Clean Technologies and Environmental Policy
https://doi.org/10.1007/s10098-024-02838-7

ORIGINAL PAPER

Does the composition of environmental regulation matter for ecological sustainability? Evidence from Fourier ARDL under the EKC and LCC hypotheses

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Received: 4 January 2024 / Accepted: 30 March 2024

Abstract

Environmental policies typically involve the definition of a goal and the use of some policy tools to achieve this goal. As one of the most critical objectives of countries is to ensure environmental sustainability, they use effective instruments such as environmental regulations, which are important public economy instruments. This study aims to test the impact of environmental regulations on the load capacity factor and ecological footprint in Turkey using data from 1990 to 2020 and the novel Fourier augmented autoregressive distributed lag (ARDL) model. We categorize environmental regulations into market-based, command and control, and technology support policies. This reveals the relative effectiveness of environmental regulation components. We also question the role of renewable energy and the validity of the environmental Kuznets curve (EKC) and Load Capacity Curve (LCC) hypotheses. The findings indicate that market-based regulations increase environmental sustainability by improving environmental quality. Again, command and control and technology support policies have no impact on the ecological balance. Therefore, we prove that the components of environmental regulations can have different impacts on environmental quality and sustainability. Moreover, we confirm the improving role of renewable energy on environmental quality. Thus, we support the view that environmentally friendly renewable energy policies are critical for environmental sustainability. Finally, we show that the EKC and LCC hypotheses are valid in Turkey during the analyzed period. Policymakers must restructure command and control regulations and technology support policies in an incentive-based, flexible, and cost-effective manner to improve environmental quality in Turkey.

This paper is based on the Oğuzhan Bozatlı's PhD Thesis submitted to Cukurova University, Faculty of Economic and Administrative Sciences, Department of Public Finance.

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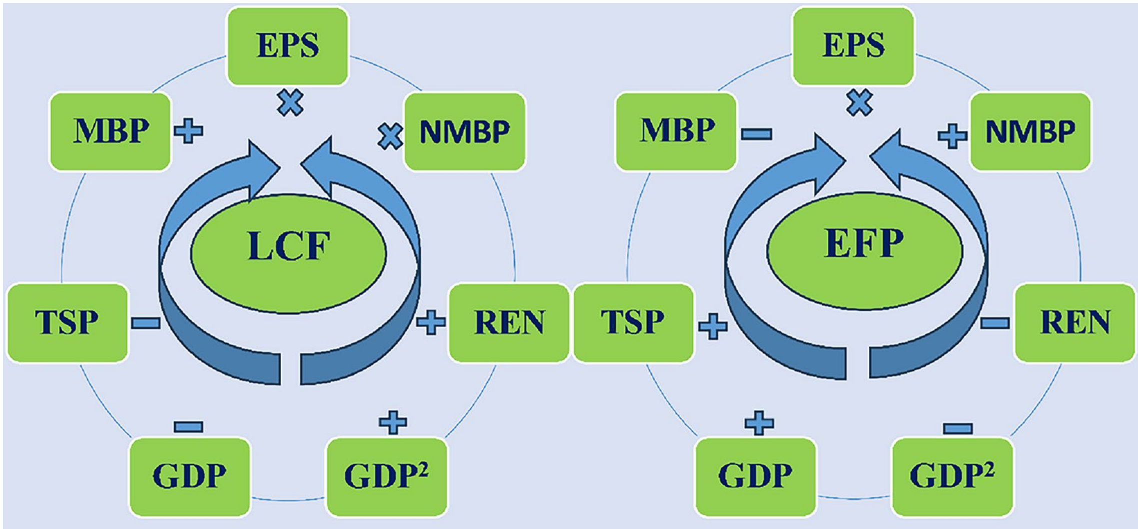
Published online: 20 April 2024

Graphical abstract



Keywords Environmental regulations · Renewable energy · EKC · LCC · Fourier augmented ARDL

Abbreviations

CO_2	Carbon dioxide emissions
EFP	Ecological footprint
LCF	Load capacity factor
GHG	Greenhouse gas
LCC	Load capacity curve
EKC	Environmental Kuznets curve
EPS	Environmental policy stringency
MB	Market-based
NMB	Non-market-based
MBP	Market-based environmental regulation
NMBP	Non-market-based environmental regulation
C&C	Command and control
TSP	Technology support policies
GDP	Gross domestic product
REN	Renewable energy
R&D	Research and development
OECD	Organization for economic co-operation and development
BRICS	Brazil, Russia, India, China, and South Africa
DOLS	Dynamic least squares
ARDL	Autoregressive distributed lag
A-ARDL	Augmented autoregressive distributed lag
ADF	Augmented Dickey–Fuller
FADF	Fourier ADF
X_{SC}	Serial correlation
X_H	Heteroscedasticity
X_N	Normality
X_{FF}	Functional form
C/CSQ	Cusum and cusum square

Introduction

Environmental issues have direct and indirect consequences, such as ecological imbalance, global warming, and climate change. The growth of the global population, varying levels of development in different countries, desires for development, globalization, and dependence on fossil-based resources are among the foremost causes of environmental problems (Ashraf et al. 2024). Global warming and climate change are not just regional matters but also global concerns that require international exertions. These exertions were initiated with the Vienna Convention and continue with the Paris Climate Agreement, in which countries are committed to reducing pollution and ensuring environmental sustainability (Qing et al. 2024). These international efforts aim to reduce global temperature increases below a certain level, monitor policy impacts, and develop actions accordingly (Aydin and Bozatli 2022). Therefore, public economic instruments are vital for achieving the set targets. In the half-century following the corrective taxes proposed by Pigou (1920) to internalize negative externalities about a century ago, environmental policy and instruments started to develop with the maturation of regulation theories. In particular, the quantity- and price-based mechanisms that emerged in this process imply that economic incentive/punishment policies for environmental protection are already preexisting policy ideas (Stavins 2000).

Environmental policies typically involve setting goals and using tools to attain those goals. These two elements, environmental policy and instruments, are often interwoven in the political process. This close relationship stems from the fact that the choice of objectives and the mechanisms designed to achieve them have important policy implications (Stavins 2003). Environmental regulations, implemented for common purposes and seen as complementary to each other, are divided into market-based (MB) and non-market-based (command-and-control) regulations, depending on their operating mechanisms and constraints (Blackman et al. 2018). It is essential to examine whether environmental regulations effectively reduce environmental pollution and ensure ecological sustainability (Guo et al. 2021).

The Porter hypothesis forms the theoretical foundations for the relationship between environmental regulations and environmental quality. The Porter hypothesis, which implies that environmental regulations can trigger green innovations, especially in energy saving and environmental protection, which will contribute to environmental sustainability, has long been discussed in the literature (Porter and Van der Linde 1995). Accordingly, firms seek ways to increase their competitiveness through the efficient use of resources through environmental regulations and resource efficiency and savings in input consumption through environmentally friendly products. In particular, the fact that green innovation depends on knowledge capacity in a way that is not easy to imitate is a factor that increases competitiveness (Liao and Zhu 2023). Therefore, the Porter hypothesis implies that optimally designed environmental regulations encourage green innovation and contribute to environmental sustainability. Although the prevailing view is that environmental regulations will force firms to engage in environmentally protective green innovations, the opposite may also occur due to the compliance and financing costs that environmental regulations impose on firms (Kesidou and Wu 2020; Wang et al. 2023a, b). On the other hand, the gains implied by the Porter hypothesis depend on the intensity and composition of environmental regulations. When the intensity of environmental regulation is optimal, gains towards environmental sustainability can be achieved. However, literature discussions and evidence on the composition of environmental regulation are insufficient (You and Li 2022; Wei et al. 2023). In this circumstance, examining the composition of environmental regulations and analyzing their impact is an important research area.

The conventional perception of environmental regulations is that they are frequently described as "command and control (C&C)" regulations because of their relatively limited flexibility in achieving objectives. In such regulations, it is assumed that the government knows the best technology and that firms should only obey orders, such as soldiers obediently following commands (Nordhaus 2021). Environmental regulations based on C&C, whose main characteristic is coerciveness, aim to direct polluters and control pollution through various standards and measures (e.g., emission standards, technical measures) introduced at the legal level. Such regulations tend to allocate the burden of pollution abatement to polluters by setting uniform standards and keeping the cost in the background. The most common C&C-based environmental regulation classifications are technology-based and performance-based standards. The former specifies the method and sometimes equipment that polluters must use to comply with a particular regulation, while the latter sets a uniform control target for polluters and provides some flexibility in achieving this target (Stavins 2003). To fulfill the standards or measures, polluters work to curb pollution by reducing production or adopting environmentally friendly production technologies. However, polluters have no additional motivation to reduce pollution after achieving targets set by C&C-based environmental regulations. Moreover, under asymmetric information, some polluters may manipulate emission information or illegally discharge pollution to avoid sanctions (Guo et al. 2021).

Unlike C&C regulations, MB environmental regulations, whose prominent feature is to control pollution through market prices, provide flexibility to polluters. If signals are correctly or optimally designed and implemented, MB environmental regulatory policies (e.g., tradable permits or environmental taxes) incentivize polluters' pollution abatement efforts. This allows the polluter to internalize the negative externality. Moreover, it allows polluters to pay for the negative externality or make environmentally friendly investments that reduce pollution. For instance, in the case of a tax-based environmental regulation policy, polluters can make the optimal decision by comparing the marginal cost of reducing pollution with the cost of environmental taxes. Moreover, polluters may be motivated by the additional benefits of reducing pollution by considering the cost of pollution in their production decisions (Stavins 2003; Guo et al. 2021). The MB environmental regulations are based on taxes and have the theoretical potential to enhance environmental quality, encourage green innovations, and motivate businesses and energy structures to be environmentally friendly (Bozatli and Akca 2023). These regulations can achieve these goals by reducing pollution, promoting green transformation, advancing environmental technology, and improving the energy structure. Researchers suggest that the implementation of MB-based environmental regulations can play a significant role in achieving environmental sustainability (Fang et al. 2022).

The effectiveness of C&C and MB environmental regulation is closely related to institutional capacity. Regulatory bodies should control the compliance of policies and impose sanctions if necessary. Nonetheless, in terms of regulatory capacity in developing countries, the effectiveness of environmental regulations decreases because of monitoring, enforcement, legal gaps and inconsistencies, qualified personnel, inadequate financing, political instability, inadequate

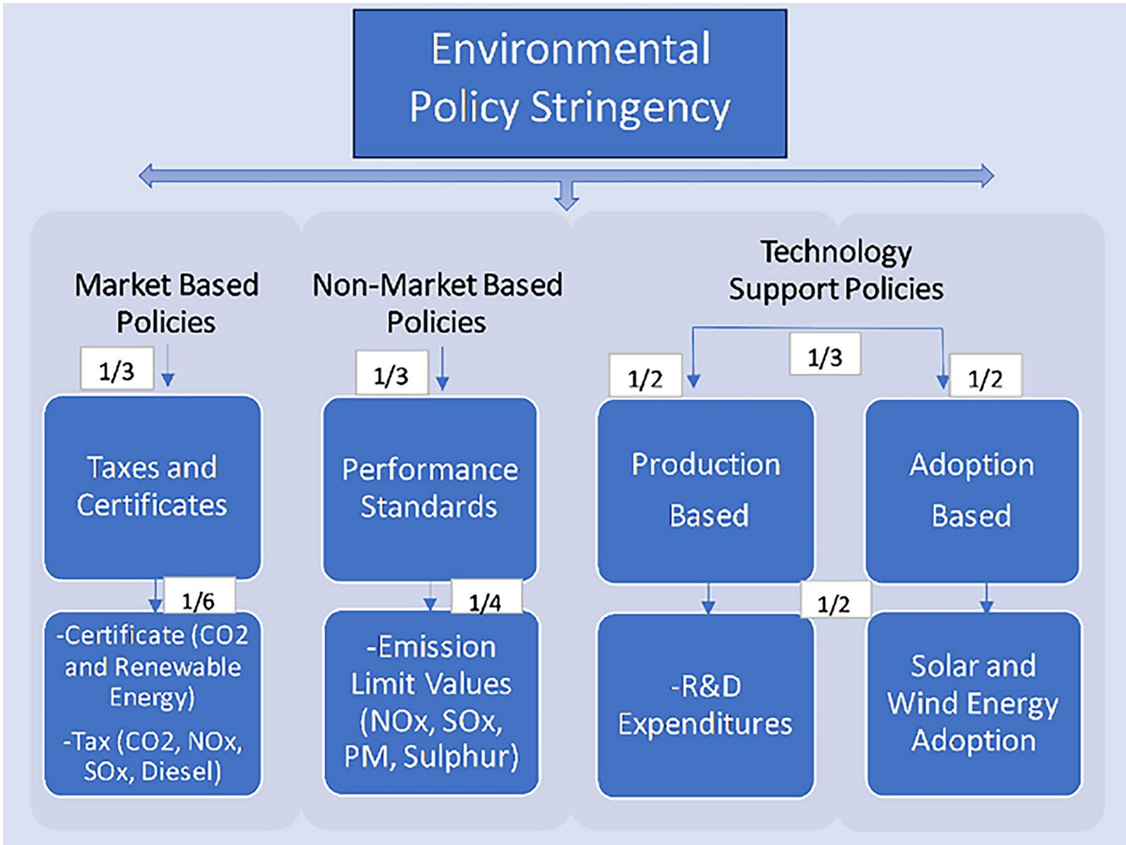


Fig. 1 Environmental policy stringency source: Kruse et al. (2022)

public pollution control facilities, and many firms that are difficult to monitor and control (Blackman et al. 2018). On the other hand, because C&C and MB environmental regulations have different structures in terms of compliance, monitoring, supervision, enforcement, and regulation, their effects may also differ. In addition, it is rather complex to isolate the effects of specific (market and traditional) environmental regulatory policies on the environment since environmental policies are designed as a whole and complementary. Therefore, considering these issues, it is an empirical problem to understand whether environmental regulations are effective and, if so, which policy choice is effective or ineffective, especially in developing countries.

So as to, monitor the trend of environmental regulations and empirically test their effects, Botta and Kozluk (2014) developed an index measuring the stringency of environmental policy in Organization for Economic Co-operation and Development (OECD) and BRICS[1] countries. Kruse et al. (2022) recently updated the index by expanding its content. While MB and C&C regulations had equal weight in the previous index, technology support policies were included in the new index. Figure 1 shows the content of environmental policy stringency and the weights used to calculate the index.

As can be seen from Fig. 1, environmental policy stringency consists of MB, non-market-based traditional C&C policies, and technology support policies. The three principal regulatory policies are given equal weight in the index calculation. MB policies include environmental taxes and certificates, whereas C&C regulatory policies comprise emission limit values. Technology support policies, newly included in the index, consist of research and development (R&D) expenditures for production and adoption and calculations for using green energy types. The index value takes a minimum value of 0 (no policy or completely flexible) and a maximum value of 6 (the strictest environmental regulations). Figure 2 presents the trend of environmental policy stringency and its subcomponents in the OECD, BRICS, and Turkey for 1990–2020.

The data presented in Fig. 2 show that, generally, environmental policy stringency, i.e., the intensity of environmental regulations, has increased over the three decades. However, regarding subcomponents, MB regulatory stringency has

[1] Brazil, Russia, India, China, and South Africa.

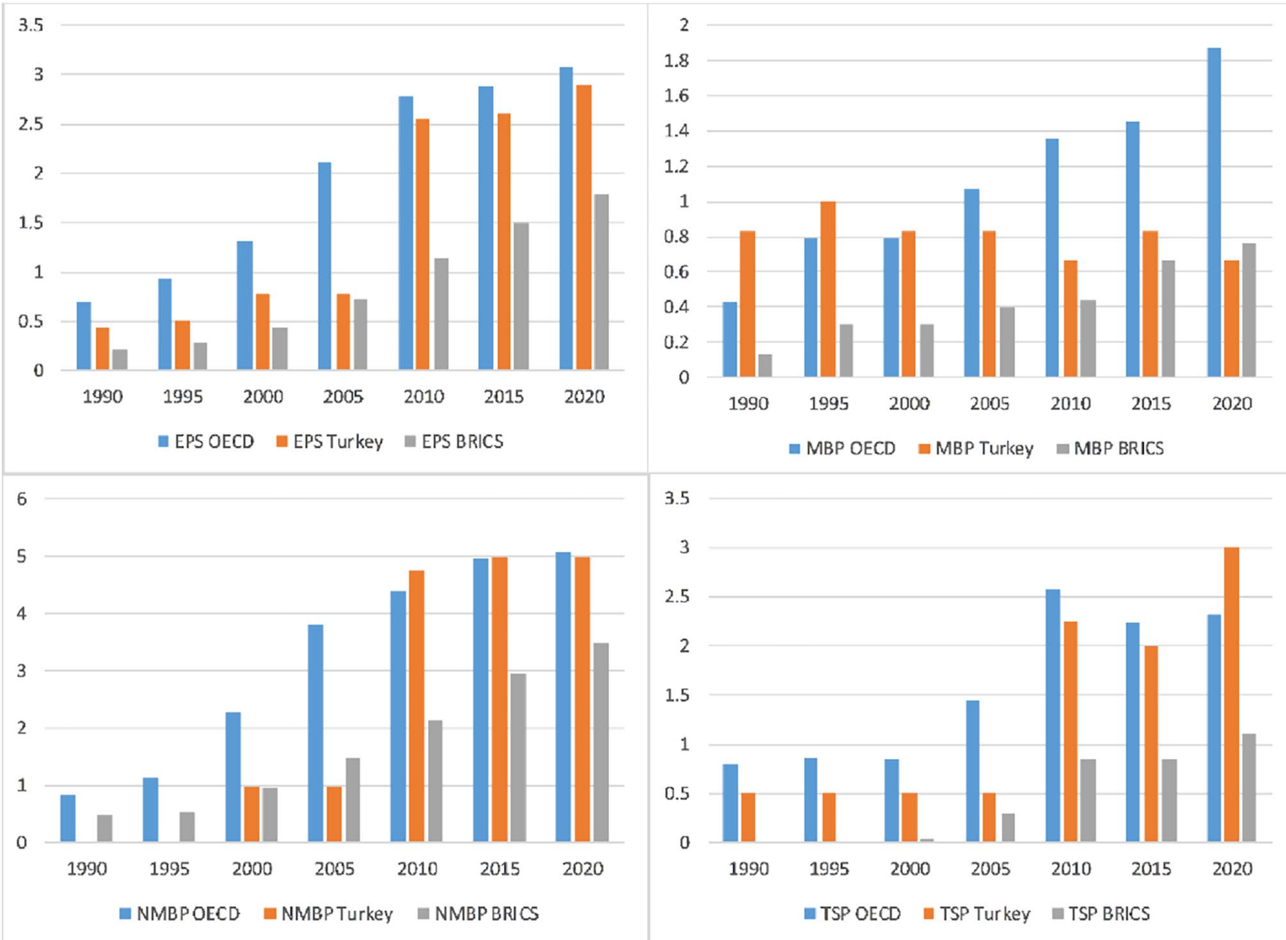


Fig. 2 Environmental policy stringency development in the OECD, BRICS and Turkey source: Kruse et al. (2022)

increased in both OECD and BRICS countries, whereas the opposite is true in Turkey. On the other hand, while it is a fact that non-market-based environmental regulations increase the stringency for each sample, Turkey has shown a relatively significant stringency trend compared with the others. Moreover, Turkey is relatively more aggressive regarding technology support policies than the OECD and BRICS countries. Although such a strict technology support policy is followed in Turkey, it ranks lower than both groups regarding environmental technological patents (Saqib et al. 2022). Therefore, testing the effectiveness of environmental regulations in Turkey would be an important empirical investigation based on these data and trends. This first argument is an essential motivation for this study.

Second, when empirical research on the connection between environmental regulations and environmental quality is examined, it is observed that studies focus on carbon dioxide ($CO_{2)}$ emissions and ecological footprint (EFP). Because these indicators reflect only the result of a demand for the environment, the supply side needs to be addressed. In other words, there is a need for an indicator that accurately reflects both the supply and demand side in terms of environmental sustainability. In order to overcome this deficiency, the load capacity factor has recently started to be preferred in the literature. The load capacity factor is a crucial metric for measuring environmental sustainability. This factor indicates the proportion of biological capacity to the EFP, which reflects the supply-to-demand ratio (Pata and Kartal 2023). As Sun et al. (2023) note, this metric is reliable for balancing the natural resources we consume and those we preserve for future generations. As far as we know, the relationship between environmental regulations and the load capacity factor has yet to be tested in the literature. This is a paramount contribution to the literature and another motivation for this study. Also, as shown in Fig. 3, Turkey's environmental sustainability is seriously threatened. In other words, biocapacity (supply) cannot meet the EFP (demand), and Turkey's load capacity is far below the sustainability limit of 1. Therefore, testing the impact of environmental regulations is necessary to develop solutions to this problem.

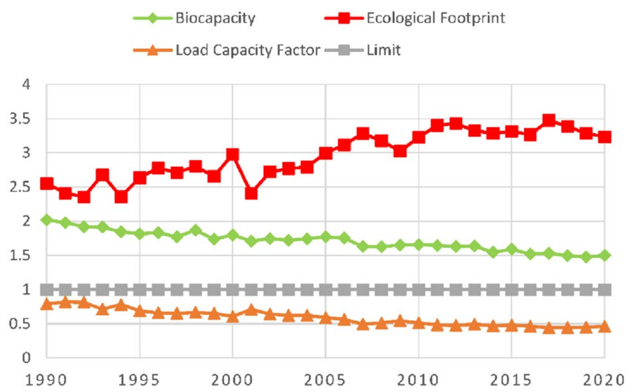


Fig. 3 Environmental sustainability in Turkey source: global footprint network

Third, to the best of our knowledge, only Guo et al. (2021) and Lee et al. (2022) have investigated the impact of MB and non-market-based environmental regulations using environmental policy stringency. Therefore, the effect of the composition of environmental regulations has also been neglected in the empirical literature and requires more evidence. On this basis, this study comparatively analyzes the impact of MB and non-market-based environmental regulations as well as technology support policies on environmental sustainability, presumably for the first time. However, in some studies analyzing the effects of environmental regulations in the literature, the findings on the validity of the environmental Kuznets curve (EKC) hypothesis need to be clarified. Moreover, no study has questioned the validity of the load capacity curve (LCC) while investigating the impact of environmental regulations. In this context, this study tests the validity of the EKC and LCC hypotheses by using the load capacity factor and EFP as dependent variables. In this way, a window comparable to the existing literature is opened, and the strengthened results are provided. Finally, we aim to obtain results robust to structural breaks using the new Fourier-based augmented autoregressive distributed lag (A-ARDL) method developed by Syed et al. (2023) and to provide the robust results by controlling with the Fourier-based dynamic least squares (DOLS) process.

The remainder of the research is structured as follows. The second section contains the literature review. The third section presents the data, models, and methodology. Section Four provides the empirical results. The findings are discussed in the fifth part. The last section presents the conclusions and policy recommendations.

Literature review

Researchers often use the environmental policy stringency index as a substitute for environmental regulation in empirical studies. In contrast, environmental quality is typically measured through indicators such as the EFP and CO_2 emissions. The results of these studies generally indicate that environmental regulations effectively decrease air pollution and other forms of environmental degradation.

However, while Hassan et al. (2022) and Afshan et al. (2022) suggest that environmental regulations have a positive effect on environmental pollution, some studies report that this effect is statistically insignificant (Asici and Acar 2016, 2018; Alkan and Bulut 2022; Hondroyiannis et al. 2022). Moreover, Yirong (2022) and Assamoi and Wang (2023) underline the asymmetric relationship between environmental regulations and environmental quality. The authors find that a positive shock in environmental regulations decreases environmental pollution and, conversely, a negative shock increases environmental pollution. Finally, some studies imply an inverted U-shaped relationship between environmental regulations and environmental quality (Wolde-Rufael and Weldemeskel 2020; Zhang et al. 2020; Wolde-Rufael and Weldemeskel, 2021; Lee et al. 2022). In other words, environmental regulations reduce environmental pollution after a particular threshold value.

In the empirical literature investigating the impact of environmental regulations, the role of renewable energy has mostly been examined. These findings strongly suggest that renewable energy improves environmental quality. Again, a limited number of studies have investigated the validity of the EKC hypothesis. Asici and Acar (2016), Albulescu et al. (2022), Li et al. (2022), Afshan et al. (2022), and Chu and Tran (2022) provide evidence in favor of the validity of the EKC hypothesis, while Asici and Acar (2018), Wolde-Rufael and Weldemeskel (2021), Alkan and Bulut (2022), Aldieri et al. (2022), Chen et al. (2022b) claim otherwise. The summary findings of the empirical literature are presented in Table 1.

Finally, the relationship between the subcomponents of environmental regulations and environmental pollution has been the subject of interest in limited empirical studies. Acemoglu et al. (2012) and Acemoglu et al. (2016), using a two-sector directed technical change model, argue that under the assumption that clean and dirty energy inputs are strong substitutes for each other, optimal MB environmental regulations consisting of environmental taxes and subsidies can prevent environmental disasters by enabling green transformation. Lamperti et al. (2020) tested the effectiveness of C&C and MB environmental regulations on technical change based on an endogenous growth and directed technical change model. The authors argue that MB environmental regulations are inefficient due to path dependence, whereas C&C environmental regulations are efficient regardless of implementation time. Lee et al. (2022) analyzed environmental regulations separately as MB and non-market-based and concluded that there is a nonlinear relationship. Guo et al. (2021) analyzed environmental regulations separately

Table 1 Literature summary

Authors	Sample	Method	Independent variables	Findings	EKC
Dependent variable: CO_2					
Albulescu et al. (2022)	1990–2015-32 Country	PQR	EPS, REC	EPS (−) REC (−)	Valid
Aldieri et al. (2022)	2002–2017 Developed Countries	GMM	EPS	EPS (−)	Invalid (N-Shaped)
Alkan and Bulut (2022)	1990–2015- Turkey	ARDL	EPS	EPS (insignificant)	Invalid
Assamoi and Wang (2023)	1985–2020 (US) 1995–2020 (China)	NARDL	(pos) EPS (neg) EPS	(pos) EPS (−) (neg) EPS (+)	–
Saqib and Usman (2023)	2012–2020 (USA and China)	QARDL	EPS, REC	EPS (−) REC (−)	–
Chen et al. (2022a)	1993–2019- China	ARDL	EPS, REC	EPS (−) REC (−)	–
Fatima et al. (2023)	1990–2020-OECD	PC	EPS	EPS (−)	–
Hafeez et al. (2022)	1995–2020 Asian Countries	PC	EPS	EPS (−)	–
Hassan et al. (2022)	1990–2020-OECD	PC	EPS	EPS (+)	–
Hondroyiannis et al. (2022)	1980–2019-OECD	PD	EPS	EPS (insignificant)	–
Junsong et al. (2022)	1995–2019-G-7	PC	EPS	EPS(−)	–
Li et al. (2023a)	2008–2018- China	PD	EPS	EPS(−)	–
Li et al. (2023b)	1990–2019-BRICS	PC	EPS, REC	EPS (−) REC (−)	–
Li et al. (2022)	2001–2018-OECD	PC	EPS	EPS(−)	Valid
Wang et al. (2020)	1990–2015-OECD	GMM	EPS	EPS (−) REC (−)	–
Wang et al. (2022)	1990–2019-BRICS	PC	EPS, REC	EPS (−) REC (−)	–
Wolde-Rufael and Weldemeskel (2020)	1993–2014 BRICST	PC	EPS, REC	EPS (Inverted U) REC (−)	–
Wolde-Rufael and Weldemeskel (2021)	1994–2015 7 Emerging Countries	PC	EPS, REC	EPS (Inverted U) REC (−)	Invalid
Yirong (2022)	1990–2019 High-pollution countries	PNARDL	EPS	(pos) EPS (−) (neg) EPS (+)	–
Zhang et al. (2020)	2008–2016-China	TR	ER	EPS (Inverted U)	–
Dependent Variable: EFP					
Afshan et al. (2022)	1990–2017-OECD	PC	EPS, REC	EPS (+) REC (−)	Valid
Afshan et al. (2023)	2000–2017- China	QARDL	EPS	EPS (−)	–
Asici and Acar (2016)	2004–2018-116 Country	PD	ER	ER (insignificant)	Valid
Asici and Acar (2018)	2004–2010-87 Country	PD	ER	ER (insignificant)	Invalid
Balsalobre-Lorente et al. (2023)	1994–2018 APEC Countries	PC	EPS, REC	EPS (−) REC (−)	–
Chen et al. (2022b)	1990–2016 27 OECD/6 Other	PC	EPS	EPS (−)	Invalid (OECD) Valid (Other)
Chu and Tran (2022)	1990–2015-OECD	PQR	EPS, REC	EPS (−) REC (−)	Valid
Dai and Du (2023)	1995–2021-BRICST	PC	EPS, REC	EPS (−) REC (−)	–
Kongbuamai et al. (2021)	1995–2016 BRICS	PC	EPS, REC	EPS (−) REC(+)	–
Lee et al. (2022)	1990–2017-132 Country	PQR	EPS	EPS (Inverted U)	–
Luo and Mabrouk (2022)	1990–2018 Resource-rich countries	PC	EPS	EPS (−)	–
Wang et al. (2023a, b)	1990–2019-EU	PC	EPS	EPS (−)	–

CO_2 Carbon Emissions *EFP* Ecological Footprint *EPS* Environmental Policy Stringency *REC* Renewable Energy Consumption *EKC* Environmental Kuznets Curve *POS* Positive Shock *NEG* Negative Shock *EU* European Union *OECD* Organization for Economic Co-operation and Development *TR* Threshold Regression *PC* Panel Cointegration *PD* Panel Data *GMM* Generalized Method of Moments *PQR* Panel Quantile Regression *ARDL* Autoregressive Distributed Lag Model *NARDL* Nonlinear Lag Distributed Autoregressive Model *QARDL* Lag Distributed Autoregressive Quantile Model

Table 2 Description of Variables

Variable	Symbol	Unit	Source
Load capacity factor	lcf	Biocapacity/ecological footprint	GFN
Ecological footprint	efp	Per Capita	GFN
Environmental regulation	eps	Index (0–6)	OECD
Market-based environmental regulation	mbp	Index (0–6)	OECD
Non-market-based environmental regulation	nmbp	Index (0–6)	OECD
Technology support Policies	tsp	Index (0–6)	OECD
Economic growth	gdp	Per Capita (2015 $ Constant Prices)	WDI
Renewable energy consumption	ren	(%) Total Energy Consumption	WDI

as MB and C&C policies. The authors argue that both C&C and MB environmental regulations affect greenhouse gas (GHG) mitigation in OECD countries, with countries favoring strict C&C environmental regulations and moderate MB regulatory policies. Moreover, the authors emphasize that C&C environmental regulations lower GHG emissions by raising technology standards rather than changing the energy consumption structure. Conversely, MB environmental regulations facilitate the mitigation of GHG by means of the mediation effects of technological advancement and energy consumption structure.

Findings from empirical studies show that environmental regulations and renewable energy relatively reduce environmental pollution. Studies have mostly used CO_2 emissions and EFP, which reflect the demand side, as environmental quality indicators. No study has used the load capacity factor variable, which is more comprehensive than these two indicators and is considered an essential environmental sustainability metric. On the other hand, while it is a standard view that the economic growth process increases environmental pollution, the findings regarding the EKC hypothesis are unclear. Considering the literature mentioned above and the review and evaluations, we can say that this study is the first to examine the impact of environmental regulations and their components (MB, C&C, technology support policies) on the load capacity factor in Turkey within the framework of the LCC hypothesis.

Data, model, and methodology

Data and the model

This study examines the impact of environmental regulations, economic growth, and renewable energy consumption on Turkey's load capacity factor and EFP within the framework of the LCC and EKC hypotheses using annual data from 1990 to 2020. Information on the data sources used in the study is presented in Table 2, and the empirical model is presented in Eq. (1) and Eq. (2):

$$\ln \mathrm{lcf}_t = \beta_0 + \beta_1 \ln X_t + \beta_2 \ln \mathrm{gdp}_t + \beta_3 \ln \mathrm{gdp}_t^2 + \beta_4 \ln \mathrm{ren}_t + \varepsilon_t \quad (1)$$

$$\ln lefp_t = \beta_0 + \beta_1 \ln X_t + \beta_2 \ln gdp_t + \beta_3 \ln gdp_t^2 + \beta_4 \ln ren_t + \varepsilon_t \quad (2)$$

The coefficients $\beta_2, \beta_3, \beta_4$ in Eqs. (1) and (2) represent the coefficients for economic growth, the square of economic growth, and renewable energy, respectively. β_0 and ε_t represent the constant coefficient and error term, respectively. X represents the set of environmental regulations. In other words, the sum of environmental regulations, MB environmental regulations, non-market-based environmental regulations, and technology support policies will be tested separately. Thus, the effectiveness of the composition of environmental regulations on environmental sustainability and the overall policy framework will be revealed.

Methodology

The study's four-stage empirical analysis procedure is shown in Fig. 4. First, the unit root features of the variables are investigated. In the second stage, a long-run relationship within the scope of the model (1–2) is investigated by the cointegration method. Long-run coefficient estimates will

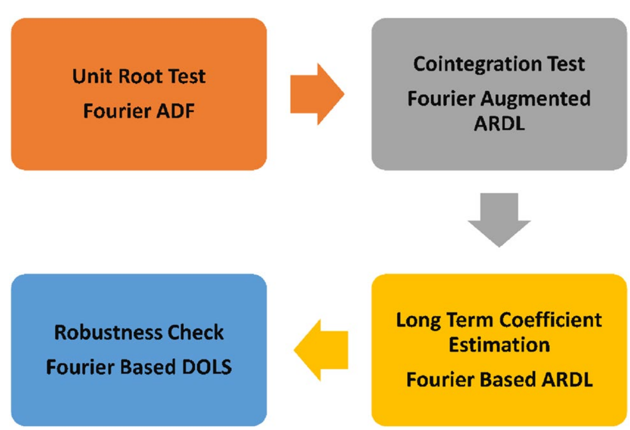


Fig. 4 Empirical strategy

be made in the third stage if a cointegration relationship is determined. In the last stage, robustness analysis of the long-run coefficient estimates is performed, and the analysis process is finalized.

Fourier ADF unit root test

Enders and Lee (2012) proposed a unit root test considering smooth structural breaks in the series. The authors used sine and cosine functions to construct a deterministic term that can capture smooth structural breaks, as shown below:

$$\alpha(t) = \alpha_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) \quad (3)$$

where k denotes the Fourier terms, by adding the deterministic term to the conventional augmented Dickey–Fuller (ADF) equation, the test becomes the Fourier ADF (FADF) unit root test.

$$\Delta y_t = \alpha_1 + \delta t + \beta y_{t-1} + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \sum_{i=1}^{p} \vartheta_i \Delta y_{t-i} + u_t \quad (4)$$

Enders and Lee (2012) proposed a two-stage procedure for applying the FADF test. In the first step, estimation is performed in the range $1 \le k \le 5$, and the model with the lowest sum of residual squares is selected as the appropriate model. In the second step, the F-test is used to assess the significance of the Fourier terms. If the Fourier terms are significant, a t-test is used to determine whether the null hypothesis of the unit root is valid. However, if the Fourier terms are insignificant, they recommend using the ADF unit root test instead of the FADF test.

Fourier-based augmented ARDL bounds test

Researchers often prefer the autoregressive distributed lag (ARDL) model developed by Pesaran et al. (2001) in empirical analyses. This test provides flexibility to researchers as it allows independent variables to have mixed degrees of integration under the assumption that the dependent variable is I(1). Nonetheless, McNown et al. (2018) and Sam et al. (2019) have recently criticized the ARDL method. As Pesaran et al. (2001) argue, especially in most empirical analyses, the requirement that the dependent variable is I(1) and the t-bound test is valid is ignored. For these reasons, as Pesaran et al. (2001) emphasize, degenerate cases emerge, and unreliable results are obtained (Sam et al. 2019). Thus, on a side note, the general F-test and t-test, McNown et al. (2018) and Sam et al. (2019) proposed the F-test for independent variables to address the aforementioned issues. The test statistics recommended for the validity of the cointegration relationship are as follows:

(i) $F - \text{overall}|H_0 : \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0.$

(ii) $t - \text{dependent}|H_0 : \beta_1 = 0.$

(iii) $F - \text{independent}|H_0 : \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0.$

For the cointegration relationship to be valid, the calculated test statistics should be greater than the critical values. If even one of the tests is less than the critical values, the cointegration relationship is invalid (Akca 2021). If the overall F-statistic and t-statistics are significant and the F-independent statistics are insignificant, a degenerate case 1 occurs. Again, if the overall F and F-independent statistics are significant and the t-statistic is insignificant, degenerate case 2 is formed (Sam et al. 2019). In this context, Pesaran et al. (2001) proposed the following ARDL model to investigate the long-run relationship:

$$\begin{aligned}\Delta y_t =& \alpha_0 + \sum_{i=1}^{p-1} \alpha_i \Delta y_{t-i} + \sum_{i=1}^{p-1} \gamma_i \Delta x_{t-i} + \sum_{i=1}^{p-1} \delta_i \Delta z_{t-i} \\ &+ \sum_{i=1}^{p-1} \upsilon_i \Delta \ln w_{t-i} + \sum_{i=1}^{p-1} \delta_i \Delta \ln q_{t-i} \quad (5) \\ &+ \beta_1 y_{t-1} + \beta_2 x_{t-1} + \beta_3 z_{t-1} + \beta_4 w_{t-1} + \beta_5 q_{t-1} + v_t\end{aligned}$$

where α_0 is the constant term and v_t is the error term. $\alpha_i, \gamma_i, \delta_i, \upsilon_i, \delta$ and $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ are the short and long run coefficients, respectively.

Again, the augmented ARDL method does not consider structural changes, which is a significant shortcoming. To overcome this problem, we follow Syed et al. (2023) and Apergis et al. (2023) and include Fourier terms in the augmented ARDL model to model smooth structural breaks.

$$\begin{aligned}\Delta y_t = \alpha_0 &+ \sum_{i=1}^{p-1} \alpha_i \Delta y_{t-i} + \sum_{i=1}^{p-1} \gamma_i \Delta x_{t-i} + \sum_{i=1}^{p-1} \delta_i \Delta z_{t-i} \\ &+ \sum_{i=1}^{p-1} \upsilon_i \Delta \ln w_{t-i} + \sum_{i=1}^{p-1} \delta_i \Delta \ln q_{t-i} \quad (6) \\ &+ \beta_1 y_{t-1} + \beta_2 x_{t-1} + \beta_3 z_{t-1} + \beta_4 w_{t-1} + \beta_5 q_{t-1} \\ &+ \beta_6 \sin\left(\frac{2\pi kt}{T}\right) + \beta_7 \cos\left(\frac{2\pi kt}{T}\right) + e_t\end{aligned}$$

If a cointegration relationship is detected, long-run coefficients will be estimated by the Fourier-based ARDL method. In addition, the models will be estimated using the Fourier-based DOLS method for the robust results.

Empirical results

In the empirical analysis process, it is first necessary to determine the degree of integration of the series. The Fourier ADF Enders and Lee (2012) test, which considers smooth structural breaks, was applied in this context. The findings are presented in Table 3:

Table 3 Unit root test results

FADF						ADF	
Variables	$I(0)$	$k(p)$	$I(1)$	$k(p)$	F-Test	$I(0)$	$I(1)$
LCF	−2.727	1(2)	−4.764*	3(2)	2.288	−1.246	−7.835*
EFP	−2.934	1(2)	−6.025*	2(1)	1.457	−1.383	−9.551*
EPS	−2.313	1(1)	−5.423*	1(1)	2.597	−0.699	−8.250*
MBP	−1.019	5(1)	−9.218*	5(0)	4.295	−1.224	−8.534*
NMBP	−1.872	1(0)	−5.655*	3(0)	2.426	−0.420	−5.305*
TSP	−0.582	2(1)	−7.365*	2(0)	1.698	−0.673	−6.472*
GDP	−0.143	4(0)	−6.244*	4(0)	0.783	0.107	−5.525*
GDP2	−0.056	4(0)	−6.146*	4(0)	0.793	0.188	−5.454*
REN	−1.657	4(2)	−6.878*	1(1)	3.024	−1.493	−5.881*

* Indicates that the null hypothesis is rejected at a 1% significance level. Optimum lag lengths (p) are chosen using SIC. k denotes the frequency number of Fourier terms

Table 4 Fourier A-ARDL cointegration test results (Model 1)

Dependent variable: LCF			Diagnostic tests				
Model	Statistics	Value	X_{sc}	X_H	X_N	X_{FF}	C/CSQ
Model_1	$F_{general}$	11.02*	1.132 (0.407)	1.717 (0.259)	0.806 (0.608)	0.962 (0.371)	Stable Stable
	$t_{dependent}$	−4.50**	lcf = f(esp,gdp,gdp^2,ren) Cointegration (✓)				
	$F_{independent}$	11.77*	Diagnostic Check (✓)				
Model_2	$F_{general}$	13.64*	6.910 (0.075)	0.608 (0.809)	1.653 (0.437)	0.123 (0.743)	Stable Stable
	$t_{dependent}$	−7.05*	lcf = f(mbp,gdp,gdp^2,ren)				
	$F_{independent}$	16.51*	Cointegration (✓) Diagnostic Check (✓)				
Model_3	$F_{general}$	10.82*	6.079 (0.045)	1.096 (0.482)	0.839 (0.657)	0.001 (0.973)	Stable Stable
	$t_{dependent}$	−5.03*	lcf = f(nmbp,gdp,gdp^2,ren)				
	$F_{independent}$	8.58*	Cointegration (✓) Diagnostic Check (✓)				
Model_4	$F_{general}$	8.14*	6.397 (0.056)	1.366 (0.370)	1.034 (0.596)	0.000 (0.977)	Stable Stable
	$t_{dependent}$	−5.43*	lcf = f(tsp,gdp,gdp^2,ren)				
	$F_{independent}$	9.82*	Cointegration (✓) Diagnostic Check (✓)				

* and ** denote significance at 1% and 5% levels, respectively. Probability values are reported in parentheses

The Fourier ADF unit root test results in Table 3 show that all series are stationary at the first difference. However, when the constraint test proposed by Enders and Lee (2012) is applied to the series, it is determined that the Fourier terms are insignificant. In this context, the conventional ADF test was also applied to the series, and the results remained valid.

After determining the degree of integration of the series, whether a long-run relationship can be examined. The relationship specified in the model (1) and (2) is tested using the Fourier A-ARDL cointegration method developed by Syed et al. (2023). The findings for cointegration and diagnostic tests are presented in Table 4 and Table 5:

According to the findings presented in Table 4 and Table 5 for both models, it is determined that there is a long-run relationship between the series. Both models' test statistics are greater than the lower- and upper-bound critical values presented in Table 6, respectively. In addition, for the cointegration relationship to be valid, the series should be normally distributed, the functional form should be significant, and finally, the Cusum and CusumSQ statistics (graphs are presented in the appendix) should be stable. The findings in Table 4 and Table 5 show no autocorrelation and heteroscedasticity problem in the model at 1% significance level, the model fits, the series is normally distributed, and the coefficients are stable. In this context, Fourier-based

Table 5 Fourier A-ARDL cointegration test results (Model 2)

Dependent variable EFP			Diagnostic tests				
Model	Statistics	Value	X_{sc}	X_H	X_N	X_{FF}	C/CSQ
$Model_1$	$F_{general}$	32.97*	0.489 (0.620)	0.600 (0.766	1.050 (0.591)	0.033 (0.855)	Stable Stable
	$t_{dependent}$	− 10.81*	efp = f(eps,gdp,gdp^2,ren) Cointegration (✓)				
	$F_{independent}$	17.25*	Diagnostic check (✓)				
$Model_2$	$F_{general}$	7.48**	6.030 (0.062)	0.490 (0.894)	1.385 (0.500)	8.349 (0.034)	Stable Stable
	$t_{dependent}$	− 5.03*	efp = f(mbp,gdp,gdp^2,ren)				
	$F_{independent}$	9.13*	Cointegration (✓) Diagnostic check (✓)				
$Model_3$	$F_{general}$	38.45*	0.785 (0.470)	0.690 (0.696)	5.764 (0.055)	0.789 (0.384)	Stable Stable
	$t_{dependent}$	− 11.61*	efp = f(nmbp,gdp,gdp^2,ren)				
	$F_{independent}$	20.57*	Cointegration (✓) Diagnostic check (✓)				
$Model_4$	$F_{general}$	14.24*	4.413 (0.066)	3.101 (0.052)	0.970 (0.615)	4.299 (0.076)	Stable Stable
	$t_{dependent}$	− 7.12*	efp = f(tsp,gdp,gdp^2,ren)				
	$F_{independent}$	17.66*	Cointegration (✓) Diagnostic check (✓)				

Note: * and ** denote significance at 1% and 5% levels, respectively. Probability values are reported in parentheses

Table 6 Fourier A-ARDL cointegration critical values

	Lower Bound I(0)			Upper Bound I(I)		
Test	10%	5%	1%	10%	5%	1%
$F_{general}$	3.43	4.15	5.85	4.62	5.54	7.57
$t_{dependent}$	− 3.13	− 3.41	− 3.96	− 4.04	− 4.36	− 4.96
$F_{independent}$	2.18	2.74	4.30	3.79	4.71	7.01

Critical values for *F*-general, *t*-dependent, and *F*-independent statistics are taken from Narayan (2005), Pesaran et al. (2021), and Sam et al. (2019), respectively

A-ARDL long-run coefficients are estimated for both models and the results are presented in Table 7 and Table 8:

Considering long-run coefficients presented in Table 7 and Table 8, it is possible to draw the following conclusions: (i) In both models, there is no statistically significant impact of environmental regulations. In other words, environmental regulations are ineffective policies on environmental quality. (ii) MB environmental regulations increase environmental quality in both models, whereas non-market-based environmental regulations are ineffective. Such a finding implies that MB environmental regulations are effective policies to improve environmental quality, while C&C regulations are ineffective. (iii) Conversely, technology support policies have a deteriorating effect on environmental quality in both models. (iv) Renewable energy improves environmental quality in both models. (v) Finally, according to the results of both models, the EKC and LCC hypotheses are valid. In this context, while income levels reduce environmental quality to a certain point, they increase

Table 7 Fourier A-ARDL long run estimation results (Model 1)

Dependent variable: LCF				
Variables	Coefficients			
EPS	0.088 (0.397)			
MBP		0.180* (0.005)		
NMBP			0.013 (0.432)	
TSP				− 0.025* (0.002)
GDP	− 38.517* (0.002)	− 30.550* (0.000)	− 30.498* (0.000)	− 24.981* (0.000)
GDP2	2.165* (0.002)	1.694* (0.000)	1.702* (0.000)	1.385* (0.000)
REN	0.869* (0.020)	0.526* (0.005)	0.553* (0.003)	0.422* (0.000)

*, **, and *** indicate significance at 1%, 5%, and 10% levels, respectively. Probability values are reported in parentheses

Table 8 Fourier A-ARDL Long Run Estimation Results (Model 2)

Dependent variable: EFP				
Variables	Coefficients			
EPS	0.036 (0.297)			
MBP		−0.128** (0.011)		
NMBP			0.018*** (0.052)	
TSP				0.040* (0.000)
GDP	17.540* (0.002)	27.704* (0.000)	17.493* (0.001)	15.243* (0.000)
GDP2	−0.950* (0.004)	−1.528* (0.000)	−0.946* (0.002)	−0.818* (0.000)
REN	−0.187** (0.045)	−0.356** (0.046)	−0.232* (0.009)	−0.033 (0.310)

*, **, and *** indicate significance at 1%, 5%, and 10% levels, respectively. Probability values are reported in parentheses

environmental quality after the turning point. This relationship is presented representatively in Fig. 5.

In order to test the robustness of the findings obtained from the Fourier A-ARDL estimator, the models were re-estimated with the Fourier-based DOLS method, and the results are presented in Table 9 and Table 10. The findings obtained from the Fourier-based DOLS estimator indicate that the results remain strongly valid.

Discussion

When the linkages of the findings with the empirical literature and the theoretical foundations are analyzed, it is possible to establish the following connections: First, it is determined that environmental regulations do not significantly affect environmental quality. Such a discovery is compatible with the findings of Asici and Acar (2016), Asici and Acar (2018,) Alkan and Bulut (2022), and Hondroyiannis et al. (2022). Again, the findings differ when the effect of the subcomponents of environmental regulations is tested. Namely, while MB environmental regulations improve environmental quality, C&C regulations and technology support policies are ineffective.

Such a finding is consistent with theoretical expectations. Namely, it is not cost-effective to regulate all polluters with the same target within the framework of C&C regulations. This is because the costs of controlling pollution vary widely across firms, and the cost-effective technology for one polluter may not be for another. Therefore, control costs may vary greatly depending on the firm's structure. However, C&C regulations can theoretically provide a cost-effective solution. Although, it is necessary to set standards specific to each pollutant and pollution source, and policymakers should be informed about the compliance costs of each firm. Moreover, C&C regulations tend to stifle technologies that could potentially lead to higher levels of pollution reduction. In particular, the lack of additional financial incentives for polluters to further increase their pollution targets prevents the adoption of new green technologies (Stavins 2003; Guo et al. 2021). In contrast, MB environmental regulations motivate polluters to adopt technologies that enable

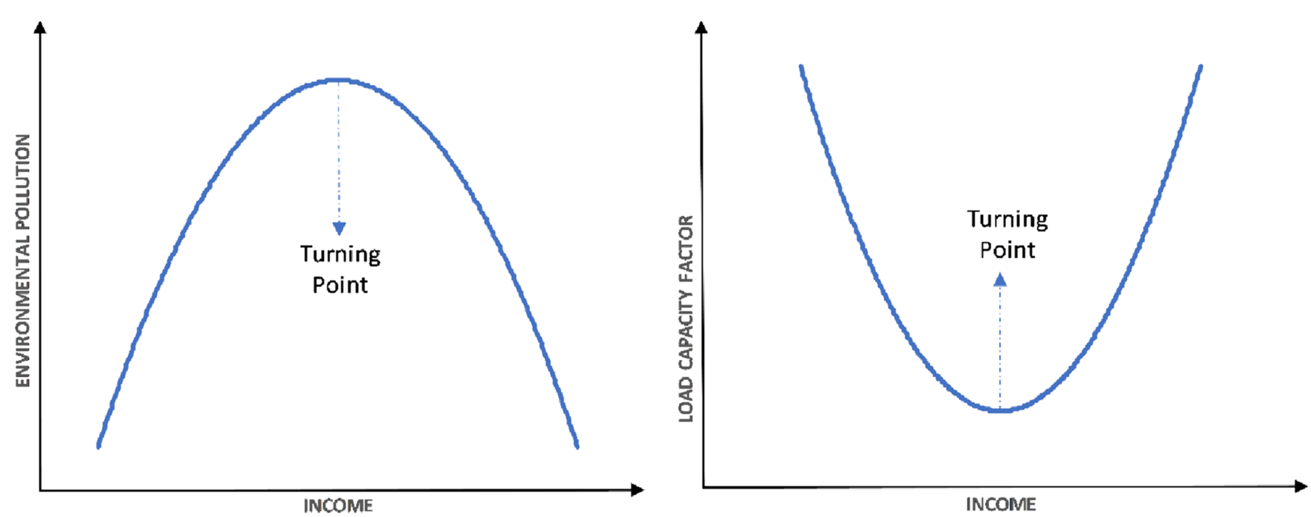


Fig. 5 Representation of the EKC and LCC

Table 9 Fourier-based DOLS estimation results (Model 1)

Dependent variable: LCF				
Variables	Coefficients			
EPS	−0.1160* (0.000)			
MBP		0.550* (0.000)		
NMBP			−0.019* (0.009)	
TSP				−0.037* (0.005)
GDP	−20.665* (0.000)	−28.528* (0.000)	−21.218* (0.000)	−16.442* (0.000)
GDP2	1.135* (0.001)	1.574* (0.002)	1.163* (0.000)	0.892* (0.000)
REN	0.331* (0.000)	0.797* (0.000)	0.466* (0.000)	0.343* (0.008)
SIN	−0.096* (0.000)	−0.181* (0.000)	−0.077* (0.000)	−0.061* (0.001)
COS	−0.078* (0.000)	−0.144* (0.000)	−0.095* (0.000)	−0.062** (0.030)

*, **, and ** * indicate significance at 1%, 5%, and 10% levels, respectively. Probability values are reported in parentheses

Table 10 Fourier-based DOLS estimation results (Model 2)

Dependent variable:: EFP				
Variables	Coefficients			
EPS	0.026 (0.374)			
MBP		−0.107** (0.046)		
NMBP			0.000 (0.990)	
TSP				0.026* (0.008)
GDP	23.698* (0.000)	24.835* (0.000)	23.023* (0.000)	20.678* (0.000)
GDP2	−1.308* (0.000)	−1.369* (0.000)	−1.268* (0.000)	−1.138* (0.000)
REN	−0.229*** (0.0596)	−0.255* (0.005)	−0.254** (0.013)	−0.164*** (0.077)
SIN	0.030*** (0.080)	0.037** (0.014)	0.026 (0.102)	0.027** (0.043)
COS	0.096* (0.000)	0.098* (0.000)	0.095* (0.000)	0.072* (0.002)

*, ** and ** * indicate significance at 1%, 5% and 10% levels, respectively. Probability values are reported in parentheses

a cost-effective allocation of resources and better pollution control/reduction without serious information (Coskun and Bozatli 2022). The results of this study support this view and show that MB environmental regulations effectively improve environmental quality. This finding is consistent with those of Acemoglu et al. (2012), Acemoglu et al. (2016), and Lee et al. (2022).

On the other side of the coin, we find that renewable energy enhances environmental quality in line with theoretical expectations. Such a finding is consistent with the empirical literature (Wang et al. 2020; Wolde-Rufael and Weldemeskel 2020; Wolde-Rufael and Weldemeskel, 2021; Albulescu et al. 2022; Chen et al. 2022a; Wang et al. 2022; Afshan et al. 2022; Chu and Tran 2022; Li et al. 2023b; Balsalobre-Lorente et al. 2023; Dai and Du 2023). Finally, each model provides evidence of the validity of Turkey's EKC and LCC hypotheses. This shows that Turkey's per capita income level has now reached a level that reduces environmental pollution. In addition, such a finding implies that in parallel with the increasing welfare level considering the income level, the environmental awareness of citizens and businesses has increased, and the demands for a cleaner and more sustainable environment have been tried to be met by the government's measures.

When the findings are analyzed against the theoretical and empirical background, it becomes clear that it is important to address the composition effect of environmental regulations. As shown in this study, focusing on policy impact in general may lead to misleading results and, hence, to useless policy guidance. In particular, given that some environmental regulations are incentive-based and flexible through the market mechanism, while others are rigid by setting limits/rules, it is important to determine whether the policies complement or undermine each other. Based on our empirical evidence, we are closer to the idea that policies of two different approaches that are part of a whole undermine each other. However, since each country has its own structure (economic, environmental, and institutional) and degree of environmental policy stringency, more research is needed to generalize the results. On the other side, the compositional effect discussed in this study is not obvious in the Porter hypothesis developed by Porter and Van der Linde (1995) regarding the relationship between environmental regulations and the environment. In this respect, the focus and findings of the study provide useful insights for improving the related hypothesis.

Conclusion and policy recommendations

It is essential to possess a profound comprehension of the effects of MB's and C&C's environmental regulatory policies to combat climate change optimally and ensure the preservation of environmental sustainability. As shown in this study, policymakers should consider the different potential impacts of MB and C&C policies. In this study, within the framework of the EKC and LCC hypotheses, the impact of environmental regulation and renewable energy policies implemented in Turkey on environmental quality is analyzed using novel Fourier-based econometric methods. The effects of environmental regulations are analyzed as a whole and separately. According to the findings, MB environmental regulations increase environmental quality in Turkey compared with C&C regulations and technology support policies. Such an effect of MB regulations, which are more flexible and cost-effective than C&C regulations, supports the perspective in the literature. Policymakers should reconsider this context's C&C regulations and technology support policies. In particular, restructuring both policies in an incentive-based, flexible, and cost-effective manner is necessary to improve environmental quality in Turkey. Generally, C&C regulations do not allow polluters flexibility on how and where to reduce emissions or pollution at an optimal cost. In such direct regulations, there is an assumption that the government knows the most appropriate solution and that polluters strictly comply. C&C regulations can also be costly as they do not provide any motivation to meet standards or targets. In this context, by using tax incentives, policymakers can reduce the R&D costs of green innovation and increase the cost-effectiveness of environmentally friendly firms that meet the specified criteria. In addition, policymakers should consider tax incentives for firms based on past green innovation achievements (Nordhaus 2021; Liao and Zhu 2023).

Regarding economic efficiency, MB approaches are often more cost-effective than C&C policies. Including C&C policies in MB policies increases market distortions and welfare losses. Therefore, MB environmental regulations are more appropriate instruments for efficient resource allocation (Tuladhar et al. 2014; Aghion et al. 2016). Although Tang et al. (2020) argue that shifting from C&C to MB policies is inevitable as countries' economic development and market systems improve, developments are moving in the opposite direction. As shown in Fig. 2, while the intensity of environmental regulations has increased in both OECD and BRICS countries, the stringency of C&C regulations has increased more significantly than MB policies. In contrast to these countries, in Turkey, the stringency of MB policies has decreased over time while the stringency of C&C regulations has increased. One reason for this situation is the effect of hiding political costs. There is evidence that citizens are more likely to support C&C regulatory policies that tend to hide political costs, as opposed to MB regulations that impose visible and perceptible costs. However, a pre-announced commitment to using the revenue generated (e.g., to subsidize public transportation using clean inputs) can counteract this negative effect (Beiser-McGrath et al. 2023). Therefore, policymakers must take action by considering the visible and perceived costs to balance the relationship between economic efficiency and political cost.

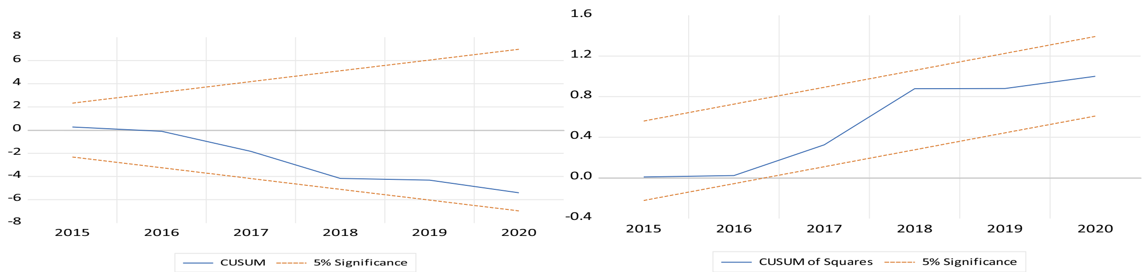
Policymakers should consider that change in technology use and green technology innovation should be at the center of a successful pollution reduction effort (Tuladhar et al. 2014). If the technological gap between dirty and clean technologies is initially too large, clean technologies will require a significant effort to catch up with dirty technology, undermining research and development efforts for clean technologies and transition to clean technology difficult (Acemoglu et al. 2016). Therefore, path dependence should be considered by policymakers and researchers when evaluating the effectiveness of different public policy instruments in the transition from traditional dirty technologies to clean, green technologies (Lamperti et al. 2020). Nevertheless, green innovation is a gradual process. In particular, investments in this direction may incur additional costs in the first stage, and the benefits may emerge in the long term. However, in the later stages, technological innovation achieved through R&D activities will provide significant environmental gains (Aydin et al. 2023). In this context, policymakers should prioritize environmental protection expenditures, environmental R&D expenditures, and environmental incentives in resource allocation.

Finally, since policy effects in one country cannot be directly applied to other countries, environmental policies must be evaluated across countries. Countries differ in many aspects, including income levels, the sectoral structure of their economies, productivity, and the structural policies implemented (Kruse et al. 2022). Therefore, environmental policies may have heterogeneous effects across countries.

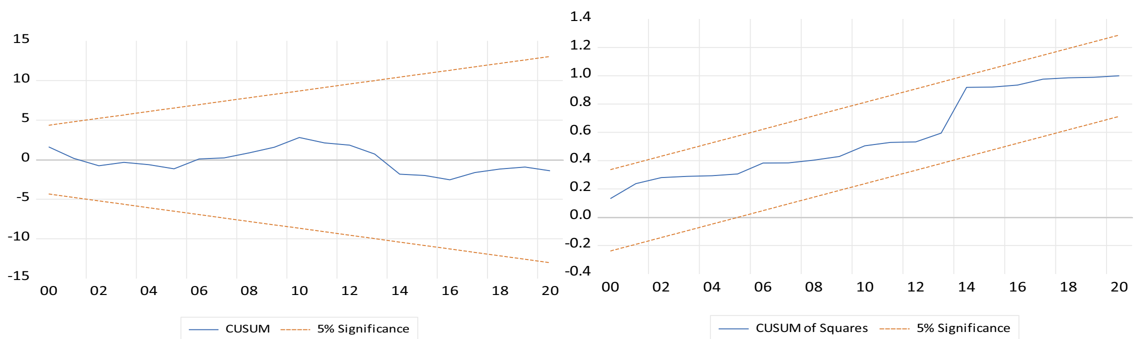
This study has some limitations. First, it is assumed that a linear relationship exists between environmental regulations and environmental quality. It would be meaningful for future studies to investigate this relationship, especially using nonlinear methods. Second, it is assumed that energy structure and technological innovation, which play an essential role in the impact of environmental regulations on environmental quality, have a mediating effect. It would be a noteworthy contribution to the literature for researchers to control the dynamic relationships among environmental regulations, energy structure, technological innovation, and environmental quality by considering this issue. Finally, further research testing the hypothesis that MB-based environmental regulations are more effective than C&C-based policies, as proposed in this study, will provide empirical clarification of the issue and pave the way for further discussions.

Appendix

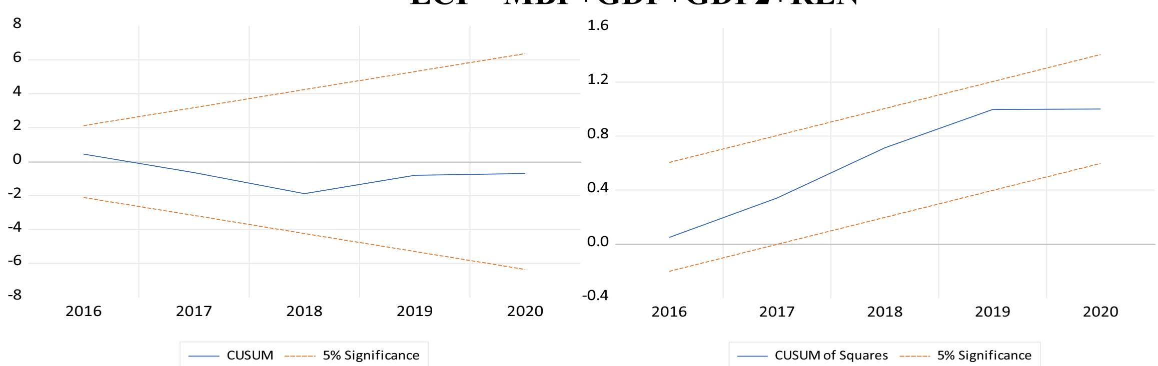
LCF= EPS+GDP+GDP2+REN



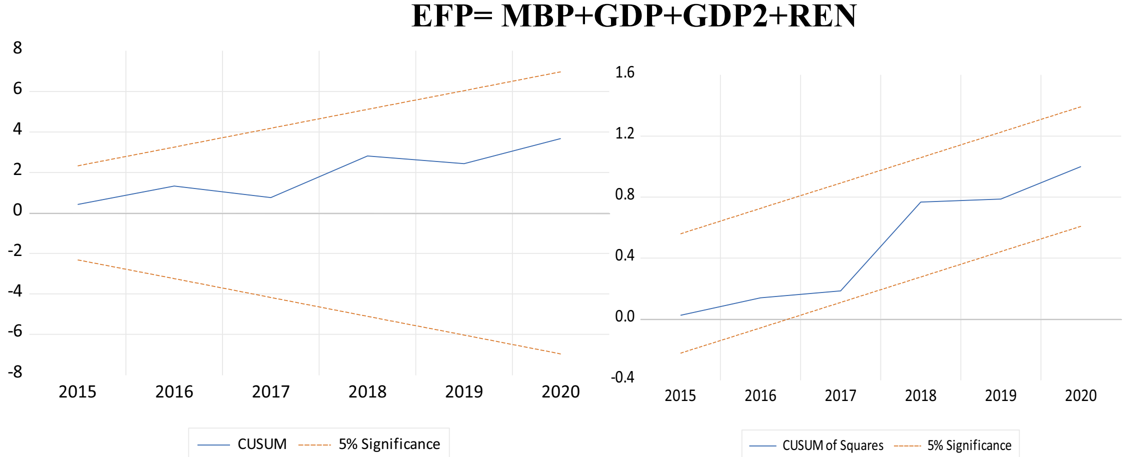
EFP= EPS+GDP+GDP2+REN



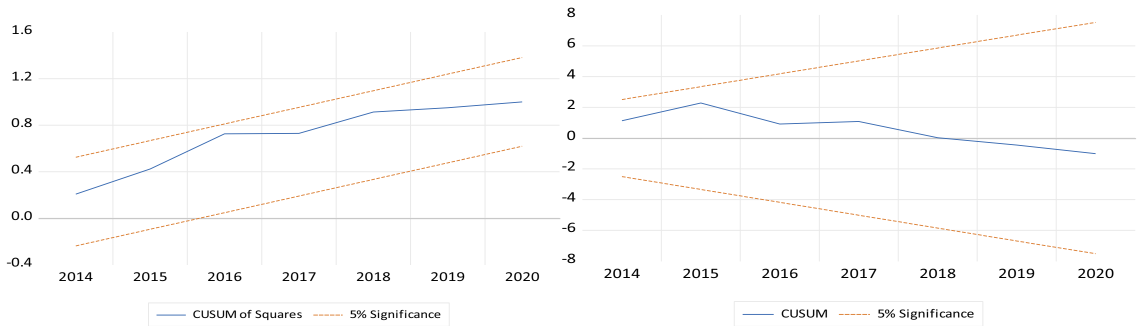
LCF= MBP+GDP+GDP2+REN



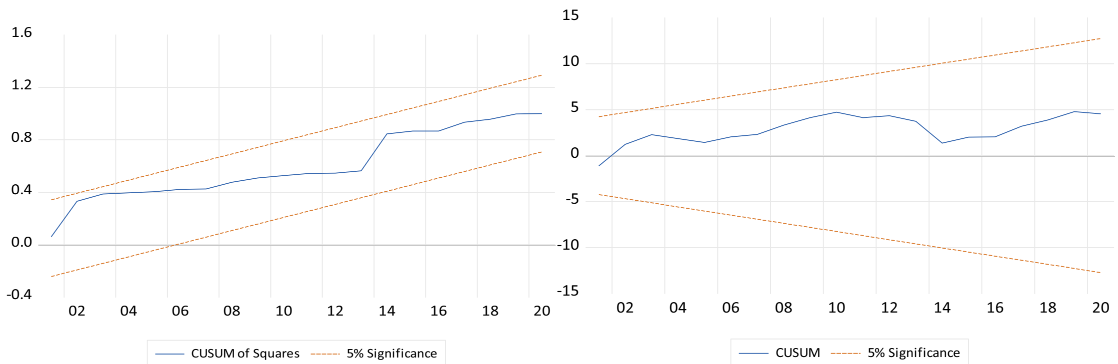
EFP= MBP+GDP+GDP2+REN



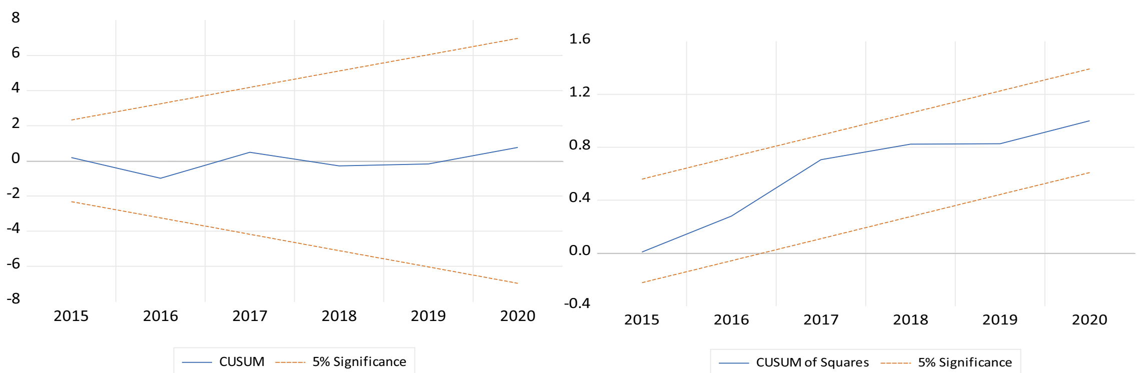
LCF= NMBP+GDP+GDP2+REN



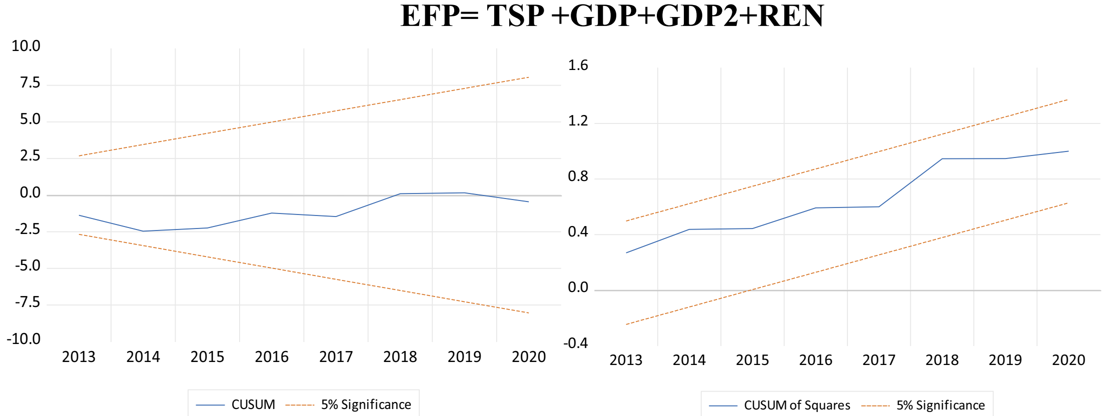
EFP= NMBP+GDP+GDP2+REN



LCF= TSP+GDP+GDP2+REN



EFP= TSP +GDP+GDP2+REN



Author contributions Corresponding author Oguzhan Bozatli carried out conceptualization, investigation, writing-original draft, formal analysis, software, supervision, writing-review and editing. Co-author Hasim Akca performed conceptualization, research, visualization, writing-original draft, writing-review and editing. All authors contributed to the study's conception and design.

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

Data availability Data used in this study are available from the authors upon request.

Code availability The codes used in this study are available from the authors upon request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

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