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Article *in* Energy · January 2023

DOI: 10.1016/j.energy.2022.126565

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Energy 267 (2023) 126565

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

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ARTICLE INFO

Handling Editor: Isabel Soares

Keywords:
Petroleum consumption
Carbon emissions
Economic growth
Technological innovation
ARDL
Bangladesh

ABSTRACT

Bangladesh has traditionally relied on fossil fuels for meeting its energy demand whereby this major South Asian economy has not been able to safeguard its environment from greenhouse gas emission-related adversities. Moreover, by ratifying several international environmental agreements, especially the Paris Accord and the Sustainable Development Goals, the government of Bangladesh has expressed its solidarity in abating greenhouse gas emissions through the deployment of relevant environmental policies. Hence, this study assesses the impacts of petroleum consumption, economic growth, and technological innovation on carbon emissions in Bangladesh using quarterly frequency data from 1972Q1 to 2020Q4. Overall, apart from confirming the cointegrating relationships among the variables, the regression findings reveal that higher petroleum consumption and economic growth stimulate environmental degradation by boosting carbon dioxide emissions while technological innovation reinstates environmental well-being by curbing the Bangladesh's emission figures. Additionally, technological innovation is seen to moderate the relationship between petroleum consumption and carbon emissions by jointly reducing the emissions with petroleum consumption. Lastly, the causality analysis shows that petroleum consumption, economic growth, and technological innovation causally influence carbon emissions. Based on these key findings, it is recommended that Bangladesh mitigates its petroleum dependency, blends environmental objectives into its economic growth policies, and develops its technological stock.

1. Introduction

The global surge in emissions of Greenhouse Gas (GHG) has triggered global warming to persistently make the planet hotter and induce multifaceted environmental adversities worldwide. It has been acknowledged that failure to counter this rising global trend in GHG emissions by taking proactive measures is likely to increase the earth's surface temperature by around 4° Celsius by 2050 [1]. Consequently, it might result in severe weather extremities and unprecedented rises in sea levels [2]. Although GHGs comprise several environmental quality-deteriorating gases, Carbon Dioxide (CO_2) is regarded as the major GHG and, therefore, it is referred to as the leading contributor to global warming [3]. Accordingly, to develop climate resilience on a global scale, environmental experts have often emphasized the adoption of carbon-abating policies that can limit the rate of discharge of CO_2 into the atmosphere in order to limit the deterioration of the environment [4].

However, before undertaking carbon-reduction initiatives, it is extremely important to get accustomed to the major drivers of CO_2 emissions. In this regard, the consumption of energy resources, especially fossil fuels, is claimed to be the central facilitator of CO_2 emissions across the globe [5]. Although withdrawing from the use of fossil fuels can be assumed to eliminate the possibility of further amplifying the global CO_2 emission levels, it is not rational to stop energy use since

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https://doi.org/10.1016/j.energy.2022.126565
Received 31 August 2021; Received in revised form 21 September 2022; Accepted 26 December 2022
Available online 27 December 2022
0360-5442/

energy is acknowledged as the major driver of the growth of the world economy [6,7]. Accordingly, to address this concern, substituting the use of fossil fuels with cleaner energy sources is often recommended as a key strategy for collectively achieving higher economic growth and low environmental pollution [8,9]. Still, the global economies are either reluctant to undergo this energy transition or most likely to be bounded by the associated constraints that deter the initiation of this clean transition within the energy system. As a result, fossil fuels still hold a lion's share in the global energy mix [10]. Especially, from the point of view of reluctance, it can be hypothesized that the global economies are not fully aware of the environmental hardships accompanying fossil fuel consumption. Consequently, more empirical studies are needed to statistically assess whether or not the use of fossil fuels harms the environment by emitting more CO_2 into the atmosphere.

Although fossil fuels embody many forms, petroleum is regarded as the most important one, particularly due to crude oils being the most-traded energy resource in the world [11,12]. Besides, both industrialized and emerging nations vastly depend on locally sourced and imported petroleum, and this dependence is believed to grow with time [13]. Notably, following the resolution of the Asian financial crisis, a surge in the increase in petroleum usage has convoyed the expansion of the Asian economies [14]. Moreover, oil accounted for more than a quarter of the total volume of primary energy consumed across the Asia-Pacific region (BR, 2022). Therefore, amid such high oil dependency, oil price fluctuations in the global market have often triggered economic growth-depressing effects, particularly in Asian countries that are predominantly dependent on imported oils [15]. This scenario has recently been glorified through the Ukraine-Russia dispute which has further exposed the acute reliance of the Asian nations on oil imports as soaring oil prices in the world markets have imposed severe macroeconomic difficulties across Asia. Besides, due to petroleum being inextricably associated with atmospheric deposits of CO_2 and other GHGs, it is particularly imperative for oil-importing Asian countries to reduce their monotonic petroleum use dependency not only for the sake of safeguarding their economies from adverse oil price-related shocks but also for significantly improving their poor environmental states.

Now, narrowing down the focus to a particular emerging South Asian net-oil importer, Bangladesh is also facing the above-mentioned environmental issues as a courtesy of its long history of importing petroleum for meeting domestic energy demand [16]. Although indigenous natural gas accounts for the major share of the nation's energy mix [17], the current natural gas supply constraints coupled with the Ukraine-Russia conflict-induced inflation of imported oil prices are putting the economy of Bangladesh under severe macroeconomic pressure [18,19]. Besides, the petroleum demand in Bangladesh is said to be rising at an annual rate of around 2%–4% [20]. Hence, it can be asserted that the nation is persistently enhancing its petroleum dependency whereby the associated macroeconomic problems, especially those linked with environmental hardships, can be anticipated to surge in the next couple of years. On the other hand, Bangladesh is regarded as one of the most climate change vulnerable South Asian nations; although this nation does not contribute significantly to the global GHG emission levels, Bangladesh has been abjectly unsuccessful in mitigating its CO_2 emission levels [10,21,22,23]. Therefore, given these grimacing economic, energy, and environmental concerns, this current study attempts to explore the impacts of petroleum consumption, controlling for key macroeconomic variables, on CO_2 emissions in Bangladesh. The findings from this study are expected to provide adequate policy implications for Bangladesh to achieve long-term environmental sustainability. Besides, this study is of further importance in enabling Bangladesh to comply with its commitments pledged under the Paris Accord and the Sustainable Development Goals (SDG).

The main contributions of this study to the environment-related literature in the context of Bangladesh are two-fold. First, since most of the available studies have examined the impacts of total energy consumption on Bangladesh's CO_2 emission levels [24], while some have attempted to explore the corresponding environmental effects associated with natural gas [25], not much is known regarding how petroleum consumption, particularly oil, affects the nation's emission figures. However, contemplating the current scenario in which Bangladesh is experiencing shortages in its domestic natural gas supplies, the nation is forced to look towards imported oil for electricity generation purposes. Such a decision can be associated with higher petroleum consumption and, therefore, the nation's emission levels can be expected to substantially increase in the future. Under such challenging circumstances, this study is expected to make a timely contribution to the knowledge stock and recommend energy and environment-related policies accordingly. Second, this study looks into another overlooked issue in the literature by probing into the possible moderating/mediating effects of other macroeconomic variables on the energy consumption-CO_2 emissions nexus from Bangladesh's perspective. Identifying these indirect impacts is important for interactive policy-making purposes which can help Bangladesh address the environmental sustainability issue more comprehensively. In contrast, the existing studies themed on Bangladesh have primarily focused on the direct and independent impacts of energy and non-energy factors on CO_2 emissions.

In the next section, the petroleum sector of Bangladesh is briefly overviewed followed by a review of literature, a description of the empirical model and the methodology considered, the interpretation of the findings, and the concluding remarks.

2. Bangladesh's petroleum sector's overview

Bangladesh is a densely inhabited nation that has come a long way in spurring robust economic growth over the last couple of decades [10,26]. Nevertheless, such favorable growth achievements have both been driven and accompanied by increased energy consumption in Bangladesh. Now the question is how has Bangladesh met its energy demand. To answer this intriguing question, it is essential to get an idea regarding the composition of different energy sources in the nation's energy profile. However, considering the fact that this current study concentrates on the use of petroleum and its environmental impacts in Bangladesh, this section specifically overviews trends and figures related to Bangladesh's petroleum sector. Petroleum products like octane, furnace oil, petrol, and diesel comprise around 20% of the country's fuel sources [27,28]. The country imports the majority of the total volume of liquid gasoline consumed domestically; contrarily, merely 6% of it is acquired from locally generated gas condensate [20]. Roughly, each year, around 5.5 million metric tons of refined petroleum and over 1.2 million metric tons of crude oil are imported by Bangladesh [20,29].

As far as the sector-wise distribution of petroleum use in Bangladesh is concerned, the transport sector utilizes almost half of the total volume of petroleum products consumed each year, followed by the power (26.94%), agricultural (15.70%), industrial (4.86%), residential (2.26%), and other (0.85%) sectors [20]. Further, Fig. 1 illustrates the shares of petroleum consumption across different sectors in Bangladesh during the fiscal year 2017–2018. It is evident that from 2012 onwards there has been a major operational transition in petroleum usage in Bangladesh. Notably, the utilization of petroleum oil in the electricity sector has gone up substantially, which is clear from the figure that the percentage share of oil in the nation's total electricity output has rapidly climbed from 6% to 8% in 2011 to 28% in 2015 [27]. This scenario can largely be explained by the government's decision to lease power plants to private investors. Fig. 2 presents the trends in different types of petroleum oil consumption over the last three decades in Bangladesh. It is evident from the upward-sloping red line plot that petroleum consumption in Bangladesh has on average increased by more than 7%, year-on-year, during this period.

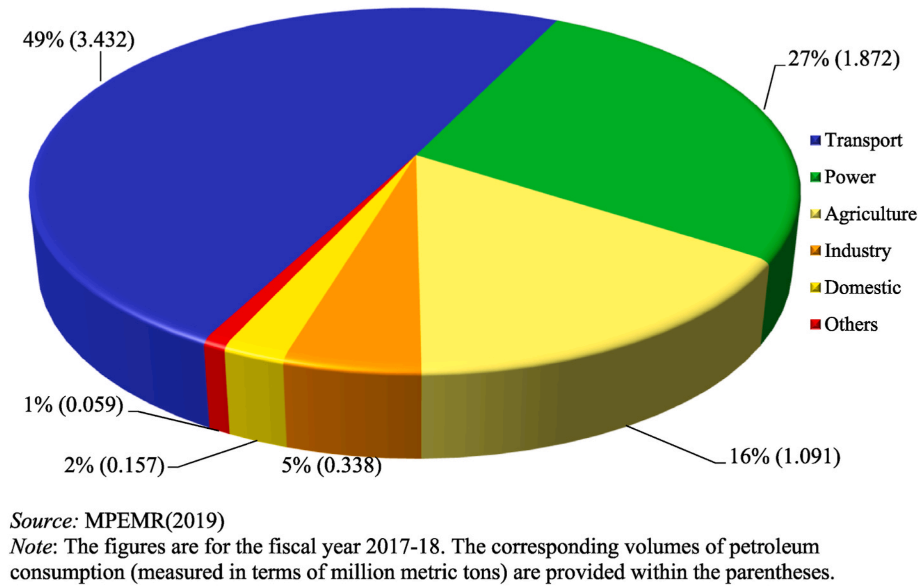


Fig. 1. Sector-wise distribution of petroleum consumption in Bangladesh
Note: The figures are for the fiscal year 2017–18. The corresponding volumes of petroleum consumption (measured in terms of million metric tons) are provided within the parentheses.
Source: MPEMR(2019)

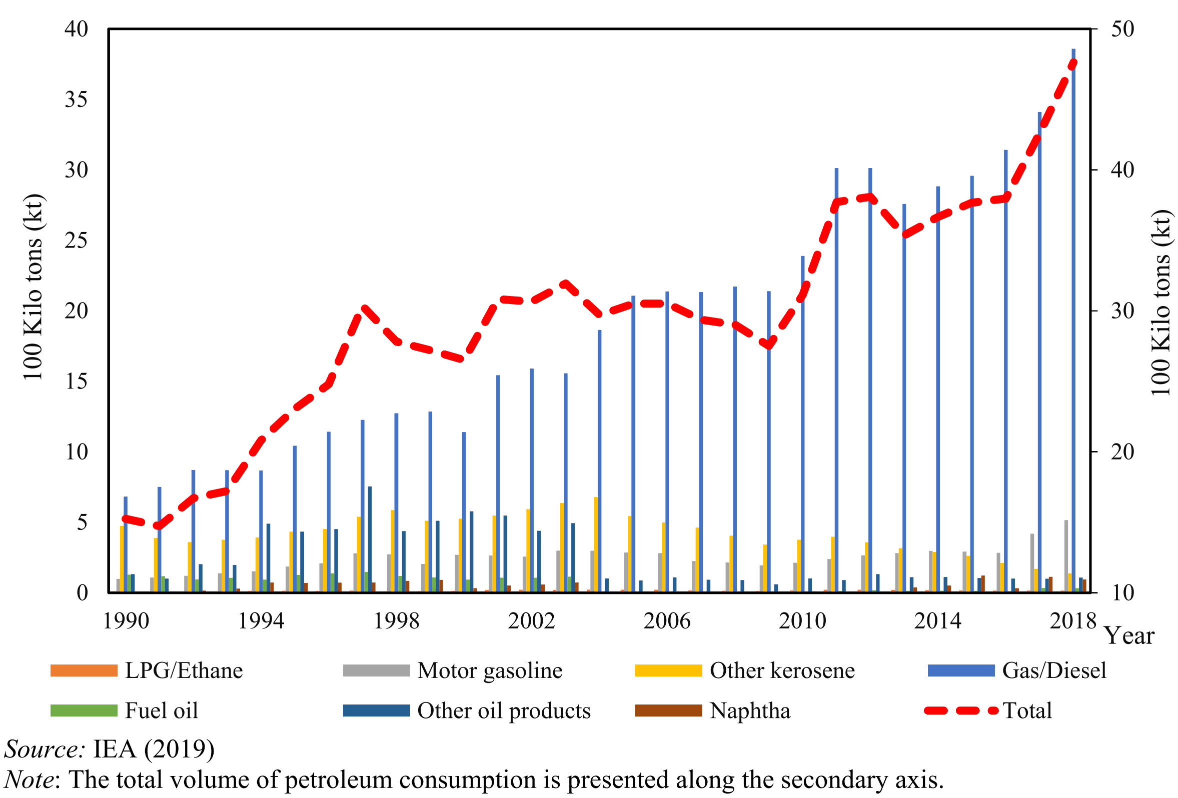


Fig. 2. Trends in different types of petroleum consumption in Bangladesh
Note: The total volume of petroleum consumption is presented along the secondary axis.
Source: [5].

3. Literature review

Several empirical studies have been carried out in recent years to better understand the factors, energy in particular, determining environmental quality. Earlier, not much emphasis was given to juxtaposing the environmental impacts associated with the consumption of different energy sources; thus, these studies have mostly used the national energy consumption level to assess the energy consumption-environmental quality linkage. Among these, especially in the context of Bangladesh [30,31], considered data from 1972 to 2006 and identified that in the short-run electricity consumption causally influences Bangladesh's CO_2 emission levels while in the long run these variables are bi-directionally associated. Later on [32,33], also conducted a similar study over the period from 1975 to 2010 and found that higher electricity consumption mitigates CO_2 emissions in Bangladesh in the short run while increasing them in the long run. Based on the findings, the authors asserted that energy use exerts long-term environmental complications in Bangladesh.

However, in the recently published studies, researchers have tried to shift the focus from assessing the environmental impacts of total energy consumption to exploring the corresponding environmental effects of different types of energy, renewable and non-renewable, in particular. For instance Ref. [24], used data from 1972 to 2016 and concluded that as the share of fossil fuels in the energy consumption level of Bangladesh goes up, it compromises the nation's environmental well-being level by boosting CO_2 emissions. On the other hand, the study conducted by Ref. [25] revealed that boosting natural gas use can help to decline CO_2 emissions in Bangladesh since compared to petroleum oils natural gas exerts relatively fewer environmental complications. Therefore, it can be clearly understood from the findings presented in these preceding studies that empirical analysis concerning the petroleum consumption-CO_2 emissions nexus in the context of Bangladesh has not been conducted before. Besides, none of these studies have attempted to identify the potential mediating/moderating roles of other factors on the environmental impacts associated with higher consumption of energy.

Similar studies in the context of other global economies also reveal equivocal impacts of energy use on CO_2 emissions. In the context of India, which is a regional neighbor of Bangladesh, Danish et al. (2021) remarked that promoting nuclear energy is the solution to India's environmental hardships since the results verified that in the long-run higher nuclear energy use abates the CO_2 emission figures in India. On the other hand, using data regarding hydro and nuclear energy use in India, respectively [34], advocated that while nuclear energy consumption helps to mitigate CO_2 emissions, hydro energy consumption imposes opposite impacts. In other relevant studies that have utilized panel data comprising Bangladesh and other global economies [35,36], found out that consumption of both gas and oil boosts CO_2 emissions in oil-importing countries like Bangladesh. Likewise, in the context of the members of the South Asian Association for Regional Cooperation (SAARC), which also includes Bangladesh [37], stated that energy consumption is one of the major CO_2 emission-boosting factors within South Asia. Hence, it is clear from the aforementioned findings from the literature that the impacts of energy consumption on CO_2 emissions not only vary from country to country but also across different sources of energy. In this regard, Table 1 provides some more findings from preceding studies.

Several studies have also evaluated the impacts of economic growth on CO_2 emissions. From a theoretical perspective, Grossman and Krueger (1991) introduced the environmental Kuznets curve hypothesis and postulated that the impacts of economic growth on environmental quality are non-linear and depict an inverse U-shape. Subsequently, many studies have both verified and condemned this hypothesis. Specifically, in the context of Bangladesh, the findings from the study conducted by Ref. [32] verified this hypothesis. Besides [41,48], also concluded that this hypothesis holds for Turkey and members of APEC, respectively; contrarily, Ajmi and Iglesi-Lotz (2021) could not validate this hypothesis for Tunisia. However, in recent studies, several methodological flaws concerning this hypothesis have been identified [49]. As a consequence, various studies have also explored the economic growth-CO_2 emissions nexus using a linear model as opposed to using the non-linear model specification proposed by Grossman and Krueger (1991). found that higher economic growth stimulates higher CO_2 emissions in Belgium, Canada, the United Kingdom, Japan, Switzerland, Finland, and South Korea but reduces CO_2 emissions in Spain and the Netherlands.

Besides energy and economic growth, technological innovation, especially in light of the Fourth Industrial Revolution, has been acknowledged as another key influencer of environmental quality.

Table 1
Summary of findings from the literature on energy use-CO_2 emissions nexus.

Study	Country/countries	Findings
[38]	Turkey	Oil and coal consumption boost CO_2 emissions both in the short- and long-run
[39]	Pakistan	Higher fossil fuel consumption boosts CO_2 emissions both in the short- and long-run
Haseeb et al. (2018)	Brazil, Russia, China, India, South Africa	Higher energy consumption boosts CO_2 emissions
[40]	Mexico	Higher energy consumption triggers greater CO_2 emissions
[41]	14 Asia-Pacific Economic Cooperation (APEC) members	Natural gas consumption reduces CO_2 emissions
[42]	South Korea	Energy consumption, as a whole, boosts CO_2 emissions; Renewable energy consumption reduces CO_2 emissions
[43]	27 European nations	Intensification of energy use boosts CO_2 emissions
Iş; ik et al. (2020)	Group of Seven (G7)	Renewable energy use curbs CO_2 emissions in France, Italy, the United Kingdom, and the United States
[44]	South Africa	In the long run, uses of primary coal, secondary coal, electricity, and hydrocarbon gas boost CO_2 emissions while higher total energy and petroleum consumption mitigate CO_2 emissions; in the short run, total energy, primary coal, secondary coal, and electricity use positively influence CO_2 emissions
[45]	India	Nuclear energy consumption reduces CO_2 emissions
[46]	China	Both production and consumption of electricity trigger greater emissions of CO_2
[47]	Gulf Cooperation Council (GCC) members	Higher oil and natural gas consumptions increase CO_2 emissions; lower oil consumption curbs CO_2 emissions in the United Arab Emirates, Kuwait, Oman, and Saudi Arabia; lower natural gas consumption reduces CO_2 emissions in Oman, the United Arab Emirates, and Qatar.

Precisely, under the theoretical principles concerning [50] Stochastic Impact by Regression on Population, Affluence, and Technology (STIRPAT) model for assessing the determinants of environmental quality, the role of technology in stimulating environmental degradation/improvement has been duly explained. In this regard, among the existing studies that have explored the effects of technological innovation on CO_2 emissions [51], remarked that the greening of technologies helps to abate CO_2 emissions in developed nations. In another related study on China, Wang and Zhu (2020) argued that technological innovation exerts equivocal environmental impacts. The authors found that technological innovations related to renewable energy and fossil fuels respectively reduce and boost the Chinese CO_2 emission figures. Recently [52], constructed an innovative technological innovation index and found evidence regarding technological innovation exerting negative environmental consequences in selected APEC countries.

4. Methodology

4.1. Models and data sources

Firstly, regarding the model considered in this study, we use the STIRPAT model proposed by Ref. [50] to assess the impacts of petroleum consumption, economic growth, and technological innovation on

Bangladesh's CO_2 emission levels. Accordingly, the benchmark model can be expressed as follows:

$$\textbf{Model 1}: \ln CO_{2t} = \beta + \delta \ln PC_t + \vartheta \ln GDP_t + \alpha \ln TCG_t + \varepsilon_t \quad (1)$$

where $\ln CO_2$ represents the natural logarithm of per capita CO_2 emissions (measured in metric tons), lnPC represents the natural logarithm of petroleum consumption (measured in tons), $\ln GDP_t$ represents the natural logarithm of per capita real GDP (measured in constant 2015 US$), and lnTCG represents the natural logarithm of technical cooperation grants received (measured in current US$). Concerning the STIRPAT model, and keeping out study's objective into consideration, we proxy environmental impact with per capita CO_2 emission levels (where higher CO_2 emissions indicate deterioration in environmental quality and vice-versa), capture affluence with per capita real GDP level (where higher real GDP level indicates a higher level of affluence/economic growth and vice-versa), and proxy technology with the value of technical cooperation grants received by the Bangladesh government (where more grants can be interpreted as more investment for technology development purposes and therefore more technological innovation and vice-versa). Besides, the environmental impact of the population within the STIRPAT model is captured by converting the CO_2 emissions and real GDP figures into per capita levels.

In equation (1), the subscript t denotes the period, ε indicates the error term, β is the intercept parameter, while $\delta, \vartheta,$ and α represent the elasticity of CO_2 emissions with respect to changes in the respective explanatory variable. All variables are natural log transformed to make sure that equation (1) is a double-log function. Next, to check whether technological innovation, apart from independently impacting the CO_2 emissions levels in Bangladesh, mediates/moderates the relationship between petroleum consumption and CO_2 emissions. This is important because it has been acknowledged in the literature that technological innovation can influence the effect of energy use on the environment [53]. Accordingly, we modify our benchmark model as follows:

$$\textbf{Model 2}: \ln CO_{2t} = \beta + \delta \ln PC_t + \vartheta \ln GDP_t + \alpha \ln TCG_t + \sigma(\ln PC * \ln TCG)_t + \varepsilon_t \quad (2)$$

where lnPC*lnTCG represents the interaction term between the variables lnPC and lnTGC whereby the elasticity parameter σ would provide an indication regarding the potential moderating/mediating role of technological innovation.

Regarding the data used in this study, the British Petroleum's Statistical Review of World Energy database (BP, 2022) provides the data for petroleum consumption, the Global Carbon Atlas database [54] provides the data for CO_2 emissions, while the World Development Indicators database (World Bank, 2022) provide the data for GDP and technical cooperation grants. Moreover, following [32,55]; and [56]; the annual frequency data acquired from the above-mentioned sources are converted into quarterly frequency using the quadratic match-sum technique; thus, the period of analysis considered in this study spans from 1972Q1 to 2020Q4. This conversion of the data tackles the limited time dimension-related concerns.

4.2. Estimation strategy

The estimation strategy is divided into three stages. In the first stage, the integration order of the variables is checked using the unit root estimation approaches suggested by Dickey and Fuller and Phillips and Perron [57,58]. This is followed by the Autoregressive Distributed Lag (ARDL) Analysis proposed by Pesaran et al. (1996 [59]; for cointegration and regression purposes in the second stage. However, the ARDL analysis has two segments in which firstly the long-run associations between the variables are checked using the bounds test. The following is an expression of the ARDL bounds testing method for checking cointegration (i.e., long-run relationships) among the variables in the context of our benchmark model (i.e., Model 1):

$$\ln CO_{2t} = \alpha_0 + \sum_{i=1}^{k_1} \beta_i \Delta \ln CO_{2t-i} + \sum_{i=0}^{k_2} \gamma_i \Delta \ln PC_{t-i} + \sum_{i=0}^{k_3} \delta_i \Delta \ln GDP_{t-i} + \sum_{i=0}^{k_4} \omega_i \Delta \ln TCG_{t-i} + \theta_{11} \ln CO_{2t-1} + \theta_{12} \ln PC_{t-1} + \theta_{13} \ln GDP_{t-1} + \theta_{14} \ln TCG_{t-1} + \varepsilon_t \quad (3)$$

where $\beta_i, \gamma_i, \delta_i, \omega_i, \theta_{11}, \theta_{12}, \theta_{13},$ and θ_{14} are the estimated parameters and Δ indicates the first difference between the variables. Akanke's Information Criterion (AIC) determines the appropriate lag lengths of k_1, k_2, k_3, and k_4. ε_t is the term for an error. In the bounds test, F-statistics are used to evaluate the impact of the lagged levels of the variables in the error-correction method of the ARDL model to ascertain if there is a long-term link among the variables. Depending on whether the model contained an intercept, trend, or both, Pesaran et al. (1996) generated two sets of suitable critical values for varied numbers of repessors. All variables in the ARDL model are expected to be I (0) in one set of assumptions, whereas all variables are assumed to be I (1) in the other. The decision is that the dependent variable has a non-spurious long-term level connection if the F statistic is larger than the higher bound critical value for a certain significance level. If the F-statistic is less than the lower bound critical value, there is no long-run level associated with the dependent variable. If it falls between the lowest and highest bounds, the outcome is indecisive. The F-statistic test's null and alternative hypotheses take the following general form:

$$H_0: (\omega_1 = \omega_2 = \ldots = \omega_k = 0);\ H_1: (\omega_1 \neq 0, = \omega_2 \neq 0)$$

$$\Delta \ln CO_{2t} = \sum_{i=1}^{k_1} \beta_i \Delta \ln CO_{2t-i} + \sum_{i=0}^{k_2} \gamma_i \Delta \ln PC_{t-i} + \sum_{i=0}^{k_3} \delta_i \Delta \ln GDP_{t-i} + \sum_{i=1}^{k_4} \omega_i \Delta \ln TCG_{t-i} + \gimel ECT_{t-i} + \varepsilon_t \quad (4)$$

In the second phase of the ARDL analysis, the short- and long-run marginal impacts of petroleum consumption, economic growth, and technological innovation on CO2 emissions are assessed. Besides, the error correction term of the ARDL model can be approximated at this phase which would show how much the dependent variable is adjusted to deviancies from its long-term equilibrium estimate. The ARDL technique has several flexible properties which makes it a suitable estimator for handling models containing (a) variables of mixed integration order (either at the level of the first difference, but not at the second difference), (b) finite time dimension by adjusting the short sample bias, and (c) endogenous covariates [60].

Once the short-and long-run elasticities/coefficients are estimated, it is imperative to run some diagnostic tests. The ARDL model requires the standard error expression to be normally distributed and serially independent which is the most crucial assumption in the ARDL bounds testing technique. As a result, to determine serial independence, the Breusch-Godfrey serial correlation Lagrange Multiplier (LM) test is used. Besides, the Ramsey Reset test is used to check for model misspecification concerns while the Breusch-Pagan-Godfrey test is utilized to check for heteroscedasticity issues. Furthermore, to assess the stability of the predicted ARDL model, the Cumulative Sum of Squares (CUSUM) and the Squared Cumulative Sum of Squares (CUMSQ) plots are generated.

For conducting a robustness check concerning the long-run findings from the ARDL analysis, the Fully Modified Least Squares (FMOLS) regression method proposed by Ref. [61] is used. This method is chosen because it can handle models including variables that are commonly integrated at the first difference [61]. Besides, this technique is also robust for handling serial correlation and endogeneity problems [62]. The use of the FMOLS estimator as a robustness check for ARDL findings has been recommended in several existing studies [63].

Finally, in the last stage, the causality analysis is conducted using the Granger causality estimation technique proposed by Ref. [64]. This method requires the variables to be cointegrated and uses a Vector Autoregression (VAR) model to test the causal relationships [64]. As a result, the formula for the Granger causality assessment with error correction is as follows:

Table 3
Correlation matrix.

	$lnCO_2$	lnGDP	lnPC	lnTCG
lnCO2	1.000			
lnGDP	0.954	1.000		
lnPC	0.982	0.445	1.000	
lnTCG	0.720	0.434	0.595	1.000

$$\begin{pmatrix} \ln CO_{2t} \\ \ln PC_t \\ \ln GDP_t \\ \ln TCG_t \end{pmatrix} = \begin{pmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \\ \mu_4 \end{pmatrix} + \begin{pmatrix} \rho_{11,1} & \rho_{12,1} & \rho_{13,1} & \rho_{14,1} \\ \rho_{21,1} & \rho_{22,1} & \rho_{23,1} & \rho_{24,1} \\ \rho_{31,1} & \rho_{32,1} & \rho_{33,1} & \rho_{34,1} \\ \rho_{41,1} & \rho_{42,1} & \rho_{43,1} & \rho_{44,1} \end{pmatrix} \begin{pmatrix} \ln CO_{2t} \\ \ln PC_t \\ \ln GDP_t \\ \ln TCG_t \end{pmatrix} + \ldots + \begin{pmatrix} \rho_{11,i} & \rho_{12,i} & \rho_{13,i} & \rho_{14,i} \\ \rho_{21,i} & \rho_{22,i} & \rho_{23,i} & \rho_{24,i} \\ \rho_{31,i} & \rho_{32,i} & \rho_{33,i} & \rho_{34,i} \\ \rho_{41,i} & \rho_{42,i} & \rho_{43,i} & \rho_{44,i} \end{pmatrix} \begin{pmatrix} \ln CO_{2t} \\ \ln PC_t \\ \ln GDP_t \\ \ln TCG_t \end{pmatrix} + \begin{pmatrix} \varnothing_1 \\ \varnothing_2 \\ \varnothing_3 \\ \varnothing_4 \end{pmatrix} ECT_{t-1} + \begin{pmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \\ \varepsilon_{3,t} \\ \varepsilon_{4,t} \end{pmatrix} \quad (5)$$

The trailing error correction expression for the long-run equilibrium model is ECT_{t-1}. For both long- and short-run causation, the ECT_{t-1} causation assessment should be statistically significant. $\varepsilon_{1,\ t}$ to ε_3 indicate the stochastic standard error expression. It shows the pace of corrections, and the value indicates how much disequilibrium will be remedied in a given period.

5. Results and discussion

In this section, we first report the descriptive statistics of the variables (shown in Table 2) to get an idea of the properties of the data being employed in this study. The highest standard deviation is observed for the variable $lnCO_2$ emissions, followed by lnTCG, lnPC, and lnGDP. Besides, the distributions of variables lnGDP and lnPC are positively skewed while those of lnCO2 and lnTCG are negatively skewed. Moreover, all variables are platykurtic (since their respective kurtosis figures are less than 3). Lastly, the probability values concerning the Jarque-Bera statistics indicate that there is no concern regarding the non-normal error distribution of the variables. On the other hand, the correlation matrix concerning the model variables is shown in Table 3. It can be seen that the outcome variables (lnGDP, LnPC, and lnTCG) are highly correlated with the response variable ($lnCO_2$).

Next, we report the unit root results derived from the Augmented Dickey-Fuller and Phillips-Perron tests. As reported in Table 4, it is observed that for both estimation techniques, the null hypothesis of non-stationarity is rejected for the variables only at the first difference. Hence, it can be said that there is a common integration among the study variables [i.e., stationary at the first difference, I (1)]. Thus, the ARDL model's first criterion of a maximum order of integration at the first difference is fulfilled.

Table 2
The descriptive statistics.

Properties	$lnCO_2$	lnGDP	lnPC	lnTCG
Mean	3.054	6.511	14.838	18.861
Median	3.095	6.382	14.962	19.102
Maximum	4.546	7.390	16.001	19.542
Minimum	1.254	5.995	13.635	16.168
Std. Dev.	0.937	0.411	0.630	0.705
Skewness	−0.073	0.714	0.102	−2.353
Kurtosis	1.810	2.252	1.972	1.839
Jarque-Bera stat.	1.489	2.214	3.150	2.432
Probability	0.410	0.325	0.203	0.258
Observations	196	196	196	196

In the next stage, the ARDL analysis is conducted. Firstly, the ARDL bounds test is conducted to assess cointegration among the variables of concern. However, before it can be done, it is important to determine the optimal lags for all the variables in both models (i.e., Models 1 and 2). Table 5 reports the possible lag structures across alternate lag selection criteria. It can be seen that for both models, the optimal number of suggested lags is 1 (confirmed by the asterisk which indicates statistical significance at 5%). Hence, the presence of cointegrating equations in the respective models fulfills the second criterion for conducting the ARDL analysis.

The results from the ARDL bounds test for assessing cointegration are presented in Table 6. It is observed that for both models, the respective F-statistics are above the lower and upper bounds' critical values whereby long-run association among the study variables are verified. Hence, upon confirmation of the cointegrating relationships, the short- and long-run elasticity parameters are estimated using the ARDL regression analysis.

Table 7 presents the short- and long-run elasticity parameters that are derived from the ARDL analysis. Firstly, the findings show that petroleum consumption exerts environmental problems in Bangladesh by stimulating higher CO_2 emissions both in the short- and long-run. Precisely, combining the results from both models, a 1% rise in the level of petroleum consumption in Bangladesh is estimated to boost the nation's

Table 4
The unit root results.

Variable	Augmented Dickey-Fuller test		Phillips-Perron test		Decision
	Intercept	Trend and intercept	Intercept	Trend and intercept	
$lnCO_2$	−0.962	−2.102	−1.995	−1.104	Non-stationary
$\Delta lnCO_2$	−5.026***	−5.088***	−5.568***	−5.725***	Stationary
lnPC	−1.500	−2.020	−1.920	−2.254	Non-stationary
ΔlnPC	−3.358**	−6.345***	−4.508***	−4.515***	Stationary
lnGDP	−2.228	−1.318	−1.197	−1.009	Non-stationary
ΔlnGDP	−4.539***	−3.817**	−6.415***	4.809***	Stationary
lnTCG	−1.985	−2.142	−1.922	−1.825	Non-stationary
ΔlnTCG	−5.489***	−5.187***	−4.541***	−5.198***	Stationary

Notes: Δ indicates first difference; lag optimality is based on AIC; *** and ** indicate significance at 1% and 5%, respectively.

Table 5
Lag structures.

Model	Lag	LogL	LR	AIC	SIC	HQ
1	0	141.342	NA	−8.876	−9.343	−9.220
	1	255.132	224.200**	−18.105**	−16.953**	−17.432**
	2	265.421	6.905	−18.001	−16.599	−16.893
2	0	125.250	NA	−8.540	−8.887	−8.789
	1	215.123	195.450**	−16.865**	−17.212**	−17.112**
	2	235.555	6.922	−16.553	−16.320	−16.985

Notes: LogL = log likelihood; LR = sequential modified LR; AIC = Akaike information criterion; SIC=Schwarz information criterion; HQ=Hannan-Quinn information criterion; ** indicates significance at 5%.

Table 6
The results from the ARDL Bounds test.

	Model 1	Model 2
F-Statistic	6.980***	7.120***
Critical values	**Lower Bound I(0)**	**Upper Bound I(1)**
1%	3.505	5.121
5%	2.618	3.863
10%	2.218	3.314

Notes: The F-statistics consider the null hypothesis of no-cointegration; the critical values are based on [65]; *** indicates significance at 1%.

Table 7
The elasticity outcomes from the ARDL analysis.

Variables	Model 1		Model 2	
	Short-run	Long-run	Short-run	Long-run
lnPC	0.235***	0.883***	0.240***	0.910***
	(0.036)	(0.130)	(0.065)	(0.095)
lnGDP	0.201	1.299***	0.195	1.336***
	(0.165)	(0.189)	(0.185)	(0.201)
lnTCG	−1.202***	−2.159**	−1.150***	−2.300***
	(0.230)	(1.077)	(0.411)	(0.616)
lnPC*lnTCG			−0.408	−2.151***
			(0.393)	(0.589)
ECT(-1)	−0.512**		−0.613**	
	(0.255)		(0.307)	
Constant	3.261		3.850	
	(2.922)		(3.120)	
R-squared	0.652		0.674	
Observations	195	195	195	195

Notes: The standard errors are shown within the parentheses; ECT(-1) = error-correction term; *** and ** indicate significance at 1% and 5% levels, respectively.

per capita level of CO_2 emissions on average by 0.235%–0.240% in the short-run and by 0.883%–0.910% in the long-run. Besides, these results also highlight that the environmental quality-deteriorating effects associated with petroleum consumption tend to increase with time. Since petroleum products are high in hydrocarbon content, combusting them results in the release of CO_2 emissions, which explains the finding of the positive nexus between petroleum consumption and CO_2 emissions in Bangladesh's case. Nevertheless, these findings are alarming for Bangladesh since the nation is currently facing shortages in local natural gas supplies whereby it is forced to import more petroleum in the future for meeting the domestic energy demand. As a result, higher imports and use of petroleum can be assumed to boost Bangladesh's CO_2 emission levels in the near future [38,44]. have also documented evidence regarding the CO2 emission-boosting impacts of petroleum consumption in Turkey and South Africa, respectively.

Similar to petroleum consumption, the results shown in Table 7 reveal that economic growth is also responsible for the deterioration of Bangladesh's environmental quality. The corresponding estimates indicate that if Bangladesh's per capita level of real GDP goes up by 1%, it is likely that the nation's per capita CO_2 emission figures would simultaneously go up on average by 1.299%–1.366% in the long run. However, in the short run, since the corresponding elasticity parameters are statistically insignificant, it can be said that changes in the economic growth level in Bangladesh cannot explain the short-run variations in its CO_2 emission levels. The long-run finding is expected since almost all economic activities in Bangladesh are powered by energy sourced from non-renewable energy resources; consequently, the economic growth policies pursued by the nation can, to a large extent, be classified as 'unclean.' Under such circumstances, it is imperative for Bangladesh to adopt clean economic growth strategies and identify factors that can somewhat neutralize the environmental adversities associated with higher growth of the Bangladesh economy. Much like the case of Bangladesh [66], also argued that economic growth deteriorates environmental quality in Belgium, Canada, the United Kingdom, Japan, Switzerland, Finland, and South Korea by increasing the respective CO_2 emission figures of these countries.

On the other hand, it can be observed from the findings reported in Table 7 that although petroleum consumption and economic growth reduce environmental well-being, technological innovation can be associated with an improvement in the environmental quality in Bangladesh. Moreover, it is also evident that the long-run environmental gains from technological innovation are larger than the corresponding short-run environmental gains. Precisely, the corresponding elasticity outputs show that if the value of technical cooperation grants received by Bangladesh goes up by 1% (synonymous with technological innovation), it is likely to reduce the nation's per capita CO_2 emission level on average by 1.150%–1.202% in the short-run and by 2.159%–2.300% in the long-run. The finding of this negative relationship between technological innovation and CO_2 emissions can be explained by the understanding that the discovery of advanced technologies can lead to a rise in the total factor productivity level in Bangladesh which, in turn, can be linked with higher economic growth. Similar arguments were provided by Ref. [51] to verify the negative nexus between CO_2 emissions and technological innovation in the case of developed nations.

Although the identified impacts of petroleum consumption and technological innovation on CO_2 emissions are obvious to some extent, a key finding from this study is that technological innovation not only independently reduces CO_2 emissions but also helps to moderate the relationship between petroleum consumption and CO2 emissions to further reduce CO_2 emissions in Bangladesh, only in the long-run. This statement is verified by the statistical significance and negative sign of the long-run elasticity parameter concerning the interaction term (i.e., lnPC*lnTCG) that was included in Model 2. In simple terms, this finding can be interpreted as technological innovation being effective in neutralizing some of the CO_2 emission-boosting effects associated with petroleum consumption in Bangladesh. This finding can be explained in two aspects. Firstly, since advanced technology is often associated with greater adoption of clean energy [8], the technological innovation-led clean energy transition can be expected to reduce petroleum consumption; consequently, the volume of petroleum consumption-related CO_2 emissions can be assumed to decline. Secondly, linking technological innovation with energy productivity improvement [67–69], it can be said that if advanced technologies can make sure that petroleum is more efficiently utilized and not wasted, the level of petroleum consumption can be expected to decline which, in turn, would help to abate the

Table 8
Outcomes from diagnostic tests.

Test	Null Hypothesis	Model 1	Model 2
		Test Stat.	Test Stat.
Breusch-Godfrey LM	No serial correlation	0.405 (0.955)	0.422 (0.920)
Ramset Reset	Model is not misspecified	0.195 (0.650)	0.211 (0.521)
Breusch-Pagan-Godfrey	Homoscedastic error variance	0.704 (0.663)	0.775 (0.680)

Note: The probability values are reported inside the parentheses.

Table 9
The outcomes from the robustness analysis.

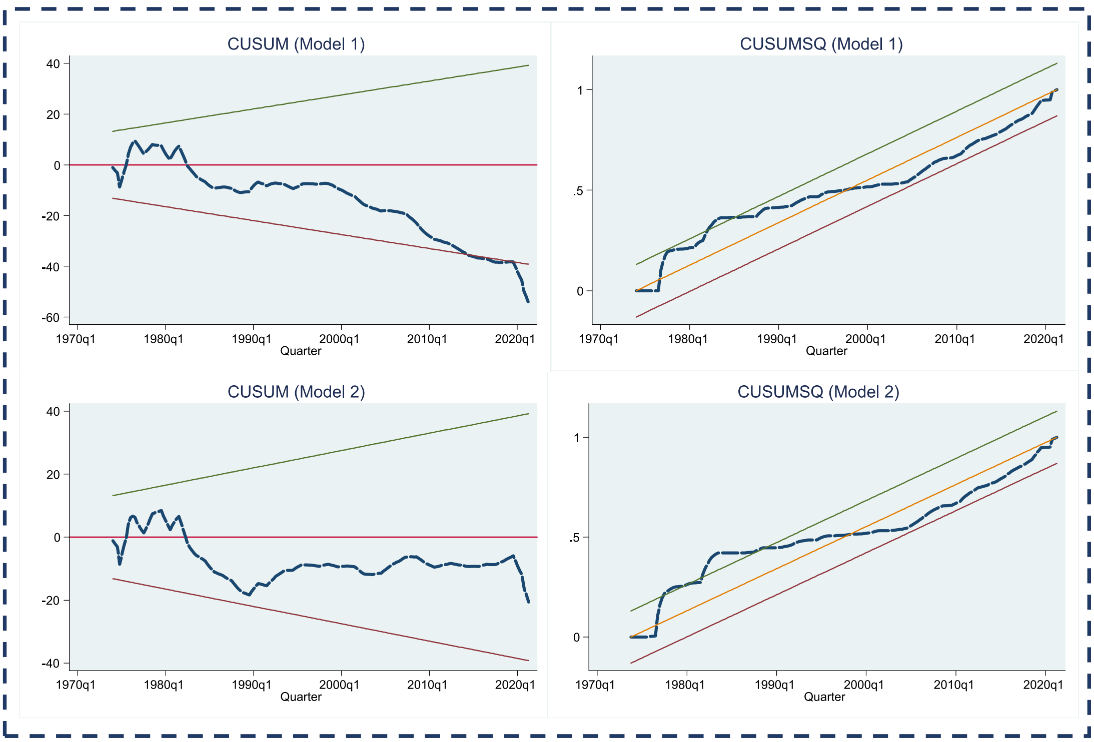
Variables	Model 1	Model 2
lnPC	0.505*** (0.212)	0.545*** (0.206)
lnGDP	2.123*** (0.450)	2.206*** (0.410)
lnTCG	−1.302*** (0.511)	−1.413*** (0.480)
lnPC*lnTCG		−2.129*** (0.529)
Constant	3.344 (3.121)	3.604 (3.130)
Adj. R-squared	0.685	0.712
Observations	195	195

Notes: The standard errors are shown within the parentheses; *** and ** indicate significance at 1% and 5% levels, respectively.

associated emissions, as well.

Besides, Table 7 also shows that the statistically significant and negative error-correction terms for Models 1 and 2 are respectively predicted at 0.512 and 0.613. Thus, error correction speeds of 51.2% and 61.3% are verified in the context of these models. Moreover, the high values of the adjusted R-squared statistics indicate that more than 65% of the total variations in Bangladesh's per capita CO_2 emission levels can be explained by variations in its per capita petroleum consumption, per capita real GDP, and the value of receipts of technical cooperation grants. Furthermore, the outcomes from the diagnostic tests displayed in Table 8 confirm that neither of the two models faces issues like serial correlation, model misspecification, and heteroscedasticity. In addition, the parametric stability of both models 1 and 2 are confirmed by the CUSUM and CUSUMSQ plots illustrated in Fig. 3.

To check the robustness of the long-run ARDL findings, the FMOLS estimator is employed. The FMOLS findings reported in Table 9 portray that FMOLS estimates corroborate the corresponding ARDL long-run estimates in terms of the predicted signs. Hence, in line with these identical findings, it can be said that the findings are robust across these different estimation methods.



Note: The stability of the parameters is ensured since the blue dashed line is more or less within the 95% confidence interval (indicated by the green and maroon lines).

Fig. 3. CUSUM and CUSUMSQ charts.

Table 10
Outcomes from Granger causality analysis.

Null Hypothesis	Chi. Sq. Statistic	Causality	Direction
$\ln CO_2 \neq \ln PC$	9.760***	Unidirectional	$\ln PC \rightarrow \ln CO_2$
$\ln PC \neq \ln CO_2$	2.922		
$\ln CO_2 \neq \ln GDP$	12.543***	Unidirectional	$\ln GDP \rightarrow \ln CO_2$
$\ln GDP \neq \ln CO_2$	2.885		
$\ln CO_2 \neq \ln TCG$	9.540***	Unidirectional	$\ln TCG \rightarrow \ln CO_2$
$\ln TCG \neq \ln CO_2$	2.653		

Notes: $\neq$ indicates does not Granger cause; *** indicates significance at 1% level.

Finally, the Granger causality analysis is performed to check the

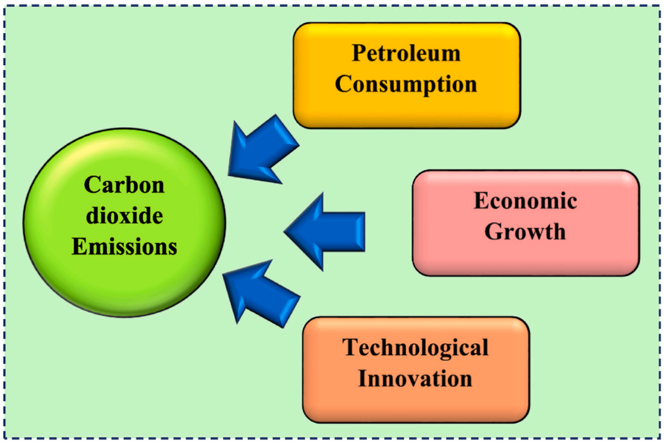


Fig. 4. The causal relationships.

direction of causation among the variables. The causality findings, as shown in Table 10[1] reveal evidence of unidirectional causal associations running from (a) lnPC to lnCO_2, (b) lnGDP to lnCO_2, and (c) lnTCG to lnCO_2. These imply that the per capita CO_2 emissions figures of Bangladesh are causally influenced by the nation's levels of per capita petroleum consumption, per capita real GDP, and receipts of technical cooperation grants. Hence, the causal associations back up the short- and long-run elasticity outcomes from the ARDL analysis to highlight that petroleum consumption and economic growth degrade environmental quality in Bangladesh while technological innovation improves it. Fig. 4 summarizes the causal relationships among the variables of concern.

6. Conclusions and implications for policy

Since Bangladesh has traditionally relied on fossil fuels, especially natural gas, to meet its energy demand, it is obvious that this emerging South Asian nation has not been able to safeguard its environment from hardships associated with rising emissions of GHG. Moreover, by ratifying several international environment-related pacts, especially the Paris Accord and the SDG of the United Nations, the government of Bangladesh has expressed its solidarity concerning the deployment of relevant policies for abating GHG emissions. Besides, since Bangladesh is presently experiencing severe shortages in its locally sourced natural gas supplies, the nation has no option other than to import more petroleum to meet the persistently surging domestic demand for energy resources. As result, higher petroleum imports can be expected to further aggravate the quality of the environment in Bangladesh in the future. Against this backdrop, this study attempted to empirically check the effects of petroleum consumption, economic growth, and technological innovation on Bangladesh's CO_2 emission figures utilizing quarterly frequency data from 1972Q1 to 2020Q4.

Overall, the long-run associations between CO_2 emissions, economic growth, and technological innovation are verified from the cointegration analysis. Besides, the regression results revealed that higher petroleum consumption and economic growth degrade the environment by boosting CO_2 emissions while technological innovation reinstates environmental well-being by curbing the emission figures. In addition, technological innovation is evidenced to moderate the relationship between petroleum consumption and CO_2 emissions by jointly reducing the emission levels with rising petroleum consumption levels. Lastly, the causality analysis corroborated the regression outcomes and verified that petroleum consumption, economic growth, and technological innovation causally influence CO_2 emissions without feedback. Based on these key findings, the following environmental quality-improving policies are recommended to the Bangladesh government.

Firstly, considering the finding of the adverse environmental consequences of petroleum consumption, Bangladesh needs to find alternative energy options that are relatively cleaner. Although switching to renewable energy is the optimal solution for addressing the environmental sustainability objective, it is not possible for Bangladesh to become renewable energy-intensive overnight. In this regard, apart from investing funds for the development of the renewable sector in the future, the Bangladesh government should focus on importing cleaner petroleum products from abroad. For instance, importing liquefied petroleum and natural gases could be credible options since these fuels, despite being dirty, are considered comparatively cleaner fuel sources than conventionally imported petroleum-based fuels. Simultaneously, the government should also emphasize enhancing the efficiency at which petroleum is consumed so that less quantity of petroleum is used without negatively affecting the rate of output production.

Secondly, keeping into consideration that higher economic growth was found to impose environmental hardships, the government of Bangladesh needs to strike a balance between its policies regarding environmental and economic development. This can only be done if the issue of environmental well-being is integrated into the existing and future economic growth policies of Bangladesh. This is important because the traditional growth policies pursued in this nation have not been conducive to safeguarding environmental well-being in Bangladesh, especially due to the nation having insufficient expertise and inadequate level of affluence required for employing clean inputs for national output generation. Besides, Bangladesh had somewhat taken its natural gas reserves for granted whereby poor supply pricing led to the overuse of this fossil fuel source. As a result, not only have the natural gas reserves of Bangladesh depleted at a brisk pace, the dependency of the nation on fossil fuels simultaneously grew, in tandem. Under such circumstances, it is time for Bangladesh to substantially diversify its national energy portfolio so that the economic policies can be made greener and more aligned with the environmental objectives. This is because if you do not have clean energy resources at your disposal or if energy inefficiency cannot be reduced, it may not be possible to adopt relevant green growth strategies.

Lastly, along with the aforementioned policies, technological innovation should be considered a major national agenda because without advancing the technological stock it is practically impossible for Bangladesh to reduce its petroleum dependency and blend environmental welfare policies within the economic growth policies. In this regard, it is important for Bangladesh to take initiatives that can both endogenously and exogenously expand the nation's technological stock. From the endogenous technological development point of view, investing in technological development-related projects is of paramount importance. Apart from public financing of such projects, the government should also motivate private sector participation, especially by guaranteeing secured returns on private investments in research and development-related projects. On the other hand, the government can also look to develop technology exogenously by attracting foreign direct investment from high-tech foreign companies. Especially, these foreign direct investments should ideally be directed at developing the renewable energy sector for Bangladesh in order to reduce the nation's petroleum and natural gas dependency.

The study's shortcoming is that it merely investigates the effects of petroleum usage on CO_2 emissions while the corresponding effects of other energy sources on different environmental indicators are left unexplored. Hence, future studies should explore these research scopes.

Authors' contributions

Xia Chen: Investigation; Review. Md. Atikur Rahaman: Conceptualization. Muntasir Murshed: Conceptualization; Interpretation of results;

[1] For ensuring brevity, only the causal associations related to CO_2 emissions are reported.

Methodology; Data analysis; Writing - review & editing; Investigation. Haider Mahmood: Interpretation of results; Data analysis; Writing - review & editing; Policy recommendations. Md. Afzal Hossain: Methodology; Data analysis; Writing - Original Draft preparation.

Funding

This study was supported by the School of Management, Jiujiang University and Center for Entreprenureship & Innovation Research Society (grant number: 43120227).'

[70–74].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

The authors would like to thank the School of Management, Jiujiang University and Center for Entreprenureship & Innovation Research Society for its financial support.

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