



How Do Economic Growth, Renewable Energy Consumption, and Political Stability Affect Environmental Sustainability in the United States? Insights from a Modified Ecological Footprint Model

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Abstract

In the last century, global warming and environmental pollution issues have reached the levels that threaten humanity. Competition on economic growth is considered one of the primary causes of environmental pollution. It has increased the significance of sustainable development and renewable energy consumption. Within the scope of sustainable development, the countries with large economies bear a greater responsibility to reduce environmental pollution. This study aims to investigate the effect of economic growth, renewable energy consumption, and political stability on environmental degradation in the United States (US) for the period 1984–2017. A comprehensive econometric analysis is conducted by using the Fourier Autoregressive Distributed Lag (FARDL) test in this study. The results of the cointegration tests indicate that economic growth, renewable energy consumption, and political stability are cointegrated with the ecological footprint pressure index representing the environmental degradation. The FARDL test results reveal that economic growth increases environmental degradation, whereas renewable energy consumption and political stability mitigate environmental degradation in both the short- and long-run. This study provides policy recommendations aiming to increase renewable energy consumption and political stability within the context of sustainable development.

Keywords Sustainable development · Environmental degradation · Environmental Kuznets curve hypothesis · Renewable energy consumption · Political stability · Fourier ARDL

JEL Classification C22 · Q01 · Q20 · Q57

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Introduction

Global warming and environmental pollution are among the most important problems of today. In a previous study titled “Limits to Growth” carried out under the direction of Dennis Meadows (1972), the relationships among population, production, raw materials, agricultural products, and environmental pollution were examined, and the concerns regarding sustainability as of the year 2100 were expressed (Bardi, 2011). The sustainable development perspective, which integrates the development models and environmentalist ideology in a new approach, was introduced first in the World Conservation Strategy organized by the United Nations Environment Programme. In this strategy, the subjects of sustainable use of natural resources and conserving genetic diversity within the context of ecological sustainability for sustainable development were discussed (ADB, 2012). In the Brundtland Report (WCED, 1987) published by the United Nations World Commission on Environment and Development focusing on the subject “Our Common Future”, the sustainable development was defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs”. Based on this definition, sustainable development is defined as economic growth through rational methods that are sensitive to environmental values and do not cause waste of natural resources, by considering the rights and benefits of future generations. It is primarily based on the use of mainly clean and renewable resources (Zakari et al., 2022).

After the Industrial Revolution, the competition between countries regarding the economic growth increased the level of energy consumption which caused harmful emissions affecting environmental sustainability. Pushing environmental sustainability into the background during the economic growth process can have significant effects on sustainable development. This is why environmental sustainability is a necessity for sustainable development (Kamoun et al., 2020; Mesagan, 2022). In the present day, economic growth and energy consumption stand out as some of the most important causes of environmental degradation (Kuldasheva & Salahodjaev, 2022). Many countries are struggling for environmental sustainability. However, the most important responsibility for environmental sustainability belongs to the largest and most populous countries that emit the most harmful emissions. Considering these criteria, the US, China, and India are among the leading countries that undertake the most responsibility for environmental sustainability. As of 2021, the US, with a population of 330 million, ranks as the third most populous country, following China and India. Considered as to be one of 25 developed countries according to the Human Development Index of the United Nations (2021) and defined as a developed country by the IMF, the US, with a GDP of \$23 trillion stands as the largest economy of 2021. On the other hand, given the British Petroleum (BP) Statistical Review of World Energy report, an increase was observed in CO₂ emission in relation to economic growth in 2021. The US accounts for 15.6% of the world’s annual energy consumption, ranking second after China (25.6%). Similarly, the US has the second-highest annual CO₂ emission level, at 13.9%, following China (BP, 2022). Also, as of 2018, this country has the second-highest ecological footprint in the world (Global Footprint Network (GFN), 2022). Besides all of these, within the

context of sustainable development plans, the share of renewable energy in primary energy sources has increased over the years. The share of renewable energy sources within the primary energy sources increased from 9% (2014) to 21% (2021) (International Energy Agency, 2021). Regarding renewable energy generation, the US ranks second in wind and solar energy generation, following China. Furthermore, the US is one of the leading countries in other renewable energy sources.

In empirical studies examining the relationships between economic, financial, and political variables and environment, the CO₂ emission has been used as the environmental degradation variable in general (Al-Mulali, 2012; Saboori & Sulaiman, 2013). Besides that, in some studies, environmental degradation is represented by different greenhouse gas emissions (Hamit-Haggar, 2012), such as CH₄ and N₂O emissions (Brizga et al., 2014), and ecological footprint variables (Al-Mulali & Ozturk, 2015). However, CO₂ emission used in measuring the environmental pollution is criticized since it solely measures the level of pollution in the air but does not provide information about the condition of water and soil (Solarin, 2019). For this reason, in the literature, there is a trend toward using the data on the ecological footprint (EFP), a more comprehensive indicator, as an environmental pollution indicator instead of relying merely on CO₂ emissions (Ulucak & Apergis, 2018). Introduced first by Wackernagel and Rees (1996), EFP measures the demand of people for natural resources and consists of six subcomponents: Carbon Footprint, Fishing Grounds Footprint, Cropland Footprint, Built-up Land Footprint, Forest Products Footprint, and Grazing Land Forest Products Footprint (GFN, 2022). CO₂ emission and EFP represent the demand aspect of environmental sustainability, while the ecological capacity representing the supply dimension of the environment is neglected (Akadiri et al., 2022). Given all these disadvantages, Wang et al. (2018) suggest the use of the ecological footprint pressure index (EFPI) considering both supply (ecological capacity) and demand (ecological footprint) dimensions of the environment simultaneously. EFPI is calculated by dividing EFP by ecological capacity. In this sense, by measuring the human intervention in the environment, it evaluates the environmental degradation from a wider perspective (Wang et al., 2018; Yang et al., 2018). The course of the ecological situation is illustrated in Fig. 1 for the US.

In Fig. 1, it can be seen that EFPI was higher than the limit, which represents the ecological balance, from 1984 to 2017. Accordingly, EFPI, which was 2.214

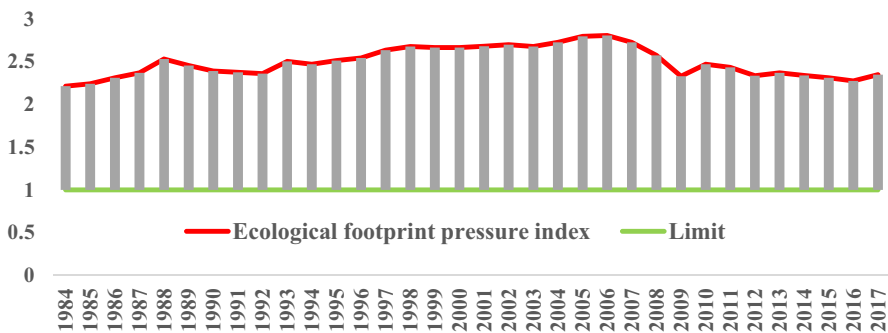


Fig. 1 Ecological situation in the US (GFN, 2022)

global hectares (gha) in the US in 1984, increased by approximately 6% in 2017 and reached the level of 2.348 gha. Moreover, the highest level of ecological pressure, 2.808 gha, was experienced in 2006. On the other hand, in order to ensure the environmental sustainability, EFPI should either be equal to or lower than the specified limit. In conclusion, it can be stated that environmental degradation has increased over the years in the US, posing a serious threat to environmental sustainability.

In recent years, significant agreements addressing global warming and environmental pollution issues have been made regarding the concept of sustainable development. The Kyoto Protocol is an important international protocol fighting against climate change caused by environmental pollution. This protocol imposes quantitative limitations on the level of emissions released into nature by countries. As in all countries, a significant majority of the population in the US is concerned about the problems of global warming and environmental pollution created by carbon dioxide emissions resulting from fossil fuel consumption. In this context, the Clean Power Plan was announced to the American public in 2015. This plan aims to reduce carbon emissions and bring them down to the levels of 2005. The Clean Power Plan focuses on similar goals as the Paris Agreement, aiming to limit global temperature increase to below 2° C compared to the pre-industrial era. However, the emission practices of the Clean Power Plan were halted by the US Supreme Court in 2016 due to legal battles involving many states and numerous companies (EPA, 2023). Moreover, in 2020, the US officially announced its withdrawal from the Paris Agreement. Some of the main reasons for this policy change were the pressures from interest groups in the economic system and the economic competition with China and India. This policy change proves how significant the influence of economic interest groups is on policy implementation. An important point in this process is that the policy change, which downplays environmental sensitivities, occurred in the US, which is one of the countries with the highest political stability according to the International Country Risk Guide (ICRG, 2022). The policy change driven by the pressure of economic interest groups in the US is highly likely to occur in many other countries in similar or different forms. During Joe Biden's presidency, the US reentered the Paris Agreement, committing to zero carbon emissions by 2050.

The main challenges faced by world economies under the pressure of rapid growth are global warming and environmental pollution. Especially, air pollution caused by carbon emissions poses significant risks for deaths and various diseases worldwide. The IQAir Report (2023) associated 7 million deaths with air pollution in 2023. Furthermore, it has been reported that the expected human lifespan is approximately 1.5 years shorter in rapidly growing societies exposed to carbon emissions (HEI, 2022; State of Global Air, 2022). Economic policies that push environmental sustainability into the background in the processes of economic competition are considered an important reason for global warming and environmental pollution. Therefore, the highest responsibility in fighting against these problems falls on the world's largest economies and countries with the highest carbon emission values. The US is one of the countries with the highest share of this responsibility. This study aims to investigate the effect of economic growth, renewable energy consumption, and political stability on environmental sustainability in the US for the period

1984–2017. The health problems faced by the world necessitate the implementation of new policies for sustainable development in economic growth processes. The solution to this problem, faced particularly by environmental scientists and economists, is the primary motivation for this study. For the solution of this problem, the US is one of the most suitable country samples in terms of economic size, carbon emission value, and population criteria. The use of a novel and robust empirical test (FARDL) in the research model and the representation of environmental degradation with a comprehensive variable such as the ecological footprint pressure index are thought to provide a different perspective to the literature. Although there are many empirical studies investigating the effect of economic growth and renewable energy consumption on environmental degradation in the literature, the number of studies examining the effect of political stability on environmental degradation is limited. This study is expected to make a significant contribution to the literature, particularly in explaining the effect of political stability on environmental degradation.

The following sections of this study are designed as follows. Section "[Theoretical Framework](#)" presents the theoretical framework, whereas Section "[Literature Review](#)" includes the literature review. Section "[Data, Model, and Method](#)" explains the data, model, and method, while Section "[Empirical Results and Discussion](#)" shows the empirical results and discussion. Finally, Section "[Conclusion, Policy Recommendations, and Limitations of Study](#)" provides the conclusion, policy recommendations, and limitations of this study.

Theoretical Framework

The energy and raw materials provided by nature for the production process are utilized to achieve economic growth, and the environment is affected negatively as a result of the production process (Xepapadeas, 2005). In the literature, the relationship between economic growth and environmental degradation has been assessed within the framework of the environmental Kuznets curve (EKC) hypothesis since the early 1990s (Panayotou, 1993; Selden and Song, 1994; Shafik & Bandyopadhyay, 1992). In the EKC hypothesis, an increase in income per capita, which represents economic growth, has a negative effect up to a turning point (Dasgupta et al., 2002; Dinda, 2004). However, beyond this turning point, increases in income per capita reduce the negative effect on the environment (Dogan & Inglesi-Lotz, 2020; Harbaugh et al., 2002). On the other side, the inclusion of the square of income with the income variable in the EKC hypothesis analysis causes multiple multicollinearity problems. Narayan & Narayan (2010) assert that the multicollinearity problem can be avoided with the approach of comparing short- and long-run income elasticities. In this approach, short- and long-run income elasticities are compared. Accordingly, if the long run income elasticity is lower than the short run income elasticity, then the EKC hypothesis is assumed to be valid. In simpler terms, this implies a decline in environmental degradation over time. Many researchers have tested the EKC hypothesis by following the study of Narayan & Narayan (2010). While some of these studies reveal that the EKC hypothesis is valid (Ahmad et al., 2021; Dong

et al., 2018; Tiwari et al., 2013), some studies cannot find evidence validating the EKC hypothesis.

In the EKC hypothesis introduced first by Grossman and Krueger (1991), the relationship between environmental degradation and level of income per capita is explained through factors such as scale economy, structural effect, and technological effect (Panayotou, 1997). First, the scale economy refers to the pollution in the environment as a result of the increase in production scale during the period, in which economies grow, especially via industrial production (Churchill et al., 2018; Stern, 2017). In this process explained by the Pollution Haven Hypothesis, environmental pollution can be ignored, especially for developing countries, in order to achieve economic growth (Akbostancı et al., 2008; Tiba & Frikha, 2020). Second, the structural effect can be seen in the case of a structural change from the industrial sector to the service sector in relation to the developmental level of countries. As an indicator of development, an increase in the share of the service sector in national income might have an effect that reduces environmental pollution (Panayotou, 1993). The technological effect is related to the development level of countries. Since income per capita reaches a specific level in developed countries, societies begin to prioritize other social factors such as the environment (Shahbaz & Sinha, 2019). While the products damaging the environment are considered inferior goods, consumers prefer environment-friendly products through the effect of income elasticity of demand. Manufacturers, on the other hand, increase technological investments, which would not cause environmental pollution (Borghesi, 1999). Nowadays, it is observed that economic growth and environmental degradation occur at the same time in many developing countries. Despite that, it is possible for countries, that adapt to sustainable development projects within the context of the Brundtland Report (WCED, 1987), Kyoto Protocol (UNFCCC, 1997), Paris Agreement (UNFCCC, 2015), and Glasgow Climate Pact (UNFCCC, 2021), to minimize the environmental degradation during the economic development (Adebayo, 2022).

The need for energy constantly increases due to advancements in technology, industrialization, and global population growth. Given the fact that the largest portion of the energy is obtained from fossil fuels causing an increase in carbon emissions, the use of fossil energy sources creates global problems, which will affect the next generations, such as climate change and environmental pollution (Bashir et al., 2021; Miao et al., 2022). Within the context of sustainable development projects, it is recommended that countries develop less-carbon energy systems to reduce carbon emissions and incorporate the use of renewable energy sources (Nathaniel & Adeleye, 2021). Despite not reaching the desired level yet, it is evident that many countries have begun transitioning from fossil fuels to renewable energy sources including hydroelectric, geothermal, solar, biomass, and wind in parallel with those recommendations and economic benefits. Renewable energy sources have lower carbon emission levels. For this reason, when compared to fossil fuels, they are cleaner and have positive effects on climate change, environmental pollution, and human health (Al-Mulali et al., 2016). Furthermore, driven by technological advancements and increased investments, the costs associated with establishing and generating energy from renewable sources have been consistently decreasing over the past decade (Gyamfi et al., 2018). As it promotes the utilization of local resources,

renewable energy generation helps decrease foreign dependency during the economic growth and development processes of countries.

Political stability refers to the implementation of structural management and practice strategies under a legitimate constitutional order and a stable government model without political and social violence (Hurwitz, 1973). Although the same government model is expected for political stability, it is not an absolute outcome. There might be political instabilities related to the same government models. The most important positive effect of political stability in an economic system is the reduction of uncertainties in the politic-economic field. Predictability in the politic-economic sphere promotes investments and, consequently, economic growth is expected to occur. Even though the global population was higher than 6 billion in 2010, it is expected to reach 11 billion by 2030. The most important expectation of the growing population from policymakers is the implementation of economic policies that reduce unemployment. As well as economic policies reducing the unemployment, the practices preventing climate change and environmental degradation are also political decisions made for sustainable development. Especially in countries where political stability could not be achieved, governments might adopt policies, which prioritize economic growth and push sustainable development policies into the background, in order to prolong their service time (Cervantes & Villaseñor, 2015). Consequently, political stability might lead to environmental degradation linked to the implemented economic policies. In some cases, in which political stability is achieved, pressure groups playing an effective role in production and consumption decisions (companies, investors, chambers of commerce) might direct the political decisions for their benefit. This pressure is implemented generally over lobby activities and other political parties (Guney, 2015). While it is easy to implement sustainable development policies in societies that value environmental sustainability, it becomes more challenging in societies lacking environmental awareness, particularly during periods of political instability (Adebayo, 2022). In those societies without established environmental awareness, implementation of sustainable development policies can be achieved via strong government models that stand against pressure groups.

Literature Review

In the past century, as the discussions on the societal effects of global warming and environmental pollution started, the concept of sustainable development gained significance within the field of environmental economics. Increasing sensitivity to environmental conditions necessitated the exploration of the effects of various economic, social, financial, and political factors on environmental degradation. For this purpose, especially in the last quarter century, modern empirical testing techniques were used to examine the effect of different factors on environmental degradation. The purpose of the literature review is to provide a current and comprehensive summary of the research topic. The scientific discussion at the end of the literature review aims to identify the determinants of environmental degradation. Additionally, this discussion will explain the contribution that this study will make to the existing literature.

In studies carried out on sustainable development, the effects of determinant factors of development including economic growth (Adebayo et al., 2021; Hashmi et al., 2020), financial development (Abbasi & Riaz, 2016; Shahbaz et al., 2013), trade openness (Halicioglu, 2009; Kohler, 2013), urbanization (Adams et al., 2016; Sarkodie & Adams, 2018), natural resources (Ahmed et al., 2020; Hussain et al., 2021), renewable energy (Acheampong et al., 2019; Yuping et al., 2021), non-renewable energy consumption (Shafiei & Salim, 2014), foreign capital investment (Chandran & Tang, 2013; Pao & Tsai, 2011), income inequality (Pata et al., 2022), and political stability (Agheli & Taghvaei, 2022; Al-Mulali & Ozturk, 2015) on environmental degradation were examined.

The effect of political stability on environmental degradation is a research topic that is discussed within the frame of interaction between politic-economics and sustainable development (Liodakis, 2010). Within this context, the study carried out by Fredriksson and Svensson (2003) is one of the first studies examining the effects on environmental degradation in the fields of politic-economics and sustainable development. In their study carried out for 63 countries by using cross-sectional data of 1990, the relationship between political implementations related to political environmental sustainability, instability, and corruption was examined. The stringency index of environmental regulations regarding the environmental sustainability was established in 1992 by using the country data prepared for the United Nations Conference on Environment and Development. As a result of their study, it was determined that political stability had a negative effect on the stringency of environmental regulations in countries with low levels of corruption, whereas it had a positive effect on the stringency of environmental regulations in countries with high levels of corruption. Moreover, corruption reduced the stringency of environmental regulations, but the effect disappeared as political instability increased.

Using the sample consisting of 43 countries in the Middle East, South Asia, Latin America, East Asia, and Africa regions, Narayan and Narayan (2010) test the validity of the EKC for the period of 1980–2004. The decision criterion for the validity of the Environmental Kuznets Curve is that the long run income elasticity of CO₂ emission is lower than the short run income elasticity. Income elasticity is estimated using time series and panel data analysis. As a result, long run income elasticity is found to be lower than the short run income elasticity only for the Middle East and Africa regions. This finding suggests that EKC is not valid for all the country groups involved in the study.

Sharma (2011) examines the factors affecting CO₂ emission levels in 69 countries, which have high, medium, and low levels of income, for the period of 1985–2005. By using dynamic panel data analysis, their study separately carries out the analysis as both a global panel for all the countries and separately for country samples having different income levels. In the analysis applied for the whole panel, it is determined that GDP per capita increases the level of CO₂ emission, whereas the urban population reduces the CO₂ emission. For high-income countries, electricity consumption per capita and total primary energy consumption per capita increase the CO₂ emission level, whereas GDP per capita increases the CO₂ emission level in medium- and low-income countries.

For 127 countries, Guney (2015) investigates the effects of pressure groups in the economic system, economic growth, population growth, urbanization, forest area size, democracy, and political stability on environmental sustainability. All the countries are classified as EU countries, G20 countries, and OECD countries. Then, the Ordinary Least Squares (OLS) and the Weighted Least Squares (WLS) methods are implemented. As a result, a negative relationship is found between pressure groups and environmental sustainability in all country classifications, especially for developed countries and OECD countries. It is concluded that economic growth negatively affects the environmental sustainability for developing countries and OECD countries, whereas political stability positively affects the environmental sustainability in all countries, G20 countries, and OECD countries.

Al-Mulali & Ozturk (2015) study the effect of energy consumption, trade openness, industrial development, and political stability on environmental degradation in 14 MENA (Middle East and North Africa) countries utilizing data stretching from 1996 to 2012. In the study, the environmental degradation variable is represented by ecological footprint. By using the Granger causality analysis, a causality relationship is found between the variables for the short and long run. The results obtained from the Fully Modified Ordinary Least Square (FMOLS) method show that urbanization, trade openness, and industrial development increase environmental degradation, whereas political stability decreases it.

Adams and Klobodu (2018), by using the Generalized Methods of Moments (GMM) method for 26 African countries for the period of 1985–2011, investigate the determinants of environmental degradation measured with CO₂ emission. The results reveal that economic growth and urbanization are among the important determinants of environmental degradation, and financial development has a positive effect on environmental degradation.

Purcel (2019) evaluates whether political stability has a preventive effect on environmental pollution in 47 developing countries, which have a mid-low income level, employing data from 1990 to 2015. Using the Panel Vector Error Correction Model (PVECM), the study uses CO₂ emission as representative of environmental pollution. The results achieved show that, after reaching a specific level, political stability has a positive effect on environmental pollution by reducing CO₂ emissions. The inverse U-shaped relationship between political stability and environmental pollution is explained by the trade-off relationship between economic growth and environmental degradation.

Agheli and Taghvaei (2022) investigate the effect of political stability on economic sustainability in 43 Asian countries between 2000 and 2019 by using the Fixed and Random Effects model in panel regression analysis. As a result of the study, it is determined that the net saving ratio is positively affected by political stability, decreasing violence events, and population density and is negatively affected by government size. Moreover, in corroboration with the Pollution Haven Hypothesis, it is concluded that political stability causes environmental pollution via trade openness.

Examining the case of Canada, Adebayo (2022) analyzes the effect of political stability on environmental sustainability by making use of the dynamic ARDL method over the period of 1990–2018. As a result of the study, the author reports that economic growth, political risk, renewable energy consumption, and trade

globalization increase the environmental quality and have a positive effect on environmental sustainability. This finding suggests that the decisions, which are globally made for sustainable economic development, are successfully implemented in Canada. However, it is also claimed that political stability attracted foreign investors to the country, and it might pose more severe problems for the Canadian government regarding the environmental sustainability and climate crisis management.

Adebayo et al. (2022) investigate the effects of political stability on environmental degradation in the top ten economically stable economies (Australia, Canada, Germany, Finland, Denmark, Norway, Holland, New Zealand, Sweden, and Switzerland). Examining the period between 1991Q1 and 2019Q4, their study analyzes the relationships between the variables by using quantile-on-quantile regression and quantile causality tests. As a result of the analysis, they conclude that political risk increases the environmental quality in Norway, Sweden, Canada, and Switzerland, whereas it causes environmental degradation in Australia, Germany, and Denmark.

Applying non-linear and Fourier-based approaches, Kartal et al. (2022) test the effects of political stability on consumption-based CO₂ emissions in Finland between 1990Q1 and 2019Q4. Test results show that, in general, political stability has a key role in CO₂ emissions. Accordingly, it is determined that positive changes in political stability reduce CO₂ emissions. However, negative changes in political stability are found to have no statistically significant effect on CO₂ emissions.

Pata et al. (2022), in four Asian countries (Pakistan, India, Sri Lanka, and Bangladesh), study the effect of income inequality and political stability on environmental degradation for the period 2002–2016. In their study, environmental sustainability is represented by ecological footprint, and the long-run coefficients are estimated using the Augmented Mean Group (AMG) test. The results achieved reveal that income inequality, economic growth, and urbanization increase environmental degradation, and political stability and renewable energy consumption have a positive effect on environmental sustainability.

Examining the case of Pakistan, Sohail et al. (2022) test the asymmetrical effect of political instability on clean energy consumption and CO₂ emission from 1990 to 2019. The results of non-linear ARDL prove that political stability does not only increase clean energy consumption but also contributes to increasing the environmental quality in the short run. Considering the conventional ARDL model results, in the long run, political stability reduces environmental degradation by decreasing CO₂ emissions.

Zhang et al. (2022) investigate the effects of the natural resources, energy consumption, and tax revenues on CO₂ emissions between 1990 and 2020 for 48 developing countries. The study employs a cross-section autoregressive distributed lag (CS-ARDL) approach. Results of the short- and long-run suggest that natural resources, energy resources, and economic growth have positive impacts on CO₂ emissions. Education level and tax revenues are associated positively with environmental sustainability.

Zahoor et al. (2022) examine the effects of the abundance of natural resources and the roles of manufacturing value-added, urbanization, and permanent cropland on CO₂ emissions for the period 1970–2016 in China. The research model is estimated by using the Generalized Linear Model (GLM) and robust Generalized

Estimating Equation (GEE). Results of the study reveal that natural resource abundance and permanent cropland improve the environmental sustainability, whereas urbanization and manufacturing value-added deteriorate it in the long run.

Ali et al. (2023) analyze the effects of biogas technology on environmental sustainability and green revolution in Pakistan. The data set of their study consists of the primary answers given by 79 participants to a structured survey form. The hypotheses of this study are evaluated by using partial least squares structural equation modeling (PLS-SEM). The findings demonstrate that the use of biogas technology has positive effects on environmental sustainability. As a policy recommendation, the authors stress the significance of governmental attention to economic strategies, owner training, daily operations, and professional technical assistance in the establishment of biogas facilities.

Azam et al. (2023) investigate the effects of alternative energy sources, natural resources, and government consumption expenditures on environmental sustainability from 1990 to 2018 for France. Analysis results for the long run are estimated by utilizing fully modified least squares (FMOLS), generalized linear model (GLM), robust least squares, and generalized method of moments (GMM). Long-run estimates show that alternative energy sources, natural resources, and government consumption expenditure have a negative effect on CO₂ emissions, but economic growth positively affects CO₂ emissions.

Saqib and Usman (2023) investigate the relationship between green growth, technological innovation, environmental policy stringency, renewable energy, and carbon net-zero emission targets in the two largest pollution-emitting economies, the US and China, for the period 2012Q1-2020Q4 by using the quantile autoregressive distributed lag (QARDL) method. The study reveals a bidirectional causal relationship between carbon emissions, green growth, technological innovation, energy policy stringency, and renewable energy consumption. Moreover, green growth, technological innovation, and environmental policy stringency in the US and China have a significant and negative effect on carbon dioxide emissions. Both the US and China advocate for technological investment policies supporting green growth to achieve the net-zero emission target.

In another study (Saqib et al., 2024a), the authors examine the effects of economic growth, financial development, eco-friendly information and communication technology (ICT), renewable energy, and human capital on carbon footprint in the nine most pollution-emitting economies (China, the US, India, Russia, Japan, Germany, Canada, UK, and Australia) for the period 1993–2020. The study discovers a bidirectional causality between renewable energy, environmental technology, and carbon footprints, and a unidirectional causality from economic growth and financial development to carbon footprints. The study highlights the mitigating effect of financial development, renewable energy, and environmental technology on carbon footprints. The researchers emphasize the significant potential of eco-friendly ICT in the pollution reduction process.

Saqib et al. (2024b) investigate the effect of environmental technologies, financial growth, and energy use on the ecological footprint and green growth in the top ten countries with the highest ecological footprint (China, the US, India, Russia, Brazil, Japan, Indonesia, Germany, Mexico, and the UK). The estimation results indicate

that environmental innovations, green growth, and renewable energy use positively affect environmental conditions, whereas financial growth and non-renewable energy use contribute to environmental degradation. Causality results suggest bidirectional causality among environmental innovations, green growth, non-renewable and renewable energy, and ecological footprint. Moreover, there is a unidirectional causality from financial growth to ecological footprint and green growth.

The results of the literature review indicate that numerous empirical studies have been carried out on sustainable development and environmental sustainability. A significant portion of these studies were carried out in the last 25 years. The increasing number of these studies after a few decades following the emergence of sustainable development and environmental concerns can be associated with the availability of sufficient data for scientific validity and reliability in empirical research. Various factors influencing environmental sustainability for different developed and developing countries and country groups were investigated by using modern empirical tests. Considering the studies in the literature, it can be concluded that economic growth, population, urbanization, and non-renewable energy consumption accelerate environmental degradation. On the other hand, positive effects on environmental sustainability are observed in many studies for factors such as renewable energy consumption, education, tax revenues, green growth, technological innovation, and environmental policy stringency. Furthermore, a noteworthy perspective argues that a free-market economy hastens environmental degradation (Saqib & Usman, 2023). In light of this perspective, the effect of economic growth, population, urbanization, and energy consumption on environmental degradation can be easily explained. Accordingly, global economies compete with each other to meet the desires and needs of the growing world population. Deregulation practices conducted within the framework of free-market conditions pushed environmental concerns into the background, and it made global warming and environmental pollution significant problems in the last century. The largest economies (the US, China, India) are also seen as major contributors to environmental degradation.

Even though explaining and predicting the impact of economic factors on environmental sustainability is relatively easier, predicting the impact of socio-political factors such as democracy and political stability is more challenging. Democracy is perceived as a costly asset for underdeveloped economies (Lipset, 1959). Therefore, predicting the expectations of society from the government in countries, where democratic understanding has not developed, is not always possible. It is also observed that many pressure groups within the economic system can influence the government in accordance with their own economic interests. Consequently, political risk factors increase and there might be periods of political instability. The US is one of the prominent economies in the world, where political stability is maintained. However, pressure groups in the US are as powerful as in other countries. Empirically proving that economic growth leads to environmental degradation in the US, the world's largest economy with political stability, could serve as an important political model example for other countries. Therefore, this study investigates the effect of economic growth, renewable energy consumption, and especially political stability on environmental degradation. In the research process, unlike many studies in the literature, the ecological footprint pressure index variable is used to represent

environmental degradation. Moreover, the research model is predicted by using the Fourier Autoregressive Distributed Lag (FARDL) test, which is a modern and robust empirical test. The use of the FARDL test might yield results supporting the existing literature on the effect of economic growth and renewable energy on environmental degradation. Nevertheless, the literature lacks a definitive consensus on the impact of political stability on environmental degradation. Consequently, the estimates derived from this study regarding the variable of political stability are anticipated to offer valuable guidance to societies and politicians in numerous countries, particularly throughout the democratization process.

Data, Model, and Method

Data and Model

In the present study, environmental degradation is represented by the ecological footprint pressure index (EFPI), which captures both the demand and supply dimensions of the environment and has become increasingly prevalent in the literature. The EFPI data (ecological footprint/bioproductivity) was obtained from the database of the Global Footprint Network website (GFN, 2022). Economic growth (GDP) is represented by the GDP per capita. These data were collected from the World Development Indicators database of the World Bank (World Bank (WB), 2022). Renewable energy consumption (REC) is represented directly by the renewable energy consumption data. The data was obtained from the official website of British Petroleum (BP, 2022). Political stability (POL) consists of 12 political risk subcomponents. Political stability is an index containing the scores of government stability, socioeconomic conditions, investment profile, internal and external conflicts, corruption, military in politics, religious tensions, law and order, ethnic tensions, democratic accountability, and bureaucratic quality. The data were extracted from the ICRG produced by the Political Risk Services (PRS) Group (ICRG, 2022). The reason for choosing the study period as 1984–2017 is the accessibility to political stability data for this period. All the data analyzed were used in the logarithmic form. Table 1 displays the descriptions of the variables.

Table 1 Description of variables

Variable	Description	Unit	Source
EFPI	Ecological Footprint Pressure Index	The index is calculated by dividing the ecological footprint by the bioproductivity	GFN
GDP	Gross Domestic Product	Per capita with constant 2015\$	WB
REC	Renewable Energy Consumption	Exajoules	BP
POL	Political Stability	Total score is between 0 and 100 score. A score of 0 shows extreme instability (high risk), while a score of 100 denotes high stability (low risk)	ICRG

Table 2 reports the synopsis of descriptive statistics. The lnGDP has the highest mean, median, maximum, and minimum values. lnREC and lnGDP have the highest standard deviation (Std. Dev.) values, respectively. The coefficient of variation (CV), calculated as the ratio of standard deviation to mean, is low for all variables, except for lnREC. Consequently, lnREC stands out as the most volatile among the variables. With the exception of lnGDP (negative skewness), lnEFPI, lnREC, and lnPOL are found to have positive skewness. Given the kurtosis values, lnPOL exhibits a leptokurtic distribution. Lastly, according to the Jarque–Bera test statistic, all variables follow a normal distribution

Considering ecological footprint and ecological capacity simultaneously, EFPI is calculated using the formula in Eq. (1) (Wang et al., 2018):

$$\text{EFPI} = \frac{\text{EcologicalFootprint}}{\text{EcologicalCapacity}} \quad (1)$$

Given Eq. (1), the relationships between ecological footprint and ecological capacity within the context of sustainable development can be presented as follows (Wang et al., 2018: 304): If.

- $0 < \text{EFPI} < 1 \Rightarrow$ Ecological source supply exceeds ecological source demand.
- $\text{EFPI} = 1 \Rightarrow$ Ecological source supply equals to ecological source demand.
- $\text{EFPI} > 1 \Rightarrow$ Ecological source demand exceeds ecological source supply.

For a sustainable development, EFPI should be between 0 and 1 ($0 < \text{EFPI} < 1$). $\text{EFPI} = 1$ refers to an ecological balance and sustainable development level is at a critical point. $\text{EFPI} > 1$ refers to the fact that sustainable development is at risk.

The estimation model designed by following Adebayo (2022) is presented in Eq. (2):

$$\ln \text{EFPI}_t = \alpha_0 + \beta_1 \ln \text{GDP}_t + \beta_2 \ln \text{REC}_t + \beta_3 \ln \text{POL}_t + u_t \quad (2)$$

In Eq. (2), *ln* refers to the logarithmic transformation of variables. Thus, it is aimed to both interpret the coefficient elasticity and prevent the heteroscedasticity.

Table 2 Synopsis of descriptive statistics

	lnEFPI	lnGDP	lnREC	lnPOL
Mean	0.912	10.745	0.242	4.404
Median	0.905	10.794	-0.044	4.396
Maximum	1.033	10.972	1.722	4.511
Minimum	0.795	10.431	-0.919	4.307
Std. Dev	0.068	0.164	0.785	0.044
CV	0.074	0.015	3.239	0.009
Skewness	0.151	-0.359	0.421	0.392
Kurtosis	1.788	1.743	2.069	3.286
Jarque–Bera	2.212	2.970	2.235	0.986
Probability	0.331	0.227	0.327	0.611
Observations	34	34	34	34

β_1 , β_2 , and β_3 refer to the coefficient parameters, while u_t and t represent the error term and time dimension, respectively. Economic activities cause environmental degradation by increasing the environmental pressure (Beckerman, 1992; Jorgenson & Wilcoxon, 1990; Rahman, 2020). Hence, GDP coefficient (β_1) is expected to be positive ($\beta_1 = \frac{\partial EFPI}{\partial GDP} > 0$). It is claimed that REC, which is an alternative and clean source, controls the environmental pollution by reducing the dependence on fossil sources (Akadiri et al., 2019; Akella et al., 2009). Thus, REC contributes to both a decrease of environmental degradation and a recovery of environmental quality. Within this context, REC coefficient (β_2) is expected to be negative ($\beta_2 = \frac{\partial EFPI}{\partial REC} < 0$). It is suggested that the political stability (POL) supports the policy actions reducing the global warming and environmental problems (Purcel, 2019; Su et al., 2021). Hence, it is accepted that political stability increases the environmental quality by reducing the pressure on the environment. In conclusion, the coefficient of POL (β_3) is expected to be negative ($\beta_3 = \frac{\partial EFPI}{\partial POL} < 0$).

Method

In this study, the effects of economic growth, renewable energy consumption, and political stability on environmental degradation in the US are tested using Fourier Bootstrap ARDL (FARDL) introduced by Yilanci et al. (2020). The reason for preferring the FARDL estimation method in the present study is explained as follows (Yilanci & Pata, 2020):

- (i) This test offers flexibility to a requirement that is mandatory in traditional tests, where variables must be stationary at the same degree. On the condition that the dependent variable is stationary at the first difference I(1), the explanatory variables can be stationary at the level I(0) or I(1). On the other hand, none of the variables involved in the model should be stationary at the second difference I(2).
- (ii) Since ARDL approach is based on the error correction model, it offers a better performance in comparison to the traditional tests.
- (iii) FARDL considers structural breaks and provides robust and reliable results even with small samples.

The FARDL approach consists of two steps. In the first step, it is tested whether there is a long-run relationship between the variables. If a cointegration relationship is found in the first step, then the second step is initiated. In the second step, the long and short run coefficients are estimated.

Within the scope of the FARDL approach, the estimation model in Eq. (2) is adapted to the error correction model, and the Eq. (3) is achieved:

$$\begin{aligned}
\Delta \ln \text{EFPI}_t &= \beta_0 + \beta_1 \ln \text{EFPI}_{t-1} + \beta_2 \ln \text{GDP}_{t-1} + \beta_3 \ln \text{REC}_{t-1} \\
&+ \beta_4 \ln \text{POL}_{t-1} + \sum_{i=1}^{p-1} \varnothing' \Delta \ln \text{EFPI}_{t-i} + \sum_{i=1}^{p-1} \varphi' \Delta \ln \text{GDP}_{t-i} \\
&+ \sum_{i=1}^{p-1} \gamma' \Delta \ln \text{REC}_{t-i} + \sum_{i=1}^{p-1} \delta' \Delta \ln \text{POL}_{t-i} + e_t
\end{aligned} \quad (3)$$

Δ refers to the difference operator, p to the suitable lag length, and e_t to the error term. Akaike Information Criterion (AIC) is used in determining the suitable lag length. Pesaran et al. (2001) suggest that, for the existence of a cointegration relationship, it is enough if F -test (F_A) and t -test (t) null hypotheses (H_{0A} and H_{0t}) are rejected. On the other hand, McNown et al. (2018), in addition to F_A and t tests of Pesaran et al. (2001), propose a third F -test (F_B). Thus, McNown et al. (2018) state that it is necessary to test the co-significance of single-lagged values of dependent and independent variables (H_{0A}) and the co-significance of single-lagged value of dependent variable (H_{0t}) and single-lagged value of independent variables (H_{0B}). Hence, the results to be achieved from F_A , F_B , and t test provide four different cases:

- Case (1): F_A , F_B , and t are significant \rightarrow Cointegration occurs,
- Case (2): F_A , F_B and t are insignificant \rightarrow No cointegration occurs,
- Case (3): F_A and F_B are significant, but t is insignificant \rightarrow Degenerate case (a),
- Case (4): F_A and t are significant, but F_B is insignificant \rightarrow Degenerate case (b).

When expanding the Eq. (3) error correction model with Fourier terms ($\sin\left(\frac{2\pi kt}{T}\right), \cos\left(\frac{2\pi kt}{T}\right)$), the final model is seen in Eq. (4):

$$\begin{aligned}
\Delta \ln \text{EFPI}_t &= \beta_0 + \lambda_1 \sin\left(\frac{2\pi kt}{T}\right) + \lambda_2 \cos\left(\frac{2\pi kt}{T}\right) + \beta_2 \ln \text{EFPI}_{t-1} \\
&+ \beta_3 \ln \text{GDP}_{t-1} + \beta_4 \ln \text{REC}_{t-1} + \beta_5 \ln \text{POL}_{t-1} + \sum_{i=1}^{p-1} \varnothing' \Delta \ln \text{EFPI}_{t-i} \\
&+ \sum_{i=1}^{p-1} \varphi' \Delta \ln \text{GDP}_{t-i} + \sum_{i=1}^{p-1} \gamma' \Delta \ln \text{REC}_{t-i} + \sum_{i=1}^{p-1} \delta' \Delta \ln \text{POL}_{t-i} + e_t
\end{aligned} \quad (4)$$

The structural changes in Eq. (4) are considered using trigonometric terms. k stands for the frequency value. k being an integer shows that breaks are temporary, whereas k being fractional means that they are permanent. The suitable frequency value is determined based on the minimum residual sum of squares, while critical values for F_A , F_B , and t are obtained by bootstrapping.

Table 3 Unit root test results

Variables	ADF unit root test		PP unit root test	
	Level	First difference	Level	First difference
lnEFPI	-1.1786 (0.380) [0]	-4.974 ^a (0.000) [0]	-1.824 (0.354)	-4.963 ^a (0.000)
lnGDP	-1.307 (0.613) [1]	-3.711 ^a (0.008) [0]	-1.931 (0.314)	-3.567 ^b (0.012)
lnREC	0.356 (0.977) [1]	-3.549 ^b (0.012) [0]	0.734 (0.991)	-3.608 ^b (0.011)
lnPOL	-3.108 ^b (0.035) [1]	-4.970 ^a (0.000) [1]	-3.130 ^b (0.033)	-4.372 ^a (0.001)

a and b indicate significance at 1% and 5% levels, respectively. () shows p-value. [] denotes the optimal lag length.

Empirical Results and Discussion

FARDL test loses its validity if the dependent variable is stationary at the level or variables are stationary at the second difference. Thus, before the long-run estimation between the variables, the stationarity properties of the variables are determined first. The stationarity characteristics of variables are determined through Augmented Dickey – Fuller (ADF) and Phillips and Perron (PP) unit root tests, and the results are summarized in Table 3.

Based on the ADF and PP unit root test results in Table 3, the null hypothesis assuming that “the variable has unit root” is rejected at the level for lnPOL, while it cannot be rejected for lnEFPI, lnGDP, and lnREC. For this reason, lnPOL variable is stationary at the level, whereas other variables of lnEFPI, lnGDP, and lnREC have unit root at the level. Regarding the first differences of the variables, it is revealed that lnEFPI, lnGDP, and lnREC variables are stationary. In conclusion, the level of stationarity is found to be I(0) for lnPOL but I(1) for lnEFPI, lnGDP, and lnREC. None of the variables is I(2), and the dependent variable is found to be I(1). Accordingly, the stationarity characteristics of the variables are appropriate for the FARDL test procedure. Table 4 illustrates the FARDL cointegration test results.

In Table 4, the suitable frequency value (k) is determined to be 1.7, indicating that the breaks in cointegration relationship are permanent. Besides that, the absolute

Table 4 FARDL cointegration test results

lnEFPI = f(lnGDP, lnREC, lnPOL)				
Selected model	AIC	k		
FARDL (3, 3, 4, 4)	-5.136312	1.7		
Bootstrap critical values				
Test statistics		0.90	0.95	0.99
F-stat. (F _A)	5.004 ^c	4.128	5.250	8.838
t-dep. (t)	-4.053 ^a	-2.154	-2.713	-3.737
F-indep. (F _B)	6.177 ^b	4.392	5.812	9.360

a, b, and c indicate significance at 1%, 5%, and 10% levels, respectively.

values of test statistics of F_A , F_B , and t are higher than the bootstrap critical values. Accordingly, since F_A statistic is significant at 10%, F_B statistic is significant at 5%, and t statistic is significant at 1%, the null hypothesis of no long-run relationship between variables is rejected. Hence, it is determined that the variables of $\ln EFPI$, $\ln GDP$, $\ln REC$, and $\ln POL$ are cointegrated. Subsequently, the coefficient estimation procedure is applied. The short- and long-run coefficient estimations based on the FARDL model are given in Table 5.

According to FARDL estimation results in Table 5, the effect of $\ln GDP$ on $\ln EFPI$ is positive and statistically significant in both the long and short run. Within this context, a 1% increase in $\ln GDP$ leads to a 3.217% increase in the long run and a 4.560% increase in the short run in $\ln EFPI$, respectively. Accordingly, the results show that increases in economic activities increase environmental pressure. These results are in compliance with the results reported by Sharma (2011), Guney (2015), and Adams and Klobodu (2018). However, as the rise in environmental degradation is less pronounced in the long run compared to the short run, the validity of the EKC hypothesis is verified according to the approach of Narayan & Narayan (2010). In other words, environmental pressure lessens in the subsequent stages of development. These results support the findings reported by Tiwari et al. (2013), Dong et al. (2018), and Ahmad et al. (2021).

On the other hand, it is evident that the effect of $\ln REC$ on $\ln EFPI$ is negative and statistically significant in both the long and short run. This finding suggests that renewable energy consumption improves the environmental quality by reducing the environmental pressure. From this respect, a 1% increase in $\ln REC$ results in a 0.195% decrease in the long run and a 0.231% decrease in the short run in $\ln EFPI$. These results are consistent with the outcomes of Adebayo (2022) and Pata et al. (2022). These results can be explained by the fact that renewable energy is a "clean" energy source that leads to less environmental pollution and pressure. Increasing the share of renewable energy in the US as a strategy to reduce ecological footprint can enhance environmental

Table 5 The results of short and long run coefficient estimations

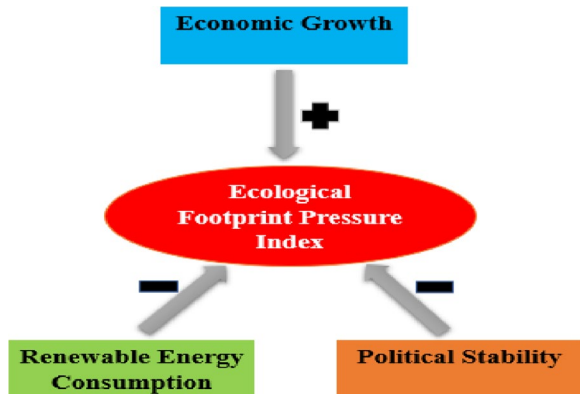
Variables	Coefficients	p-value
Long run		
$\ln GDP$	3.217 ^a	0.000
$\ln REC$	-0.195 ^c	0.065
$\ln POL$	-0.968 ^a	0.000
Constant	-29.592 ^a	0.000
Short run		
$\Delta \ln GDP$	4.560 ^a	0.000
$\Delta \ln REC$	-0.231 ^c	0.063
$\Delta \ln POL$	-0.917 ^a	0.005
Sin	-3.242 ^a	0.000
Cos	6.390 ^a	0.000
ECT_{t-1}	-2.674 ^a	0.000

a and c indicate significance at 1% and 10% levels, respectively.

quality by lowering the ecological footprint. In this context, replacing fossil fuels with clean and renewable sources in the US will decrease the demand for dirty sources, thereby increasing biocapacity. The environmental pressure will diminish accordingly as this transition occurs. The US is one of the prominent countries worldwide in fossil fuel and renewable energy consumption. Fossil fuels constitute more than 80% of the US's energy mix. On the other hand, the share of renewable energy consumption in 2021 was 13% in the US. Despite being a leading country in renewable energy consumption, the share of renewable energy consumption in the US has not reached a satisfactory level yet. Considering these reasons, the US government should further encourage the use of renewable energy (Appendix Table 6 and Table 7).

It is found that the effect of $\ln\text{POL}$ on $\ln\text{EFPI}$ is negative and statistically significant in both the long and short run. Accordingly, it can be stated that an increase in the political stability level of the US decreases the environmental degradation. Within this context, a 1% increase in $\ln\text{POL}$ causes 0.968% and 0.917% decreases in the long and short run in $\ln\text{EFPI}$, respectively. These results support the findings reported by Al-Mulali and Ozturk (2015), Guney (2015), Kartal et al. (2022), and Sohail et al. (2022). The negative relationship between political stability and environmental degradation demonstrates the capacity of state institutions in the US to implement regulations that enhance environmental quality. Furthermore, in a stable political environment, environmental and economic issues are promptly recognized, whereas the opposite applies to the political instability. Therefore, ensuring political stability could be a critical strategy for reducing environmental degradation in the US. Otherwise, regulatory institutions might lose their control and incentive capabilities over industries in an atmosphere of political instability, potentially leading to an increase in environmental degradation. In such circumstances, the political instability diminishes the motivation for the widespread adoption of modern technology and research and development (R&D) activities, constrains the vision of policymakers, and creates an uncertain atmosphere where entrepreneurs tend to exploit natural resources for personal gain. Additionally, political instability often deviates countries from their primary goals, causing delays and failures in achieving environmental improvements and sustainable development. In this context, political instability and uncertainty might lead companies to postpone decisions regarding investments and the transition to eco-friendly technologies. This negative atmosphere can incline companies toward risk avoidance and deter them from environmentally friendly investments. Conversely, a politically stable environment encourages companies to shift towards clean and modern energy sources instead of relying on low-cost fossil fuels. Furthermore, during periods of high political stability, governments can implement environmental policies and management strategies more effectively. Therefore, ensuring political stability presents a significant opportunity for companies and governments to promote environmental sustainability. Figure 2 shows a summary of FARDL estimation results.

Fig. 2 Summary of FARDL estimation results



Conclusion, Policy Recommendations, and Limitations of Study

Conclusion

The present study scrutinizes the effects of economic growth, renewable energy consumption, and political stability on environmental degradation in the US for the period of 1984–2017 by utilizing novel and robust test methods within the framework of Narayan and Narayan's (2010) EKC hypothesis. Cointegration test results reveal that the variables of environmental degradation, economic growth, renewable energy consumption, and political stability are cointegrated. The estimation results prove the validity of the EKC hypothesis in the US. Besides, based on the estimation results, it is concluded that economic growth exacerbates environmental degradation, whereas renewable energy consumption and political stability mitigate it in both the short- and long-run (Appendix Fig. 3).

Policy Recommendations

In conclusion, the results obtained can provide useful insights to policymakers. In this context, given these results, several policies are recommended for the US as follows:

- When formulating environmental policies in the US, it is crucial to consider not only technical factors but also political stability factors. Within this framework, closer collaboration and solidarity between civil society and government institutions should be established to draft more efficient laws and regulations and promote political stability.
- Regulatory bodies in the US should enhance their control methods on industries and diversify their incentive portfolios. In this way, the government can shield itself from the negative impacts of motivation loss caused by political

instability and the uncertain business environment where environmental sustainability is overlooked.

- The US policymakers should create incentive programs specifically for companies focusing on low carbon footprint or renewable energy usage to support the transition to eco-friendly technologies. In this regard, providing additional tax exemptions to companies using clean energy and expediting the transition to sustainable technologies by offering privileged credit and advanced services through financial institutions should be considered.
- The US should increase support for R&D activities aimed at reducing the usage cost of renewable energy sources. Simultaneously, it should gradually implement more rigorous policies, such as additional taxation and usage restrictions, to decrease fossil fuel consumption.

Limitations of the Study

The present study has some limitations. First, the political stability data for the US spans from 1984 to 2017. The second limitation is that financial and socioeconomic variables, which have the potential to affect the environmental degradation, are not included in the model. In the present study, the effect of economic growth, renewable energy consumption, and political stability on environmental degradation in the US for the period of 1984–2017 is analyzed using the FARDL test. Future studies can investigate the relationships among economic growth, renewable energy consumption, political stability, and environmental degradation in subcomponents of ecological footprint pressure index such as carbon footprint pressure index, fishing grounds footprint pressure index, cropland footprint pressure index, built-up land footprint pressure index, forest products footprint pressure index, and grazing land footprint pressure index. Thus, each subcomponent of the ecological footprint can be examined in detail and more effective policies and sustainable strategies specific to each component can be developed.

Appendix

See Annex 1.

Table 6 Diagnostic check

Tests	Test stat	p-value
LM	3.007	0.104
BPG	0.958	0.553
Glejser	1.322	0.333
Ramsey	1.487	0.171

See Annex 2.

Table 7 VIF test for multi-collinearity

Variable	VIF	1/VIF
lnGDP	5.89	0.167
lnREC	5.96	0.169
lnPOL	1.05	0.952
Mean VIF	4.30	

See Annex 3.Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

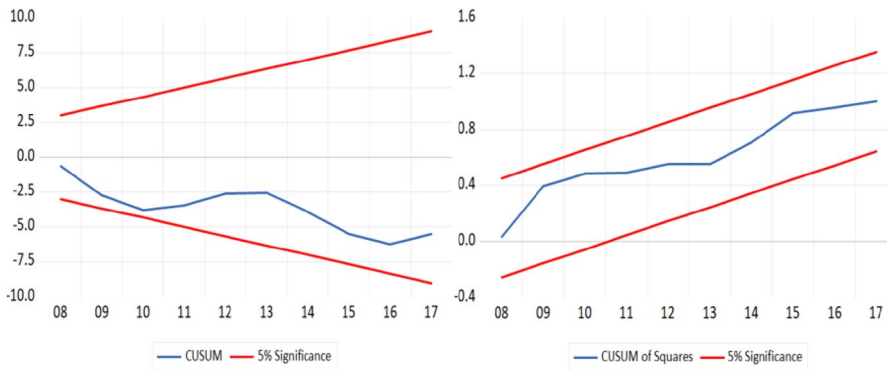


Fig. 3 Plots of CUSUM and CUSUM of Squares

Data Availability The sources of data have been duly mentioned in the study.

Declarations

Ethical Approval This study follows all ethical practices during writing.

Competing Interests The authors declare no competing interests.

Disclaimer The contents of this paper are the author's sole responsibility. They do not necessarily represent the views of any of the institutions.

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