



# Another look at the nexus between economic growth trajectory and emission within the context of developing country: fresh insights from a nonparametric causality-in-quantiles test

Tomiwa Sunday Adebayo<sup>1</sup> · Festus Victor Bekun<sup>2,3</sup> · Husam Rjoub<sup>4,5</sup> · Mary Oluwatoyin Agboola<sup>6</sup> · Ephraim Bonah Agyekum<sup>7</sup> · Bright Akwasi Gyamfi<sup>8</sup>

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## Abstract

Achieving environmental sustainability has become a global concern amidst increasing climate change threat. Using quarterly frequency data for the case of Russia from 1992 to 2018, the present study explores the interaction between disaggregated energy consumption (renewable energy and non-renewable energy), trade flow and economic growth on a broader measure for environmental degradation (ecological footprint). The choice of the variables draws strength from initiative of the United Nations Sustainable Development Goals (UN-SDG, 7, 8 11 and 13) for responsible energy consumption and clean energy consumption while mitigating climate change issues. The study applied the quantile-on-quantile regression (QQR) and nonparametric causality-in-quantiles to capture these associations. The outcomes from the QQR disclosed that in the majority of the quantiles, trade openness and renewable energy use contribute to environmental sustainability, while nonrenewable energy amplifies ecological footprint. Furthermore, growth in Russia escalates its ecological footprint. Moreover, in the majority of the quantiles, all the exogenous variables can predict ecological footprint. Given the outcomes of this study, it outlines the need for a paradigm shift for alternative and clean energy consumption in Russian energy mix amidst its economic growth trajectory while accounting for green-development approaches. Pathways to fully achieve the sustainability targets are carefully outlined in the concluding section.

**Keywords** Energy conservation · Renewable energy · Environmental sustainability · Quantile-on-quantile technique · Nonparametric causality

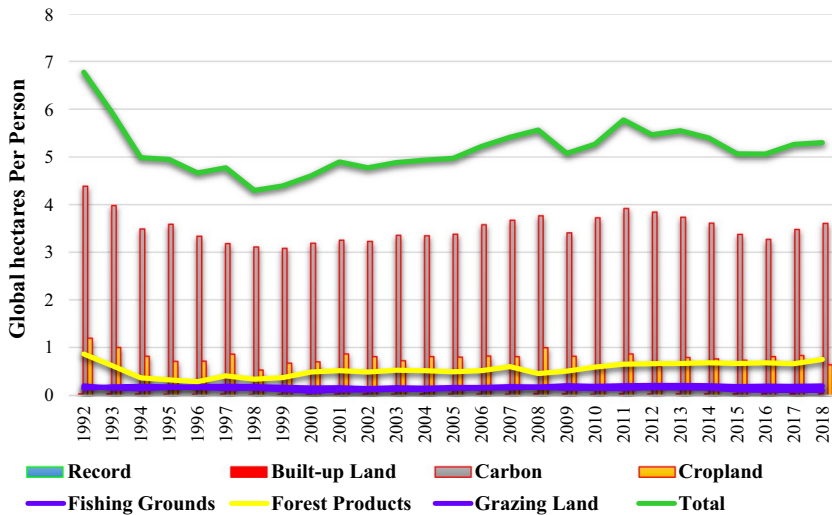
## 1 Introduction

Environmental quality rapidly degrades across every nation's growth route, particularly during the fledgling period of expansion, owing to worsening ambient air quality, continual change in the pH value of water, loss in forest cover, soil erosion, and a variety of other

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✉ Festus Victor Bekun  
fbekun@gelisim.edu.tr

Extended author information available on the last page of the article



**Fig. 1** Ecological situation in Russia from 1992 to 2018

factors (IPCC, 2015). When considering the influence of economic expansion on the ecosystem, contaminants are frequently used as an ecological indicator; Ecological Footprint (ECF) was utilized as an index of environmental deterioration in this research. ECF determines the earth's carrying capacity, as defined by Rees (1992) and Wackernagel and Rees (1997), and, because this metric contains an underlying future aspect, it is also an indication of sustainability. It is, as per them, the capability of a combined ecological region to create the resources used by parties participating in economic activity while simultaneously having the potential to engross the waste generated by those parties. Cropland, forest, grazing, fishing, built-up land, and carbon emissions are the six components of this metric (see Fig. 1), which indicates the extent of human demand from the environment.

Although there has been some controversy about using ECF as a measure of ecological sustainability (Wiedmann & Barrett, 2010), ECF is a valid measure for measuring the quality of the environment since it depicts human reliance on the natural system (Sinha et al., 2020). For numerous reasons, this study used ECF as a measure of environmental integrity. Firstly, EF represents the Earth's carrying capacity, making it a more powerful measure of ecological sustainability. It is the sole metric that represents the planet's biological capability for supporting economic activity, as defined by the SDGs (Ahmad et al., 2021; Balsalobre-Lorente et al., 2020). Secondly, natural resources are used in the course of economic activity, and this use might take the form of water, minerals, land resources and forest. As a result, utilizing emissions as an ecological indicator can limit the emphasis on ecological sustainability in big industrial operations, overlooking other human activities that threaten environmental integrity (Bekun et al., 2019a, 2019b; Shahbaz et al., 2017). Finally, a country's ecological sustainability is dependent on its capability to engross pollutants from the atmosphere, which is imperative in terms of accomplishing the SDGs (Adebayo et al., 2022; Akadiri et al., 2022).

Prior to going on to the issue of sustainable development (SD), the present study first addresses the global concern regarding ECF. Countries rely on energy usage to accomplish economic expansion, while the Earth's carrying capacity is harmed as a

result of the contamination that results. Growing environmental consciousness forces governments to adopt corrective steps after a certain degree of economic growth, and this is when countries begin to see technological advancement (Chen & Lee, 2020; Cheng et al., 2021). This technological improvement is said to be accomplished through the transfer of technology, as various countries can specialize in various technological areas. ECF begins to decline as countries start exploiting technological innovations. Due to increased environmental problems, this is also the moment when countries begin to favor renewable energy options over nonrenewable energy alternatives. The gradual transition from nonrenewable to renewable energy options improves environmental quality.

From the standpoint of emerging countries like Russia, it is now vital to comprehend the necessity to separate sources of energy to examine their effects on the ECF. Renewable energy (REC) and nonrenewable (NREC) sources account for the majority of Russia's energy use, and both have differing effects on the country's overall development and growth. As a result, the term "segregation" is used to describe the two separate energy sources employed in Russia. When discussing SD, it is important to emphasize the importance of energy policy in not just decreasing the destruction of the environment, but also in creating sustainable jobs that are made possible by clean growth. By implementing greener production regulations as well as segregated energy solutions, Russia can create plans to meet the SDGs. In this context, Russia deserves special notice since it is concentrating on policy coherence to achieve synergy across social, environmental and economic programs. Scholars have now discovered the influence of renewable energy consumption in all three policy areas stated above (Destek & Sinha, 2020; Shahbaz et al., 2018). Nevertheless, focusing solely on REC while ignoring the role of NREC might stifle economic progress, as NREC still dominates Russia's energy mix. Regardless of the state of development, sole reliance on REC has yet to be witnessed, and developmental actions will be heavily reliant on NREC, possibly in the form of enhanced efficiency of energy and the execution of greener production technology, until the transition to renewable energy is complete.

Considering this context, it is critical to evaluate the segregated energy usage effect on ECF in Russia, in order to provide the groundwork for synergetic, sustainable policy design (Ahmed et al., 2021; Baloch et al., 2019). The present study used the word segregation to refer to the two types of energy sources employed in processes of production, namely non-renewable and renewable energy sources, an usage separation approach adapted from studies by Al-Mulali and Ozturk (2015), Balcilar et al. (2018), Altinoz and Dogan (2021) and other scholars. By and large, the literature has concentrated on the influence of energy usage on ambient air pollution for a variety of emerging and developed countries, generally ignoring the larger depiction of SD, which has been reintroduced through the SDGs. This is the subject of the current research, wherein this study has assessed the energy consumption impact on ECF for Russia between 1992 and 2018Q4. The analysis of this research is done by separating the energy (NREC and REC), thus highlighting the effects of two separate types of energy use on EF and, as a result, ensure efficient policy recommendations. It is necessary to understand the differential influence of these two forms of energy use on environmental quality to have a better understanding of the current economic picture and fulfill the SDGs' objectives.

Having said that, the study points out that energy segregation also includes the advancement of technology in Russia, which might be harnessed through the transfer of technology through trade networks (Destek & Sinha, 2020; Ibrahim & Ajide, 2021; Li et al., 2021). As a result, trade openness can be used as a proxy for economic growth in Russia since trade openness is a facilitator of economic expansion. Because the study's main backdrop

is Russia, the study includes trade openness into our model. Since renewable energy solutions might well be difficult to execute without improvement in technology, trade openness must be integrated in the framework to designate both technological advancement and economic growth, whereas economic expansion will have a scale effect, and segregated energy usage will have a composition effect, trade openness will have a technical impact on ecological sustainability (Sinha et al., 2020). Despite the considerable influence of the aforementioned variables, which should not be overlooked, several investigations (Acheampong & Boateng, 2019; Fareed et al., 2021; Miao et al., 2022; Shahzad, 2020) have neglected the aforementioned facts based on the premise that economic development is the sole factor that determines ecological degradation.

The present environmental and energy economics research has mostly centered on assessing the influence of segregated energy usage on air pollution (Adebayo & Kirikkaleli, 2021; Akram et al., 2021; Isik et al., 2021). Nevertheless, while the effect of energy-led industrialization may be viewed via the entire ecological disparity, ambient air pollution cannot accurately depict ecological harm. Furthermore, in order to attain sustainable economic expansion, the influence of the energy mix on total ecological integrity should be considered in light of the SDGs. This is where the current research comes in by adding to the previous literature in various aspects. Firstly, from the standpoint of SD, it is necessary to examine the influence of energy usage on a country's ecological footprint.

This work adds to the body of knowledge in environmental and energy economics by examining the influence of energy usage on ECF in the context of achieving the SDG goals. Secondly, the influence of separated energy (NREC and REC) has been found mostly on air pollution in the literature (Alola & Ozturk, 2021; Apergis & Payne, 2014; Kirikkaleli & Adebayo, 2020; Shahbaz et al., 2018). Nevertheless, in order to meet the SDGs' targets, it is necessary to examine the influence of REC and NREC on Russia's ECF. While meeting the goal of climate change, concentrating just on air contaminants may not offer a whole perspective; consequently, the purpose of this research is on the influence of segregated energy usage on ECF. Thirdly, the study which employed quantile-on-quantile regression (QQR) is initiated by Sim and Zhou (2015). When compared to traditional econometric methodologies, the QQR method is used to investigate how the quantiles of exogenous variables impact the provisional quantiles of endogenous variable, resulting in improved accuracy in the estimated findings. Lastly, the nonparametric causality initiated by Balcilar et al. (2016), which can capture causality in mean and variance, was utilized.

The remaining sections of the paper are organized as follows: Sects. 2 and 3 present a summary of literature and methods, Sects. 4 and 5 present findings and implications for theory and practice and Sect. 6 concludes the study.

## 2 Review of related literature

The seminal study of Kraft and Kraft (1978) on the nexus between economic growth (GNP) and energy for the USA served as invitation for several studies in over four decades of literature. This section of the present study presents a stylized review of related literature on the theme under review. After the groundbreaking Kraft and Kraft study, the last two decades introduced another concept known as environmental Kuznets curve, as popularized by Grossman and Krueger (1991), which highlights the nexus between economic growth trajectory and emission level (CO<sub>2</sub>), for instance, on the nexus between GDP and emission. For the case of South Korea, Adebayo et al. (2021) used annual frequencies

data from 1965 to 2019 and investigated the nexus between emission and economic growth using ARDL methodology and Wavelet method. The study submits that economic growth (GDP) triggers increased emission level, which degrades environmental quality. The wavelet causality also resonates with the regression as the study outlines a uni-directional causality flow running from GDP to CO<sub>2</sub> emission.

Furthermore, the energy and environmental literature has experienced a significant growth in documentation on the determinant of environmental degradation as accelerated by human anthropogenic activities. This has drawn the attention of governmental officials and stakeholders on the determinants of environmental pollution. Notable in the literature is the role of income level and urbanization and, as an example, Katircioglu et al. (2018) explored the carbon-income nexus for the case of Turkey within the EKC framework. The study validated that increased economic growth and urban population triggered economic growth. In the same fashion, Bekun et al. (2019a) examined the role of disaggregated energy into renewable and nonrenewable energy and natural resources on emission level for EU economies. The study outlines the risk of how natural resources exploration or exploitation on environmental quality in the EU, as well as fossil fuel, distort the quality of environment in the study blocs. However, renewable energy consumption shows strength to improve environmental quality in the study area over the sampled period. This study also aligns with the study of Bekun (2022) that focuses on the case of India where investment in renewable energy accomplishes environmental sustainability and helps mitigate climate change over a highly industrialized economy such as India.

Furthermore, there exist a few strands of study that have deviated on measuring environmental degradation with carbon dioxide emission to use ecological footprint, a broader and more encompassing measure for environmental degradation (Bekun et al., 2019b; Destek & Sinha, 2020; Katircioglu et al., 2018; Nathaniel et al., 2019; Udemba, 2020). For instance, the study of Bekun et al. (2019b) focuses on South Africa, a high emitter, and was built on the EKC phenomenon. The study outlined the detrimental role of consumption of energy from a fossil fuel base and emphasized the need of decoupling South African economic growth from environmental degradation by focusing on energy efficiency. Additionally, Rafindadi and Usman (2019) used the FMOLS and CCR model to explore the pertinent role of globalization, energy consumption and economic growth to determine emission levels for South Africa. The study's empirical outcomes unveil that energy consumption had an elastic and inelastic effect of emission level in South Africa. Similar fashion was seen between economic growth and CO<sub>2</sub> emission with an estimated tipping point of EKC estimated as \$6502.88 over the investigated period. The study suggested the need for energy transition to cleaner alternatives.

While there exists flourishing documentation on the carbon-income function for single country cases, region, and blocs, there is limited study for the Russian Federation, which holds a rich energy mix (Agboola et al., 2022; Bozdağ, 2021; Mitrova & Melnikov, 2019; Pao & Tsai, 2011). None of these studies account for the pertinent role of economic growth and disaggregated renewable energy as a channel for environmental degradation. However, the role of trade flow and wave of global interconnectedness, which has increased over the last decades, brings with it environmental degradation. Given the highlighted literature survey on economic growth and emission level, the empirical results are inexhaustive and there is no consensus in the extant literature. To this end, our present study advances the literature for the case of the Russian Federation by using a broader and more composite indicator for environmental degradation relative to previous literature that uses CO<sub>2</sub> emission, which has its limitation. Thus, our study claims to innovate in terms of scope of variables selected that align with the United Nations Sustainable Development Goals (SDGs)

targeted for 2030, which is limited in the extant literature. Additionally, this study contributes in terms of method applied as it deviates from traditional econometrics modeling and uses state of the art techniques such as quantile-on-quantile regression relative to conventional OLS or traditional quantile regression; the QQR presents robust estimate and coefficients for adequate policy construction.

### 3 Data and methods

#### 3.1 Data

This empirical study utilizes quarterly data spanning between 1992 and 2018 based on its availability to assess the effect of energy (nonrenewable and renewable), economic growth and trade openness on the ecological footprint (ECF) in Russia. The dataset for trade openness is measured as trade % of GDP and collected from the World Bank database. Renewable and nonrenewable data are gathered from the British Petroleum database and measured in exajoules. Ecological footprint data are measured in global hectares per person and obtained from the global footprint network database. The datasets in this empirical analysis are transformed into a natural logarithm. Figure 2 presents the flow of analysis.

#### 3.2 Methodology

##### 3.2.1 Methodological sequence

The present study leverages on the quantile-on-quantile methodology as advanced by Sim and Zhou (2015). The technique is used to explore the nexus between economic growth, carbon emission, energy consumption, gross capital formation for the Russian Federation. The quantile-on-quantile (QQR, hereafter) approach is superior to the conventional quantile regression and comes handy when there is need to explore the characterization of one variable across a distribution of quantiles. The QQR techniques aggregate both the nonparametric and QR in an environment where the quantile of one series is regressed on another.

For adequate understanding of the QQR approach, the QQR is fitted in two steps; First, traditional quantile regression (QR) as proposed by Koenker and Bassett (1978) and Sim and Zhou (2015) is employed to investigate the independent variables in our study case, economic growth, energy consumption, gross capital formation, on various quantiles of a dependent variable, in this study case carbon emission. Relative to the ordinary least squares, QQR is preferred in scenarios where there is need to explore the impact of explanatory variables at tail and median characterization of study dependent variable. These rich traits of the QQR enable a detailed investigation among series. In the second step, the QQR adopts the use of traditional linear regression as outlined by Stone (1977) and Cleveland (1979). This allows to examine the estimation of the spatial effect of a single quantile of each independent variable on the dependent variable. This intuition will help circumvent the dimensionality issues, as this problem usually plagues nonparametric techniques. The QQR is constructed on a linear regression around perspective points among the outlined variables. These inherent traits of the QQR on its reduction dimension strength make it a superior or more advantageous estimator to the traditional QR and OLS methods, as the QQR provides more robust and reliable estimates. In summary, the QQR technique is more advantageous while exploring impact of variable characterization on data. For instance, the

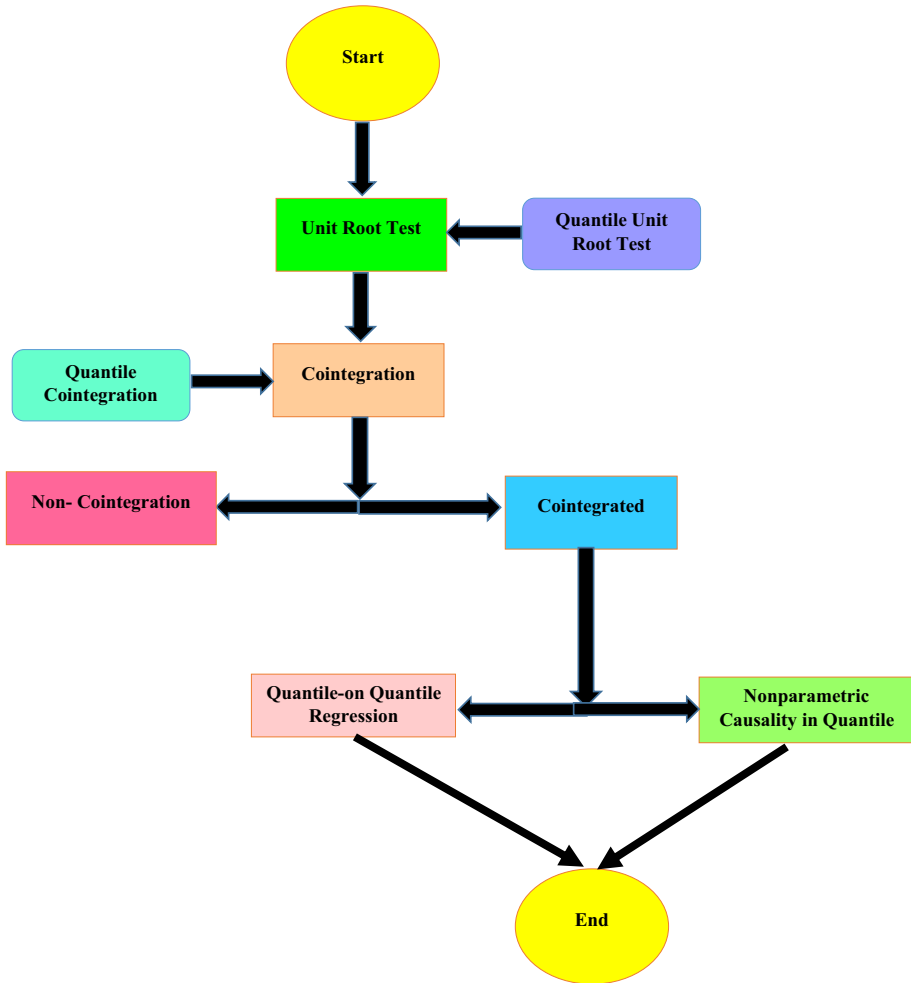


Fig. 2 Flow of analysis

impact of quantile  $X$  on quantile  $Y$ . The QQR is built from the traditional QR environment model as outlined in Eq. (1)

$$Y_t = \beta^\theta(X_t) + \mu_t^\theta \tag{1}$$

Here,  $Y_t$  and  $X_t$  depict the dependent and independent variables, respectively, over the investigated period, the subscript  $t$  highlights time frame while  $\theta$  is the  $\theta$ th representing the quantiles of  $Y$  conditional distribution and the error term of the quantile is presented as  $\theta$ th is 0, while the  $\mu$  is the error term for the study. Additionally, the unidentified function is depicted via  $\beta^\theta(\cdot)$ , this is attainable due to the prior information connecting explained and explanatory unidentified variables, i.e.,  $X$  and  $Y$ . The impact of  $X$  on the distribution of  $Y$  is computed through quantile regression approach which accommodates for the impact of the explanatory,  $X$  to vary over several quantiles of the explained variable, i.e.,  $Y$ . The

advantage of the logic in the QR is rooted in its constancy, while, on the other hand, its weakness lies in its inability to capture broad dependency. To this end, the quantile techniques (QR) ignore the likelihood that the present shock in the explanatory variable ( $x$ 's) affects the nexus on  $Y$  and  $X$ . Thus, the results of this positive  $X$  shocks vary from those of minor positive  $X$  shockwaves. Furthermore, an inverse and direct shock impact of  $X$  will result in an inequitable reaction on  $Y$ .

Thus, the relationship between  $\theta$ th quantile of  $Y$  and  $\tau$ th of  $X$  is denoted by  $X^\tau$ , and the local LR is used to evaluate  $X^\tau$  region. The unidentified function given by  $\beta^\theta(\cdot)$  is evaluated as a first-order Taylor expansion centered on  $X^\tau$  quantile, as shown in Eq. (2);

$$\beta^\theta(X_t) \approx \beta^\theta(X^\tau) + \beta^{\theta_1}(X^\tau)(X_t - X^\tau) \tag{2}$$

where  $\beta^\theta(X_t)$  is the partial derivative, while  $X$  is shown by  $\beta^{\theta_1}$ . Here,  $\beta^\theta(X_t)$  is the partial derivative, while  $X$  is shown by  $\beta^{\theta_1}$ . This is seen as a response and is comparable to the coefficient slope in a long run horizon. The distinction of Eq. (2) is that  $\beta^\theta(X^\tau)$  and  $\beta^{\theta_1}(X^\tau)$  parameters are twice indexed in  $\tau$  and  $\theta$ . Provided that  $\beta^\theta(X^\tau)$  and  $\beta^{\theta_1}(X^\tau)$  are functions of  $\theta$  and  $X^\tau$  and  $X^\tau$  is a function of  $\tau$ , it is clear that  $\beta^{\theta_1}(X^\tau)$  and  $\beta^\theta(X^\tau)$  are both functions of  $\tau$  and  $\theta$ . In addition,  $\beta^\theta(X^\tau)$  and  $\beta^{\theta_1}(X^\tau)$  are depicted as  $\beta_0(\theta, \tau)$  and  $\beta_1(\theta, \tau)$ . Thus, Eq. (2) is transformed in Eq. (3):

$$\beta^\theta(X_t) \approx \beta_0(\theta, \tau) + \beta_1(\theta, \tau)(X_t - X^\tau) \tag{3}$$

When Eq. (3) is put into Eq. (2), Eq. (4) is obtained as follows:

$$Y_t = \underbrace{\beta_0(\theta, \tau) + \beta_1(\theta, \tau)(X_t - X^\tau)}_{(*)} + \mu_t^\theta \tag{4}$$

Equation (4) is the  $\theta$ th conditional quantile of  $Y$  and it is represented by (\*).

Though this deviates from the traditional conditional quantile function, this approach shows the connection between  $\theta$ th of  $Y$  and  $\tau$ th quantile of  $X$  because  $\beta_0$  and  $\beta_1$  parameters twice index in  $\theta$  and  $\tau$ . These parameters may change across different separate  $\theta$ th quantiles of  $Y$  and  $\tau$ th quantiles of  $X$ . Additionally, no linear nexus among the series under review is presumed at any point. Consequently, in Eq. (5), the generic dependency arrangement between  $Y$  and  $X$  is fitted on the correlation between varying distributions.

In addition,  $X_t$  and  $X^\tau$  is substituted by  $\hat{X}_t$  and  $\hat{X}^\tau$  when estimating Eq. (5). The parameters  $b_0$  and  $b_1$ , which are  $\beta_0$  and  $\beta_1$  estimates, are gathered by fixing the following issue of minimization:

$$\min_{b_0, b_1} \sum_{i=1}^n \rho_\theta \left[ Y_i - b_0 - b_1(\hat{X}_i - \hat{X}^\tau) \right] K \left( \frac{F_n(\hat{X}_i) \Pi - \tau}{h} \right) \tag{5}$$

The authors showed the quantile via  $\rho_\theta(u)$ , and  $\rho_\theta(u) = u(\theta - I(u < 0))$ ,  $I$  is a typical function of the series. The function of kernel  $h$ , a parameter kernel bandwidth, is represented by  $K(\cdot)$ . The Gaussian kernel used to weigh the interpretations in  $X^\tau$  region is mostly used in kernel functions, specifically in finance and economic literature, due to the easy computation and consistency in estimates.

The kernel of Gaussian is linear around zero; these present less remarks of weights that are extra out. These are inversely related to the distance among the analytical distribution



function of  $\hat{X}_t$ , shown via  $F_n(\hat{X}_t) = \frac{1}{n} \sum_{k=1}^n I(\hat{X}_k > \hat{X}_t)$ . The function of distribution value that supports with the  $X^r$  is shown via  $\tau$ . In nonparametric analysis, bandwidth selection is also a pertinent decision. This helps to manage the evenness of the matching estimate and subsequently it stipulates the scale of the district neighboring the broad theme. Worthy of mention on these techniques is that a broader bandwidth spells a higher risk of estimation distortion in the system, while a smaller bandwidth displays a higher risk of uncertainty likelihood. Accordingly, it is pertinent to select optimum bandwidth for stability between variances. To this end, our study is fitted on the motivation and study of Sim and Zhou (2015) where the study adopts the use of bandwidth  $h=0.05$  for the current study.

## 4 Findings and discussion

### 4.1 Preliminarily test outcomes

Table 1 presents data brief information. The mean of GDP (8880.135) is the highest and it ranges from 5480.291 to 11,976.48, NREC (6907.739) which ranges from 6172.812 to 8944.736, REC (853.2332) which ranges from 722.0512 to 990.0919, TR (55.89827) which ranges from 46.06306 to 55.89827 and ECF (5.167033) which ranges from 4.250217 to 7.102658. The kurtosis values reported that ECF, GDP, REC, NREC and TR are leptokurtic. Furthermore, ECF, NREC and TR are positively skewed, which implies that the right tail of the distribution is longer than the left, while GDP and REC are skewed negatively, which implies that the left is longer than the right. The Jarque–Bera test also reported that ECF, GDP, REC, NREC and TR do not align with normality. In addition, the study used the BDS to identify the variables’ nonlinearity characteristics of ECF, GDP, REC, NREC and TR and the outcomes show that all the series do not align with normality (see Table 1). These outcomes comply with the Jarque–Bera outcomes. These outcomes give support for using nonlinear techniques to assess the association between ECF and GDP, REC, NREC and TR (Table 2).

**Table 1** Descriptive statistics

	ECF	GDP	REC	NREC	TR
Mean	5.167033	8880.135	853.2332	6907.739	55.89827
Median	5.078140	8923.212	867.0925	6917.245	52.20560
Maximum	7.102658	11,976.48	990.0919	8944.736	131.5608
Minimum	4.250217	5480.291	722.0512	6172.812	46.06306
Std. Dev.	0.508762	2322.006	69.80953	543.9252	13.20720
Skewness	1.149539	- 0.102924	- 0.121573	1.545192	3.329703
Kurtosis	5.559764	1.370155	4.407207	6.188722	16.65594
Jarque–Bera	53.27170	12.14446	9.847358	88.73290	1038.746
Probability	0.000000	0.002306	0.000000	0.000000	0.000000
Observations	108	108	108	108	108

## 4.2 Quantile unit root outcomes

The quantile unit root (QUR) outcomes are reported in Table 3. In QUR test, the persistent value is denoted by  $\beta(\pi)$ , and the critical values shown by CV. In addition, the null hypothesis is that  $H_0 = \beta(\pi) = 1$  for each quantile. In our case, the null hypotheses of non-stationarity are refuted for ECF, GDP, REC, NREC and TR in each quantile.

## 4.3 Quantile cointegration outcomes

Subsequently, the study employs the quantile cointegration (QC) test initiated by Xiao (2009) to assess the long-run association between (i) ECF and GDP; (ii) ECF and REC; (iii) ECF and NREC; and (iv) ECF and TR. Table 4 shows supremum norm values,  $\beta$  coefficient and  $\gamma$  coefficient with their CV (CV1, CV5, and CV10) at a significance level of 1%, 5%, and 10%, respectively. The results of the research show that  $\beta$  and  $\gamma$  coefficients are above the level of significance of 1% which unveils the existence of long-run connection between ECF and GDP; (ii) ECF and REC; (iii) ECF and NREC; and (iv) ECF and TR (see Table 4). These outcomes reveal a nonlinear interrelationship between (ii) ECF and REC; (iii) ECF and NREC; and (iv) ECF and TR.

## 4.4 Quantile-on-quantile regression outcomes

The QQR estimates outcomes show that the influence of GDP on ecological footprint differs in each quantile of exogenous and exogenous variables. Furthermore, across all tails (0.1–0.95) of GDP, it positively influences all tails (0.1–0.95) of ecological footprint; though the influence is stronger in the higher tails (see Fig. 3a). This demonstrates that positive shift in GDP influences ecological footprint positively. This section of the results corroborates with the outcomes gathered by Tony Odu et al. (2022) for India, Adebayo (2022a) for Spain, Miao et al. (2022) for newly industrialized nations, Onifade et al. (2021) for E7, Bamidele et al. (2022) for Nigeria, Appiah et al. (2022) for Sub-Sahara Africa countries and Awosusi et al. (2022) for BRICS.

Furthermore, the study found that, in the middle and lower tails (0.1–0.65) of REC and ecological footprint, the influence of REC on ECF is negative and weak. Nonetheless, the upper tails (0.70–0.95) of REC positively impact ecological footprint (see Fig. 3b). These findings are interesting because, in the high and middle tails, REC contributes to the enhancement of the environment while, in the higher tails, REC amplifies the degradation of the ecosystem. In summary, the negative effect of REC on ecological footprint is more pronounced than the positive effect. Therefore, REC amplifies the environmental

**Table 2** BDS test

	ECF	GDP	REC	NREC	TR
M2	21.451*	45.263*	20.262*	31.745*	17.806*
M3	22.308*	47.697*	21.155*	32.915*	18.550*
M4	23.317*	50.880*	22.333*	34.662*	19.453*
M5	24.894*	55.908*	24.428*	37.597*	20.831*
M6	27.133*	62.948*	27.258*	41.885*	22.762*

\*1% significance level

**Table 3** Quantile unit root test

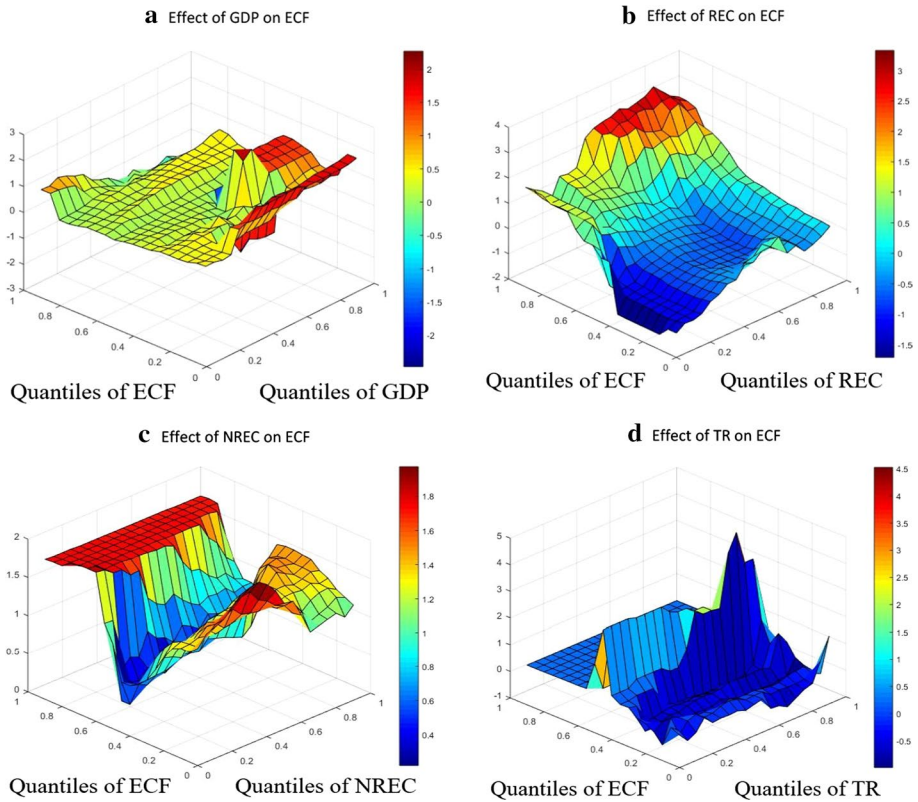
	ECF		GDP		REC		NREC		TR	
	$\alpha(\tau)$	T-statistic	$\alpha(\tau)$	T-statistic	$\alpha(\tau)$	T-statistic	$\alpha(\tau)$	T-statistic	$\alpha(\tau)$	T-statistic
0.10	1.0077	-1.9638	0.9699	-1.6731	0.9895	-0.6298	0.9970	-0.3907	0.9917	-0.6978
0.20	1.0009	1.7493	0.9831	1.7392	0.9991	-0.8954	0.9212	-0.5786	0.9729	-0.9791
0.30	0.9893	0.8902	0.8996	2.0033	0.8953	1.6292	0.9720	-0.0996	0.9810	-1.5736
0.40	0.9893	0.6930	1.0010	1.3894	0.9615	-1.4282	0.8928	-0.0865	0.9654	-1.1894
0.50	0.9732	-0.4472	0.9862	2.1830	0.9751	1.3382	0.9628	-0.1974	0.8956	-2.0179
0.60	1.0200	-0.8183	0.9072	1.8932	0.8950	-1.2869	0.9828	-0.7640	0.9613	-1.8054
0.70	0.9837	0.3820	0.9720	1.6324	0.9908	1.7528	0.8820	-1.0745	0.8913	-1.9743
0.80	1.0101	-1.1783	0.9933	1.5037	1.0004	1.6022	0.9872	-1.7582	0.9675	-1.8097
0.90	0.9631	-0.5892	0.9026	1.2346	0.9024	-1.5385	1.0040	-1.3525	0.8942	-1.9053
0.95	0.8936	-0.2482	1.0040	1.5936	0.9795	-1.6268	0.9413	-1.6074	0.9069	-0.8783

If the critical value  $> t$ -statistic, then the  $H_0$  hypothesis of  $\beta(x) = 1$  is dismissed at the 5% level

**Table 4** Quantile cointegration test outcomes

Model	Coefficient	$\text{Sup}_\tau  V_\pi(\tau) $	CV1	CV5	CV10
ECF <sub>t</sub> versus GDP <sub>t</sub>	<i>B</i>	6709	4120	2608	1584
	$\gamma$	643	354	227	102
ECF <sub>t</sub> versus NREC <sub>t</sub>	<i>B</i>	7968	5515	3975	1816
	$\gamma$	722	516	327	218
ECF <sub>t</sub> versus REC <sub>t</sub>	<i>B</i>	2905	1890	1734	910
	$\gamma$	206	119	88	53
ECF <sub>t</sub> versus TR <sub>t</sub>	<i>B</i>	3820	2377	1540	758
	$\gamma$	316	225	115	82

1%, 5%, and 10% significance level denotes CV1, CV5, and CV10, respectively. The critical values were generated by using 1000 Monte Carlo simulations



**Fig. 3** **a** Effect of GDP on ECF, **b** effect of REC on ECF, **c** effect of NREC on ECF, **d** effect of TR on ECF

quality. As expected, the authors observe that, across all tails (0.1–0.95) of NREC and ecological footprint, the effect of NREC on ecological footprint is positive and significant; however, the influence is weak in the middle tails (0.40–0.65) (see Fig. 3c). In summary,

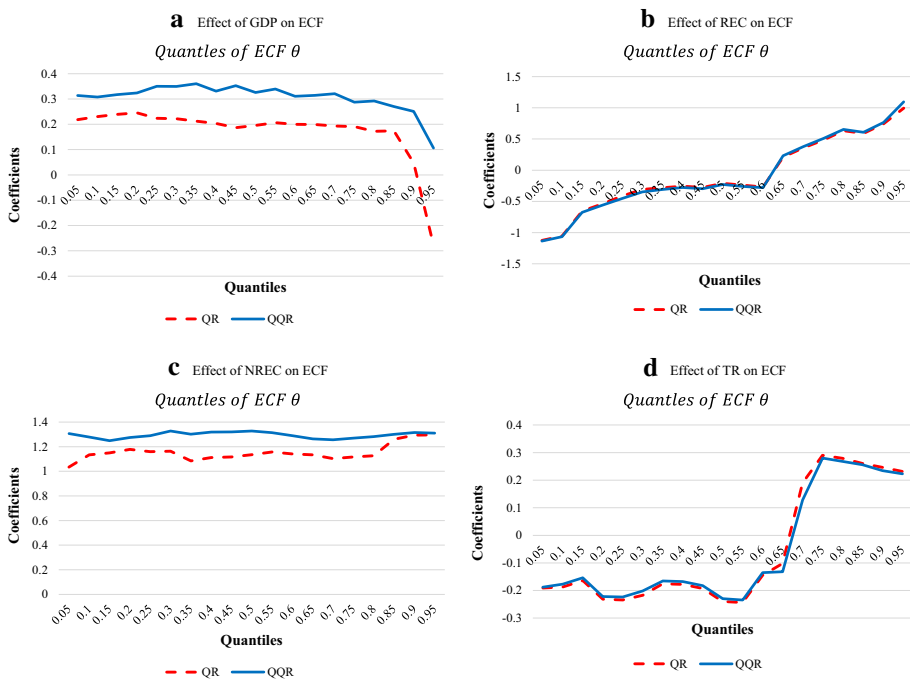
this study notice that the amplification of ECF is triggered by an increase in NREC. Thus, NREC contributes to damage to the ecosystem. Therefore, increasing the use of renewable energy decreases the ecological footprint, while increasing the use of non-renewable energy increases the ecological footprint. The findings suggest that a surge in REC and NREC decreases and increases ecological footprint, respectively. These results align with the outcomes obtained by Güngör et al. (2021) for Chile, Kirikkaleli and Adebayo (2021) for India, Agyekum et al. (2022) for MINT nations, Gyamfi et al. (2021) for E7 economics and Gyamfi et al. (2022) for Mediterranean nations; however, this outcome contradicts the results obtained by Pata and Aydin (2020) for Turkey, Gyamfi et al. (2020) for G7, Alola et al. (2022) for China, Adedoyin et al. (2021) for E7 and Tony Odu et al. (2022) for China.

Lastly, in the lower tails (0.1–0.35) and higher tails (0.70–0.95), the influence of TR on ECF is negative; however, in the middle tails (0.35–0.65), the authors observed that TR impacts ECF positively (see Fig. 3d). In summary, the negative effect of TR on ecological footprint is dominant more than the positive effect. Therefore, a decrease in ecological footprint is triggered by an increase in TR. International trade allows for the transfer of cross-border technologies, allowing countries to get access to environmentally friendly technologies, lowering their ecological footprint and improving ecological sustainability. This portion of the results complies with the outcomes obtained by Oladipupo et al. (2021) for Portugal and Adebayo (2022b) for Canada and disagrees with the result of He et al. (2021) for Mexico.

To summarize, the study asserts that Russia's growth has a negative impact on the environment. This has important implications for Russia's sustainable development prospects. Moreover, the study unveils that the elasticity of NREC is larger than that of REC, and, as a result, the influence of technical improvements in producing cleaner manufacturing processes may be neutralized. Nevertheless, the nature of the income-ecological footprint relationship suggests that Russia's present energy policies should be revised to match the SDGs' targets since, with this level of progress, environmental damage in Russia might worsen as the economic expansion continues. As a result, Russia has to examine its current energy policy, trade policies, and research and development efforts. Since fossil fuel-based alternatives are so prevalent in Russia, policymakers should concentrate on substituting them with clean and renewable energy alternatives.

#### 4.5 Robustness check

Subsequently, the research compares the estimates of QQR with the traditional QR. Figure 4 provides these findings for the impact of economic growth on ECF (see Fig. 4a), the impact of renewable energy on ECF (see Fig. 4b), the impact of nonrenewable energy on ECF (see Fig. 4c) and the impact of trade openness on ECF (see Fig. 4d). The results of QQ estimates are generally congruent with those of conventional quantile regression. There are, nonetheless, a few exceptions. The QR estimates disclosed the positive effect of GDP on the ecological footprint in all quantiles, which is similar to the QQR outcomes (see Fig. 4a). Moreover, in the lower and middle tails (0.1–0.70), the authors observe a negative effect of REC on ecological footprint with a positive effect in the higher quantiles (see Fig. 4b). These outcomes are consistent with the QQR estimates. Furthermore, the QR estimates disclosed the positive effect of NREC on ECF in all quantiles, which is similar to the QQR outcomes (see Fig. 4c). Lastly, in the lower and middle tails (0.1–0.70), the present study observes a negative effect of trade openness on ecological footprint with a



**Fig. 4** a Effect of GDP on ECF, b effect of REC on ECF, c effect of NREC on ECF, d effect of TR on ECF

positive effect in the higher quantiles (see Fig. 4d). These outcomes are consistent with the QQR estimates.

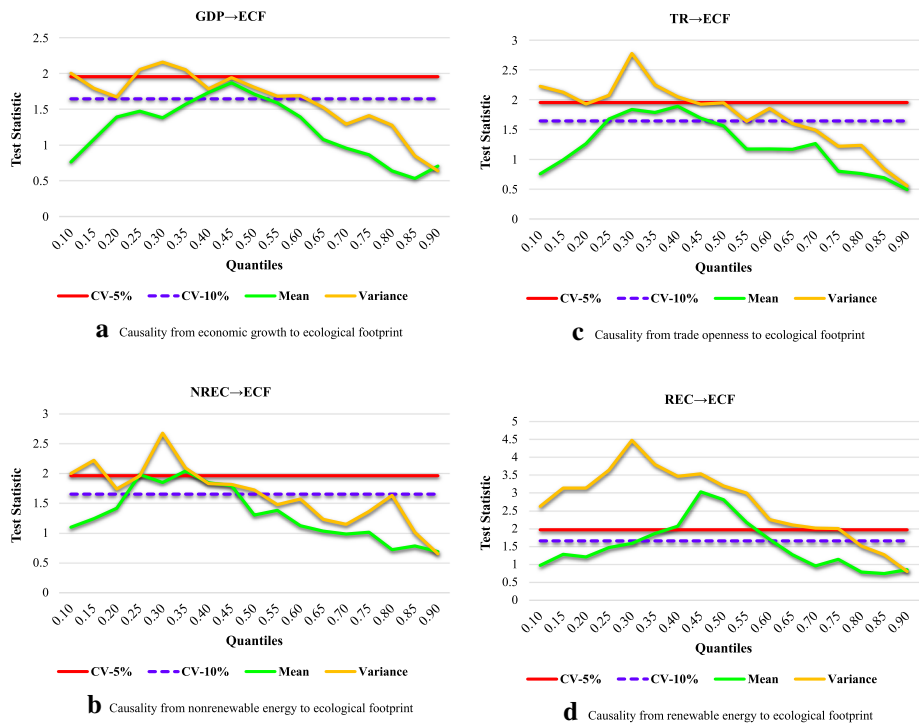
#### 4.6 Nonparametric causality outcomes

Table 5 and Fig. 5a–d present the causality (mean and variance) from NREC, TR, GDP and REC to ecological footprint in Russia. In the middle tails (0.35–0.55), there is causality from GDP to ECF at the conditional mean of ECF (see Fig. 5a). In addition, there is a significant causal effect of the volatility of GDP on ECF in the lower and middle tails (0.1–0.65). Furthermore, Fig. 5b shows the causal association from NREC to ECF with the outcomes displaying evidence of causality from REC to ecological footprint in the lower tails (0.25–0.45) at the conditional mean of ECF (see Fig. 5b). In addition, there is a significant causal effect of the volatility of REC on ECF in the lower and middle tails (0.2–0.55). Moreover, in the lower tails (0.25–0.40), there is causality from trade openness to ECF at the conditional mean of ECF (see Fig. 5c). Additionally, there is a significant causal effect of the volatility of trade openness on ECF in the lower and middle tails (0.1–0.70). Moreover, Fig. 5d displays the causal interconnection from REC to ECF with the outcomes displaying evidence of causality from nonrenewable energy to ecological footprint in the middle tails (0.30–0.60) at the conditional mean of ECF (see Fig. 5d). In addition, there is a significant causal effect of the volatility of nonrenewable energy on ECF in the lower, middle and upper tails (0.1–0.80) (see Fig. 5d). In summary, these outcomes show that GDP, TR, REC, and NREC can forecast the ecological footprint in Russia at different quantiles.

**Table 5** Causality in quantiles

	CV-5%		CV-10%		Renewable energy		Trade openness		Nonrenewable energy		Economic growth	
	Mean	Variance	Mean	Variance	Mean	Variance	Mean	Variance	Mean	Variance	Mean	Variance
0.10	1.96	1.65	0.9643	2.6171*	0.7597	2.2327*	1.0931	1.9971*	0.7658	2.0088*		
0.15	1.96	1.65	1.2741	3.1282*	0.9951	2.1319*	1.2378	2.2195*	1.0829	1.7979**		
0.20	1.96	1.65	1.2016	3.1307*	1.2673	1.9337**	1.4138	1.7373**	1.3958	1.6756**		
0.25	1.96	1.65	1.4637	3.6350*	1.6817**	2.0817*	1.9789*	1.9588*	1.4769	2.0600*		
0.30	1.96	1.65	1.5815	4.4684*	1.8442**	2.7849*	1.8466**	2.6745*	1.3851	2.6653*		
0.35	1.96	1.65	1.8556**	3.7896*	1.7908**	2.2551*	2.0402*	2.0878*	1.5736	2.0580*		
0.40	1.96	1.65	2.0613*	3.4603*	1.8964**	2.0558*	1.8412**	1.8275**	1.7392**	1.7902**		
0.45	1.96	1.65	3.0243*	3.5298*	1.6971**	1.9318**	1.7947**	1.8126**	1.8745**	1.9463**		
0.50	1.96	1.65	2.8026*	3.1887*	1.5660	1.9557**	1.2983	1.7193**	1.7167**	1.8111**		
0.55	1.96	1.65	2.1666*	2.9891*	1.1782	1.6440	1.3786	1.4732	1.5931	1.6861**		
0.60	1.96	1.65	1.6931**	2.2490*	1.1805	1.8608	1.1198	1.5691	1.3956	1.6948**		
0.65	1.96	1.65	1.2639	2.0988*	1.1720	1.6056	1.0283	1.2255	1.0808	1.5291		
0.70	1.96	1.65	0.9494	2.0066*	1.2704	1.4959	0.9797	1.1437	0.9592	1.2958		
0.75	1.96	1.65	1.1361	1.9963**	0.8052	1.2245	1.0105	1.3584	0.8659	1.4159		
0.80	1.96	1.65	0.7780	1.5067	0.7645	1.2407	0.7157	1.6294	0.6403	1.2802		
0.85	1.96	1.65	0.7344	1.2614	0.6957	0.8454	0.7791	1.0087	0.5340	0.8514		
0.90	1.96	1.65	0.8451	0.7933	0.4957	0.5586	0.6833	0.6459	0.7084	0.6411		

\* and \*\* depict 5% and 10% significance level, respectively



**Fig. 5** **a** Causality from economic growth to ecological footprint, **b** causality from nonrenewable energy to ecological footprint, **c** causality from trade openness to ecological footprint, **d** causality from renewable energy to ecological footprint

## 5 Inferences for theory and practice

As the effects of the impact of GDP, nonrenewable energy, renewable energy and trade openness on ECF in Russia have been evaluated, the study proceeds to derive ramifications for practice and theory, since the empirical findings revealed several insights into sustainable development and cleaner production processes plans in Russia. The study outcomes disclosed that trade openness and renewable energy use contribute to environmental sustainability, while nonrenewable energy amplifies ecological footprint. Furthermore, growth in Russia escalates its ecological footprint. In this case, the research findings might be crucial for Russian policymakers, since they can assist them in achieving some of the SDGs goals.

Economic expansion defines Russia, and to attain that degree of growth, energy consumption is needed. Russia now relies primarily on fossil fuel-based energy solutions to meet its rising energy demand, since current renewable energy solutions are not yet mature enough to meet the current demand level. As a consequence, the ongoing use of fossil fuels is proving to be damaging to ecological quality by increasing the ecological footprint. As a result, in order to ensure Russia's sustainable development, fossil fuel alternatives must be phased out and replaced by renewable energy solutions, allowing the growth trajectory to continue unaffected (Akinsola et al., 2021; Destek & Sinha, 2020; Sarpong et al., 2020; Sinha et al., 2021; Steve et al., 2022). People's participation can make a huge



impact in this process since the effective implementation of fossil fuel substitution requires increased environmental awareness among the people, which can be achieved via fostering people–public–private partnerships. Cleaner manufacturing methods will begin to acquire importance in Russia whenever the phase-wise move away from fossil fuel-based solutions is accompanied by a rise in environmental consciousness, and Russia will be able to develop green employment as a result.

While generating jobs, it is equally important to consider the negative effects of trade openness on the environment. Russia's policymakers should utilize foreign trade as a means of maintaining ecological integrity. Since small-scale industrial participants may not be able to establish endogenous green production processes, international trade can be leveraged to acquire greener technologies that can be utilized by such participants. Players at all levels of the business will have enough time to create their own green manufacturing techniques, and they will be able to make use of the advantages of technology transfer during this time. Green trade policy can thus assist Russia to not only reduce its ecological footprint through trade openness but also give it the time it needs to create endogenous renewable energy alternatives and cleaner production. Since Russia is a pioneer in SDGs, it is now Russia's exclusive responsibility to illustrate the SDG accomplishment processes in a succinct and all-encompassing style so that the global community may learn from it. Furthermore, initiatives to enact renewable energy solutions in Russia will inspire greener processes of production, and a rise in environmental consciousness could help Russian policymakers to stimulate the endogenous development of alternative energy options. It will aid Russia in accomplishing SDG 13 (UNDP, 2019).

The exploration of renewable energy should be encouraged by the government of Russia, so that Russia will be capable to cut its NREC more easily. This will help Russia in formulating sustainable and energy alternatives that are affordable for everyone; therefore, achieving SDG-7 (UNDP, 2019). Now that these operations are in place, authorities should continue backing and growing people–public–private partnerships, which will enable the generation of several green jobs, and, as a result, will contribute to Russia's economic progress. Moreover, people will be capable to witness a reasonable growth-oriented lifestyle in this manner, and Russia will be getting close to attaining SDG 8 (UNDP, 2019). These initiatives will aid Russia in taking progressive efforts toward accomplishing these goals by 2030, with greener production serving as the engine in this process. Lastly, Russia should endeavor to assist its trading partners in improving their administrative systems in order to prevent unjustified waste transfer across borders. This plan of action will not only help Russia expand its international trade contacts, but it will also assist it in more effectively fulfilling the SDG goals.

## 6 Conclusion and policy suggestions

Using a quarterly dataset between 1992 and 2018, the study assesses the drivers of Russia's ecological footprint. The drivers include renewable energy, trade openness, nonrenewable energy and economic growth. The current research employed Quantile-on-Quantile regression (QQR) and causality in quantiles tests to uncover these connections. The study outcomes disclosed that trade in the majority of the quantiles, trade openness and renewable energy use contributes to environmental sustainability, while nonrenewable energy amplifies ecological footprint. Furthermore, in all quantiles, economic growth in Russia escalates ecological footprint. Moreover, the conventional quantile causality validates the

QQR outcomes. Furthermore, the quantile causality revealed that renewable energy, trade openness, economic growth and nonrenewable energy can forecast ecological footprint at various quantiles.

Based on the results, Russia should enhance various environmental regulatory norms, particularly in the field of renewable energy technologies. These regulatory actions might include ecological taxes, the elimination of damaging incentives, and the defining of public property rights. Internalizing the adverse effects on the environment created by human operations is one of the primary reasons for these regulatory enforcements. While strengthening regulatory requirements, policymakers should also consider how to execute the regulations, which can be accomplished through increasing public environmental consciousness. The Russian government should now support people–public–private collaborations to raise awareness. These alliances might have a variety of advantages, including assisting Russia in achieving SDG goals. Some of these advantages include (a) Since individuals will be psychologically acquainted with the benefits of renewable energy solutions, the shift from conventional non-renewable to renewable sources of energy can be easy; (b) Endogenous implementation of a greener process of production might lead to new job possibilities; and (c) Increased environmental consciousness and the creation of green jobs can encourage policymakers to spend more on R&D.

Consequently, to put these regulations in place, authorities should take care not to disrupt the economic expansion trend while substituting renewable energy solutions for fossil fuel-based alternatives. As a result, they must contemplate a phase-wise shift in this scenario, which will affect both businesses and households. To facilitate the transition, renewable energy solutions will be offered to both industries and households at a government-determined rate, with the solutions for households being subsidized. The government will give alternatives in exchange for a loan, and the rate of interest on the loan will be determined based on the firms' financial situation. The revenue generated from the industrial sectors can be utilized to make renewable sources more accessible to families. Households can also obtain government-subsidized loans to purchase renewable energy solutions, as well as an interest rate holiday and tax rebate. This may make it possible for households to switch to renewable energy sources for their everyday needs. Companies having a bigger ecological footprint can face a higher rate of interest, allowing cleaner industries to benefit at the expense of the comparably dirty industries.

These solutions indicate that the negative externalities created by fossil fuel-based economic expansion are being internalized. Policymakers should strive to discourage the industrial sector from using environmentally degrading fossil fuel energy sources by imposing Pigouvian levies or withdrawing detrimental subsidies on fossil fuel alternatives while implementing phase-wise energy source transition. Taxing negative environmental externalities should be done in a progressive way, according to the magnitude of the negative externalities. When doing so, policymakers should keep in mind that imposing a high Pigouvian tax rate from the outset could impede the activities of the industrial sector, which might have a deleterious effect on Russia's economic expansion patterns.

As a result, the Pigouvian tax rate should be progressively augmented so that the industrial sector has enough time to switch sources of energy. Likewise, policymakers should concentrate on outlining the regulatory steps that will be done to assist those who are harmed by the sectors' negative externalities. Fear of legal action from the state could also deter firms from continuing to utilize nonrenewable sources of energy. People–public–private partnerships should be used to supplement this particular effort. While doing so, policymakers should concentrate on the endogenous development of renewable energy alternatives to reduce reliance on fossil fuel-based alternatives. As a result, the government

will be actively pushing the creation of new clean employment that makes full use of clean manufacturing processes. Trade policies may well be changed to meet changes in energy regulations and will be aimed at improving ecological integrity, i.e., Russia will adopt clean trade policies. The excess energy can be sold to other countries with high energy demand, increasing national income, which could then be used to fund the exploration of new alternative energy sources and the creation of more advanced clean technological alternatives. In this approach, Russia might well be capable of helping itself to meet the SDGs' goals by 2030.

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## Authors and Affiliations

**Tomiwa Sunday Adebayo**<sup>1</sup>  · **Festus Victor Bekun**<sup>2,3</sup>  · **Husam Rjoub**<sup>4,5</sup>  ·  
**Mary Oluwatoyin Agboola**<sup>6</sup> · **Ephraim Bonah Agyekum**<sup>7</sup> · **Bright Akwasi Gyamfi**<sup>8</sup>

Tomiwa Sunday Adebayo  
tadebayo@ciu.edu.tr

Husam Rjoub  
hrjoub@ciu.edu.tr

Mary Oluwatoyin Agboola  
maryagboola@dau.edu.sa

Ephraim Bonah Agyekum  
agyekumephraim@yahoo.com

Bright Akwasi Gyamfi  
bagyamfi@ticaret.edu.tr

- <sup>1</sup> Department of Economics, Faculty of Economics and Administrative Science, Cyprus International University, 99040 Nicosia, Turkey
- <sup>2</sup> Faculty of Economics Administrative and Social Sciences, Istanbul Gelisim University, Istanbul, Turkey
- <sup>3</sup> Adnan Kassar School of Business, Department of Economics, Lebanese American University, Beirut, Lebanon
- <sup>4</sup> Department of Business Administration, Faculty of Management Sciences, ILMA University, Karachi 75190, Pakistan
- <sup>5</sup> Department of Accounting and Finance, Faculty of Economics and Administrative Sciences, Cyprus International University, 99040 Haspolat, Mersin 10, Turkey
- <sup>6</sup> Finance and Banking Department, College of Business, Dar Al Uloom University, Riyadh, Saudi Arabia
- <sup>7</sup> Department of Nuclear and Renewable Energy, Ural Federal University Named After the First President of Russia Boris Yeltsin, 19 Mira Street, Ekaterinburg, Russia 620002
- <sup>8</sup> Economic and Finance Application and Research Center, İstanbul Ticaret University, Via Mersin 10, Nicosia, North Cyprus, Turkey