. (2023) found that technological innovation is negatively and significantly linked to the EFP in the long run for G20 countries during the period 1990–2021. Kayacan and Erkut (2023) explored the association between technological innovation and the EFP for the Mediterranean countries, including Jordan, Israel, Bosnia and Herzegovina, Spain, Italy, Türkiye, France, Portugal, Morocco, Greece, and Tunisia, for the period 1992–2020. The study revealed that the impact of technological innovation on the EFP is insignificant in the Mediterranean countries except for Portugal, where the effect was significant and positive. Rout et al. (2022) concluded that technological innovation and renewable energy improved environmental sustainability significantly in BRICS countries for the period 1990–2018. Chu (2022) endorsed a long run cointegration between green technologies and the EFP for 20 OECD countries from 1990 to 2015; Appiah et al. (2023) found the same results for OECD countries. Ahmad et al. (2021) established that eco-innovation lowers the EFP in the G7 countries for the period 1980–2016. Kongbuamai et al. (2023) proved empirically that communication technology decreases the EFP for the Next-11 (N-11) countries for the period 1992–2015. In conclusion, the literature demonstrates that technological innovation is the most effective approach to addressing a wide range of environmental issues. The technological advancement increases energy efficiency, which, in turn, fosters greater investment in environmentally friendly technologies. The above literature prompts us to examine the relationship between technological innovation and the EFP in Saudi Arabia.

In conclusion, the existing literature on the relationship between urbanization, energy consumption, natural resources, economic growth, technological innovation, and the EFP is inconsistent. The findings are contradictory, indicating that the level of impact may differ not only among countries but also over different time periods. Several studies demonstrate that this contradiction is related to data and methodologies. Another body of literature highlights that the relationship between urbanization, energy consumption, natural resources, economic growth, technological innovation, and the EFP is complex. However, the primary gap in the literature is the failure to consider all these variables collectively. Providing new empirical insights enhances the existing literature. In general, studies on this topic in the context of Saudi Arabia are very limited. Therefore, this study is the first attempt to investigate these factors together in Saudi Arabia. Additionally, we have created Table 1 to present additional studies that focus on the EFP from various perspectives.

3 Data and methods

Data was collected from various international sources, including the World Bank, World Development Indicators (WDI), the GFN, and the EIA. The data covers the period from 1990 to 2022. Table 2 presents the dependent variable, which is the EFP, and independent variables of the study. The measurement of variables is determined by the aforementioned international organizations, as indicated in Table 2. For example, the EFP is measured in global hectares *per capita* (gha/person) based on the GFN. This research builds on the studies conducted by Ulucak and Khan (2020), Danish and Khan. (2022), Khan et al. (2023), Nathaniel et al. (2020), and Eregha et al.

TABLE 1 Recent studies on EFP.

Author	Period	Variables	Method	Results
Guliyev (2024)	1992–2020	Biocapacity; energy consumption; industrialization; financial development globalization; life expectancy; EFP	BMA	Biocapacity, energy consumption, financial development, globalization, industrialization increase EFP in the long run while life expectancy reduces
Bekhet and Othman (2018)	1971–2015	Renewable energy; GDP; and environmental quality	ARDL	The renewable energy improves environmental quality, while GDP pertains to nurture the environment
Sharif et al. (2020)	1965Q1–2017Q4	Energy consumption; renewable energy; GDP; and Ecological footprint	QARDL	There is long-run relationship between the variables
Koengkan et al. (2021)	1990–2016	GDP; energy consumption; renewable energy; and air pollution	Quantile Regression	GDP and energy use increase air pollution, while renewable energy reduces it
Dam et al. (2024)	1992–2018	Technological innovation and EFP	PMG-ARDL	Technological innovation reduces EFP in E-7 countries
Wang et al. (2020)	1998–2014	Urbanization and air pollution	DOLS	The effect of urbanization depends on income panel of the economy
Danish and Khan (2022)	1992–2016	GDP; renewable energy; urbanization; and EFP	FmOLS DOLS	Renewable energy, natural resource, and urbanization increase the EFP
Andersson (2024)	1962–2021	Income inequality; wealth inequality; GDP; urbanization; agriculture; and EFP	OLS-ARDL	Economic inequality's impact on the environment in France, Netherlands, the United States, and the United Kingdom
Luo et al. (2021)	1999–2016	Urbanization and air pollution	FMOLS DOLS	Urbanization has positive influence on air pollution varying cities to cities
Li et al. (2015)	2009–2014	Urbanization; GDP; and air pollution	OLS and 2SLS	GDP has a negative effect where urbanization has a positive effect on air pollution

TABLE 2 Study variables.

Variable	Measurement	Source
Dependent variable		
EFP	EFP *per capita* as global hectares (gha/person)	GFN
Independent variables		
Urbanization (URB)	Urban population (% of total population)	WDI
Energy consumption (EC)	Total primary energy consumption (quadrillion Btu)	EIA
Economic growth (GDP)	GDP (constant 2015 US$)	WDI
Natural resources (NR)	Total natural resources rents (% of GDP)	WDI
Technological innovation (TECH)	Patent application, Residents	WDI

(2023) regarding the adoption of variables. Additionally, the selection of variables is based on several gaps mentioned earlier in the introduction and literature sections that need to be addressed.

The fundamental goal of this study is to investigate the effects of urbanization, energy consumption, economic growth, natural resources, and technological innovation on the EFP in Saudi Arabia. Following Narayan and Narayan (2010), the general formula of the model can be written as:

$$EFP_{2t} = f\ (GDP_t, EC_t, URB_t, TECH_t, NR_t) \tag{1}$$

The specification of the model is based on the previous studies (Nathaniel et al., 2020; Ulucak and Khan, 2020; Danish and Khan, 2022; Eregha et al., 2023; Khan et al., 2023). Hence, we can express the model using natural logarithms as follows:

$$\ln EF_t = Y_0 + Y_1 \ln GDP_t + Y_2 \ln EC_t + Y_3 \ln URB_t + Y_4 \ln TECH_t + Y_5 \ln NR_t + +e_t \tag{2}$$

Where t proxies for the time period from 1990 to 2022, e_{it} is the error term, and $Y_0 \ldots\ldots Y_5$ represents the log-run coefficients of variables used in this study.

The study applies an autoregressive distributed lag (ARDL) bound test provided by Pesaran et al. (2001) to determine the causal relationships of EFP with all independent variables. The ARDL model is the most suitable approach for this study. It is considered the best econometric approach when variables are stationary at I (0) or integrated of order I (1) (Pesaran et al., 2001). It provides realistic and efficient estimates, particularly in capturing both short-term and long-term effects of independent variables (Pesaran et al., 2001; Gupta et al., 2022; Alper et al., 2023;

TABLE 3 Description of study variables.

Variables	Mean	Minimum	Maximum	Standard deviation
EFP	4.56	2.4	6.9	1.341
URB	81.5	76.58	84.72	1.97
EC	7.295	3.342	12.269	2.999
GDP	20,960.66	13,249.18	35,689.59	6,034.782
NR	35.35	17.31	55.02	10.23
TECH	323.75	16.00	1,294	419.256

Andersson, 2024), aligning closely with the study's objectives. Many studies have utilized an ARDL model to investigate the influence of different factors on the EFP (e.g., Bekhet and Othman, 2018; Alola et al., 2019; Sharif et al., 2020; Gupta et al., 2022; Alper et al., 2023; Andersson, 2024). Thus, we first use the Augmented Dickey-Fuller (ADF) test and the Phillips-Perron (PP) test to assess the stationary of the variables. To estimate the long-term and short-term associations between study variables, the ARDL model shows these causal relationships using ordinary least squares (OLS) (Pesaran et al., 2001). Specifying cointegration between variables can be estimated using OLS, a conditional, unrestricted error correction model. Hence, the third formula, which is based on Pesaran et al.'s (2001), for the ARDL model becomes as follows:

$$Y_t = \gamma^{oi} + \sum\nolimits_{(i=1)}^{P} \delta_i \, \mathrm{Y}_{t\text{-}I} + \sum\nolimits_{(i=0)}^{q} \beta_i \, \mathrm{X}_{t\text{-}I} + \mathrm{e}_{it} \tag{3}$$

Where Y_t is a vector and the variables in (X_t) refers to I (0) (i.e., lower bound) and I (1) (i.e., upper bound), β and δ are proxies for coefficients; γ denotes the constant, I = 1, . . ., k; p and q are proxies for optimal lag orders; e_{it} represents error term.

Regarding I (0) (i.e., lower bound) and I (1) (i.e., upper bound) when the calculated F value exceeds the upper critical bound, this means that the variables are cointegrated, while if the F value is less than the lower critical bound, this means there is no cointegration between the variables. If the F value ranges between the upper and lower critical bounds, the results are inconclusive.

According to Pesaran et al. (2001), if there is cointegration, the ARDL model can be formulated as shown in the fourth formula.

$$Y_i = \gamma^{oi} + \sum\nolimits_{(i=1)}^{P} \delta_i \, \mathrm{Y}_{t\text{-}I} + \sum\nolimits_{(i=1)}^{P} \beta_i \, \mathrm{X}_{t\text{-}I} + \lambda \mathrm{ECT}_{i_{=1}} + \mathrm{e}_{it} \tag{4}$$

Finally, stationary is checked using diagnostic tests such as normality, heteroscedasticity, functional form, and serial correlation. The CUSUM estimator and the CUSUMSQ estimator were used to evaluate model stability.

4 Empirical results and discussion

According to Table 3, the mean of the EFP is relatively high at 4.56, and the EFP increased significantly from 2.4 to 6.9 over the last 3 decades. Figure 1 shows that the highest increase in EFP *per capita* (6.9) occurred in 2015, with this average decreasing to 5.7 in 2022, indicating a positive change in EFP relatively. The urbanization rate has increased significantly from 76.5% in 1990 to 84.7% in 2022. The availability of services, increased business activities, and employment growth in urban areas have contributed to the increasing rate of urbanization. However, the increase in urbanization rate has been associated with a rise in the GDP *per capita* (constant 2015 US$), which amounted to $20960.66 for the period 1990–2022, as depicted in Table 3. Figure 1 shows that the lowest GDP *per capita* was $17018 in 2000, and the highest was $21068 in 2022. Generally, the GDP *per capita* tends to be higher compared to many countries, especially in the Middle East. According to Table 3, the average total primary energy consumption during the study period was 7.295 quadrillion Btu. Figure 1 shows that the average rose from 3.340 quadrillion Btu in 1990 to 9.859 in 2010, and to 9.175 quadrillion Btu in 2021, increasing fourfold between 1990 and 2022. The descriptive statistics in Table 3 show that the natural resource rents account for 35.35% of GDP, which is relatively high. However, Figure 1 shows that this indicator is trending downward positively, as it decreased from 47.20% in 1990 to 25.56% in 2022, highlighting the effectiveness of policies in utilizing resources efficiently. Technical innovation has increased significantly, with the number of patents rising from 16 in 1990 to 1,294 in 2020, highlighting the progress of the technological sector. Finally, Table 3 also demonstrates low standard deviations for the mean values, suggesting that the means are representative in this study.

4.1 Results from unit root analysis

The study examines the stationary of variables by employing unit root analysis. Table 4 presents the ADF test and the PP test, which show that the EFP, urbanization, energy consumption, economic growth, natural resources, and technological innovation are all stationary at first difference, but they are all non-stationary at level. These results indicate that we can employ further empirical analysis for the ARDL model to determine the long-run and short-run causal relationships for study variables.

4.2 Results from cointegration analysis

To compute the long-run relationships of study variables, the F value should be estimated. A fit model should have a large F value (greater than one, at least). Table 5 shows that the F value is 10.67 based on the bounds test, which is significant ($p < 0.01$). The results show existing cointegration between the EFP, urbanization, energy consumption, economic growth, natural resources, and technological innovation at a significance level of 1%.

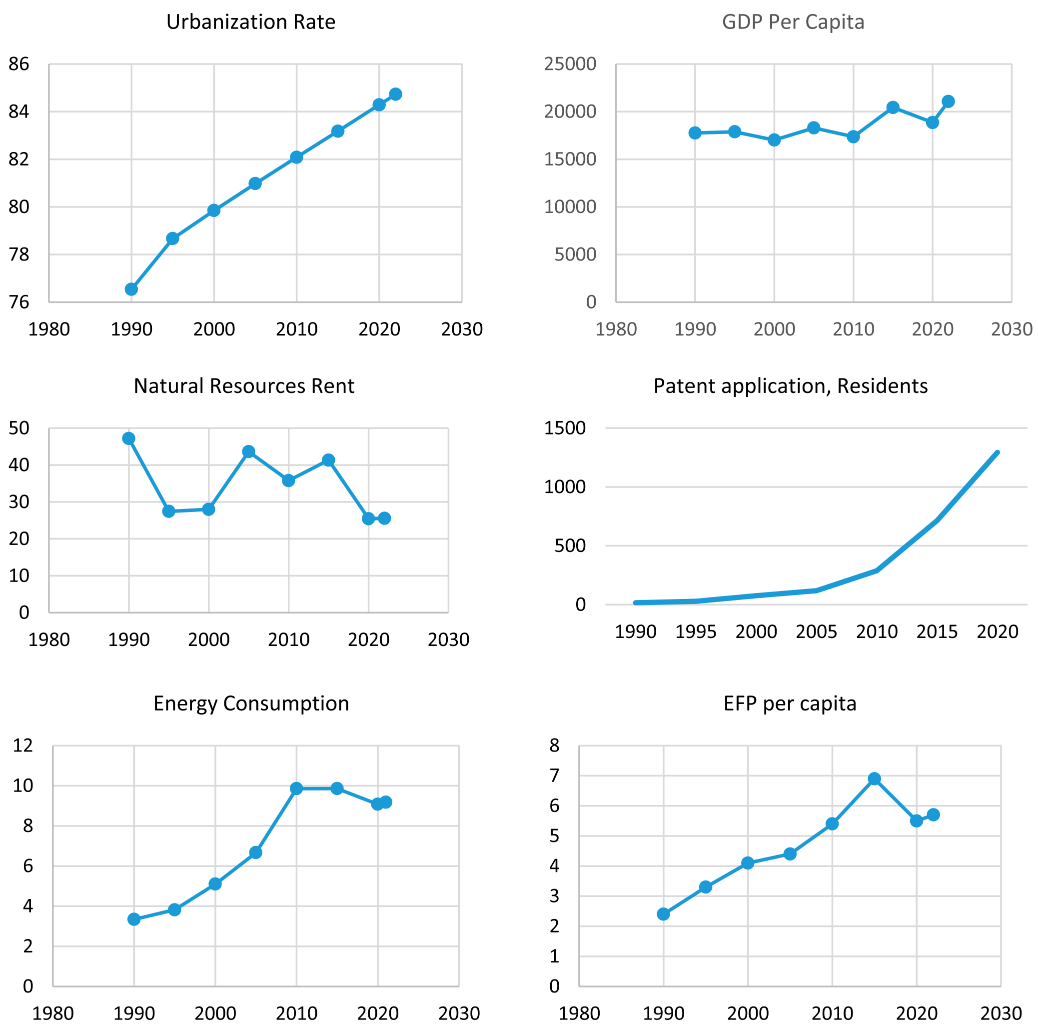

FIGURE 1
Study variables from 1990 to 2022.

TABLE 4 Results of stationary.

	ADF	PP	ADF	PP
	Level		First Difference	
LnEPI	−2.824	−2.824	−6.815**	−7.241**
LnURB	−1.694	−1.435	−4.491**	−5.442**
LnEC	−2.571	−1.562	−6.315**	−8.734**
LnGDP	−1.766	−1.282	−5.713**	−6.527**
LnNR	−1.652	−1.427	−5.120**	−7.253**
LnTECH	−1.742	−1.232	−7.658**	−9.856**

**Significant level is 0.05.

The ARDL model estimates the long-run and short-run relationships among the variables of study, as shown in Table 6. The statistical indicators in Table 5 confirm that the model is fit and stable. The findings reveal that all independent variables are significantly linked to the EFP in both the long run and the short run.

TABLE 5 ARDL-bound test.

$CO_{2t} = f\ (AT_t, TO_t, GDP_t)$		
F value 10.67		
Critical value bounds		
Sig	Lower bounds	Upper bounds
1%	2.786	4.045
5%	3.475	5.214
10%	4.815	7.851

Empirical results show that urbanization has a negative and statistically significant impact on the EFP. An increase of 1% in urbanization decreases the EFP by −0.112% in the long run and −0.298% in the short run. Urbanization plays a vital role

TABLE 6 Long run and short run elasticities.

Variables	Coefficients	Std. error	t statistic	Prob
Long-run coefficients				
URB	−0.112	0.032	−3.500	0.006
EC	0.146	0.028	5.214	0.000
GDP	0.277	0.091	3.043	0.008
NR	−0.286	0.078	−3.666	0.004
TECH	−0.178	0.042	−4.238	0.002
C	−0.395	0.084	−4.702	0.001
Short-run coefficients				
ΔLEFP (−1)	0.248	0.101	2.455	0.002
ΔL URB	−0.298	0.064	−4.655	0.001
ΔL EC	0.421	0.108	3.898	0.001
ΔL GDP	0.564	0.157	3.592	0.005
ΔL NR	−0.514	0.148	−3.472	0.002
ΔL TECH	−0.412	0.128	−3.218	0.006
ECM (−1)	−0.768	0.119	−6.453	0.000
Diagnostic tests				
Functional form		0.82 (0.44)		
Serial correlation		2.74 (0.03)		
Heteroscedasticity		0.77 (0.56)		
Normality		3.75 (0.12)		

in driving resource demand both directly, through spatial expansion, and indirectly, by affecting lifestyle options such as urban smartness. Cities of Saudi Arabia have been growing and shifting into smart cities such as Riyadh which was ranked 30th out of 148 worldwide cities (World Competitiveness Center, 2023), demonstrating how the improvement in urban policies can reduce EFP. The smart cities initiatives in cities such as Mecca, Madinah, and Jeddah have helped mitigate residents' EFP without mitigation in quality of life. On the other hand, it is evident that Saudi Arabia's urbanization has associated with socio-economic benefits like investment in infrastructure, education, health, and technology, which contribute to reducing the EFP. Furthermore, urbanization raises people's awareness of public health and the environment (Kahn and Schwartz, 2008). The results imply that urban policies are efficiently connected to environmental policies. Our empirical results are in accordance with many recent studies that confirmed that urbanization decreases the EFP, such as a study by Ullah et al. (2023) for Türkiye, Khan et al. (2023) for India, Quito et al. (2023) for 107 countries worldwide, Nathaniel and Khan (2020) for ASEAN countries, Nathaniel et al. (2020) for MENA countries, and Ulucak and Khan (2020) for BRICS countries.

The empirical outcomes in Table 6 show that energy consumption has a positive impact on the EFP. Under these circumstances, a 1% increase in energy consumption leads to a 0.146% increase in the EFP in the long run and a 0.421% increase in the short run. Saudi Arabia is a developing country that has been experiencing rapid economic growth over the last few decades. Saudi Arabia relies on non-renewable energy sources, especially fossil fuels, to fulfill its industrialization, transportation, and construction requirements, leading to a significant level of pollution. In addition, many industries depend on power generation, and most of the total energy used in power generation comes from non-renewable sources. Furthermore, massive smoke emissions from industrial activities have detrimental effects on the environment and also impact productive sectors like agriculture and forestry. The problem is further complicated by the decline in oil prices in the country, which encourages an increase in domestic demand for energy, as it is one of the largest oil-exporting countries in the world. The results highlight that energy policies are unable to meet the national demand for energy across cities in Saudi Arabia. The country faces an urgent imperative to recalibrate its energy portfolio, transitioning towards renewable energy sources such as solar, wind, and thermal, which help preserve the environment. Our empirical findings are aligned with many studies, such as Shahzad et al. (2021) for the United States, Arnaut and Dada (2023) for the United Arab Emirates, Rout et al. (2022) for BRICS countries, Ibrahiem and Hanafy (2020) for Egypt, Khan et al. (2023) for India, and Alper et al. (2023) for Saudi Arabia, Germany, China, and Iran.

The empirical results illustrate that economic growth has an increasing impact on the EFP. Statistical coefficients indicate that a 1% increase in GDP leads to a 0.277% increase in the EFP in the long run and a 0.564% increase in the short run. This result suggests that an increase in economic growth raises the demand for energy, leading to environmental degradation. The results demonstrate the ineffectiveness of economic policies in reducing the EFP, highlighting a weak correlation between economic policies and environmental objectives. Recently, Saudi Arabia has started diversifying its economy, leading to an increased demand for energy and natural resources. Thus, the conflict between economic development and the environment will persist during the current phase of economic transformation, as the country believes that prioritizing development inevitably compromises environmental sustainability. Currently, the income level in Saudi Arabia supports environmental sustainability. However, pressure on natural resources, accompanied by increasing demands, will exacerbate resource consumption. Consequently, EFP will intensify. The results show that economic development is a driving force of environmental degradation, and immediate policies are needed to achieve sustainability. Our empirical findings are consistent with the studies conducted by Ritu and Kaur (2024), Eregha et al. (2023), Magazzino (2024), Neifar et al. (2023), Çakmak and Acar (2022), and Danish and Khan. (2022).

The empirical findings reveal that natural resource rents have a negative and statistically significant effect on the EFP. Natural resources are improving environmental quality in the long run and in the short run by mitigating the EFP. This illustrates that a 1% increase in natural resources reduces the EFP by −0.286% in the long run and −0.514% in the short run. Saudi Arabia is endowed with a plethora of natural resources, particularly oil, which it mainly uses to generate revenues. It has been argued that an increase in population and economic activities depletes natural resources. The abundance of natural resources, such as oil, in Saudi Arabia is sufficient to meet the national demand for goods and services, contributing to mitigating the EFP. The result indicates that the practices of natural resources management are effective. Our empirical finding aligns with a study conducted by Amer et al. (2022), where it was shown that natural resource rent reduces the EFP in Saudi Arabia, the United Arab Emirates, Oman, Kuwait, Qatar, and Bahrain. The result also supports the works provided by Kongbuamai et al., 2020; Danish and Khan, 2022; Nathaniel et al., 2021; Shittu et al., 2021.

The result shows that technological innovation has a negative impact and is statistically significant on the EFP. The result shows that a 1% increase in technological innovation decreases the EFP by −0.178% in the long run and −0.412% in the short run. Technological innovation improves environmental quality and contributes to achieving sustainable development. Over the last 2 decades, Saudi Arabia has enormously spent on technological innovation to improve sustainable development and enhance quality of life. The adopted technology in Saudi Arabia has many advantages, including the achievement of strategic goals, the ability to address local and global problems, enabling the Saudi market (i.e., increasing competitiveness and productivity), and ease of use (Ministry of Environment, Water, and Agriculture, 2023). These options have facilitated green growth. Technological innovations have significantly contributed to enhancing ecosystem monitoring, grazing land management, waste management, and innovative irrigation techniques for trees and wild plants (Ministry of Environment, Water and Agriculture, 2023). For instance, the National Center for Wildlife Development uses different techniques to monitor ecosystems, including hyperspectral imaging cameras, radio telemetry, and web-based geographic information systems (Ministry of Environment, Water, and Agriculture, 2023). Additionally, the role of research and development in the context of climate change by leading scientific institutions, including King Abdulaziz City for Science and Technology (KACST), King Fahd University of Petroleum and Minerals (KFUPM), and King Abdullah University of Science and Technology (KAUST), has also contributed to enhancing technological development and increasing production. Consequently, technological innovation reduces the EFP. Saudi Arabia is rich in non-renewable energy sources, leading to low energy prices. This finding is consistent with the empirical study conducted in Saudi Arabia by Kahouli et al. (2022), which indicates that technological innovation reduces the EFP. The finding supports the studies of Raza et al. (2023), Kongbuamai et al. (2023), Ahmad et al. (2019), and Rout et al. (2022).

5 Conclusion and policy implications

The main objective of this study was to investigate factors affecting the EFP, including urbanization, energy consumption, economic growth, natural resources, and technological innovation during the period 1990–2022. The findings reveal that urbanization, natural resources, and technological innovation reduce the EFP in both the long and short run. However, both energy consumption and economic growth increase the EFP in the long run and short run.

The study concludes that economic growth in Saudi Arabia has failed to reduce the EFP due to a mismatch between economic development policies and environmental goals. Therefore, policymakers should align economic development policies with environmental goals by decreasing dependence on energy sources, adopting clean technologies, and promoting eco-friendly practices, all while maintaining economic growth. As economic development expands day by day, it also leads to an increase in energy demand. The increase in energy demand necessitates a shift in energy consumption patterns, moving away from dependence on fossil fuel-based energy consumption towards adopting renewable energy alternatives. Hence, the electrification of the economy is one of the innovative solutions that maximize environmental and economic benefits. Despite the electrification of the economy causing losses in terms of oil revenues and taxes, the ability of citizens to save will increase. This will boost spending and enhance purchasing power, ultimately accelerating the cycle of economic growth and advancing the national economy. Additionally, the electrification of the economy will reduce costs in several sectors, including transportation, industry, tourism, and housing.

Besides transitioning to electrification in the economy, reducing the demand for non-renewable energy should also be taken into consideration. Encouraging investment in clean technologies can reduce the demand for non-renewable energy, especially in Saudi Arabia, where the climate is ideal for producing solar and wind energy. Reassessing the pricing system for energy and increasing taxes on carbon-based energy would also reduce the EFP. Given the crucial role of current energy consumption in increasing the EFP, it is necessary to reassess current energy laws and regulations.

Ultimately, the empirical findings of this study have contributed to a better understanding of the factors affecting the EFP in Saudi Arabia. These findings provide an empirical opportunity to validate the theoretical link between economic activities, environmental dynamics, and the adoption of energy solutions in Saudi Arabia. Further, this empirical study could be improved by considering other environmental indicators such as PM2.5, NO_2, and SO_2 in future studies. Furthermore, future research should encompass variables reflecting cultural activities, which harbor diverse priorities across nations, including social and political barriers. Additionally, it should consider variables associated with institutional capacity that could impact technological innovation and its repercussions on environmental sustainability. Finally, as this study is limited to a single case study, future research could expand by conducting comparative research with other countries.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.footprintnetwork.org, https://data.

worldbank.org/country/SA, https://www.eia.gov/international/analysis/country/SAU.

Author contributions

AA: Writing–original draft, Writing–review and editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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