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How do energy efficiency, technology, natural resources and globalization impact environmental sustainability? Fresh evidence from load capacity curve theory

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For sustainable development, the roles of energy efficiency and renewable energy is undeniable. We are passing through the era of globalization and economies are expanding their economic activities across borders. In this scenario, nations are striving for sustainable economic development without hurting the climatic conditions. Therefore, this study employs Bai and Carrion-i-Silvestre unit root test and Westerlund cointegration tests. The variables were found to have mix order of integration and Westerlund test shows cointegration in the panel data. The Method of Moments Quantile Regression (MMQR) is used to ascertain the effects of energy efficiency and economic, environmental, and globalization factors on the load capacity factor (LCF), a measure of environmental quality in G-20 countries. Key findings supporting the Load Capability Curve (LCC) theory show that while initial economic growth (GDP) has a negative impact (coefficient of −0.035 at the median quantile), advanced economic growth (GDP^2) improves LCF (coefficient of 0.513 at the 90th quantile and 0.388 at the median). The median quantile coefficient of 0.055 indicates a positive association between the consumption of renewable energy and LCF. Natural resources exhibit a coefficient of 0.061 at the 90th quantile and 0.037 at the median. However, there are drawbacks to both financial globalization and contemporary environmental technology; their coefficients at the median quantile are −0.021 and −0.058, respectively. The work suggests targeted strategies, including more stringent environmental legislation, backing for renewable energy, sustainable resource management, advancements in environmental technologies, regulation of financial globalization, and bolstering of international cooperation.

KEYWORDS

energy efficiency, globalization, renewable energy, load capacity curve, MMQR, G-20 countries

Introduction

Environmental pollution is a serious problem that has a substantial impact on both human wellbeing and ecosystems (Qayyum et al., 2024; Wang et al., 2023). It is also a major contributor to climate change. In recent decades, the most talked-about environmental challenges globally have been climate change and worldwide warming (Ali et al., 2022; Kirikkaleli and Ali, 2023). Among experts and policymakers in both established and emerging economies, this is the most discussed problem. A comprehensive comprehension of the factors that contribute to climatic pollution is essential for identifying and accomplishing sustainable development goals (SDGs) (Ali and Kirikkaleli, 2024). For both wealthy and developing countries to reduce carbon emissions and manage global warming, a shift to renewable energy is essential (Baba Ali et al., 2023; Tariq et al., 2024).

The argument over how important natural resources is to ecological quality has grown contentious. According to (Balsalobre-Lorente et al., 2023a), natural resources improve ecological quality. Natural resource usage has, as we all know, expanded significantly in recent decades; in nations where natural resources are plentiful, this improves revenue creation (Ge and Mehmood, 2024). Despite being vital to a nation's economic growth, these resources also contribute to environmental contamination. Several research have found that enhancing ecological sustainability requires the use of green energy (Radmehr et al., 2023; Zhao et al., 2023).

Carbon emissions (CO2) and ecological footprints (EF) impacts are used to measure environmental pollution in most of previous works. EF includes biocapacity (supply side) and demand to take the environmental elements (Chunling et al., 2021; Yang et al., 2021). EF was employed in several research,

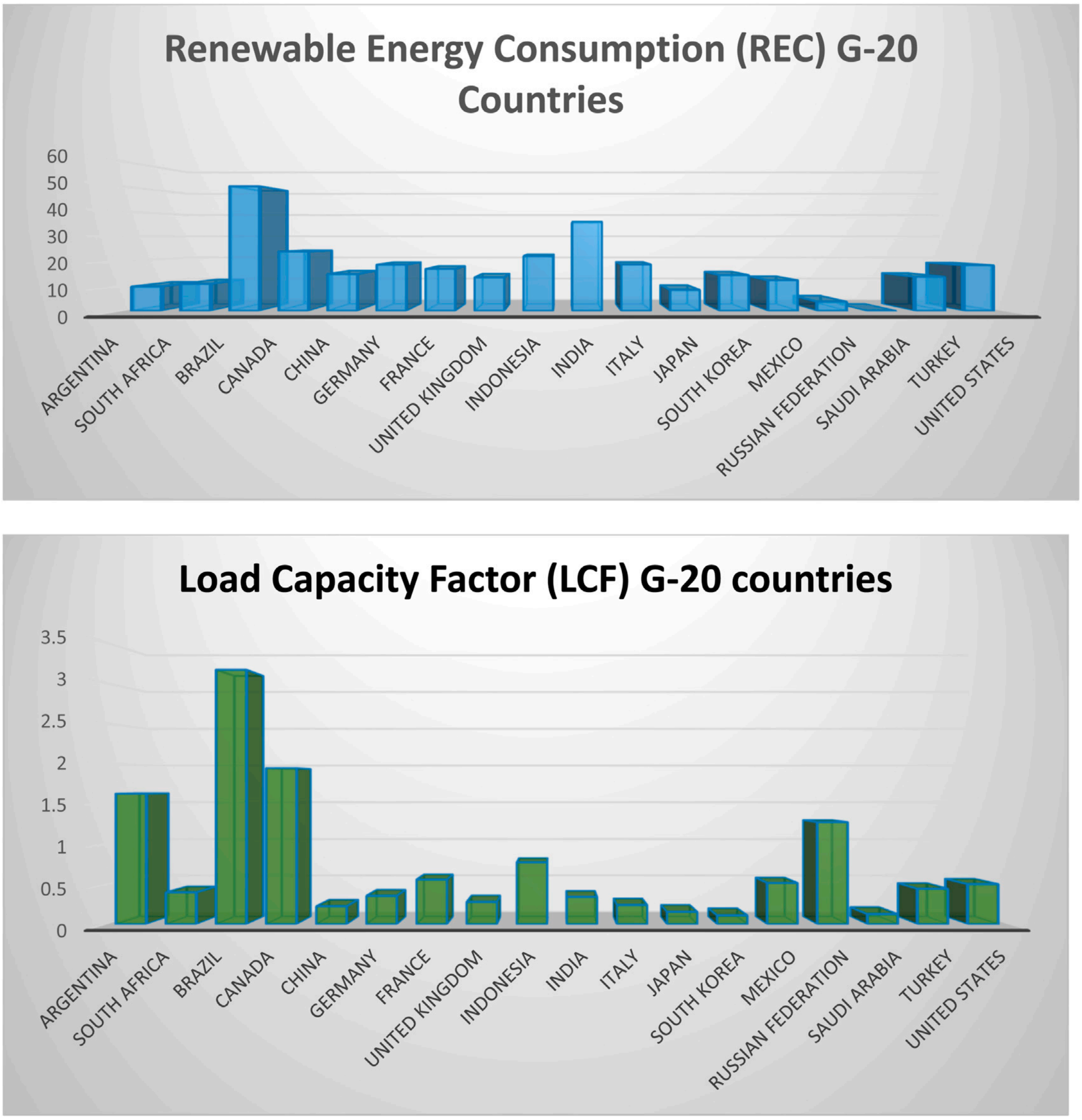

FIGURE 1
Renewable energy use in G-020 nations (2021).

FIGURE 2
Graphical Form of results.

but biocapacity, the ecosystem's supply side, was overlooked. This study uses the load capacity factor (LCF), to capture environmental quality. Economic growth (GDP) is often employed to explain LCF determinants (Shang et al., 2022; Feng et al., 2024). Grossman (Grossman and Krueger, 1991) introduced the Environmental Kuznets Curve (EKC) to explain the income-environmental quality link. Wealth and environmental degradation create an inverted U, according to the EKC theory. The relationship between LCF and wealth can be U-shaped. Rising wealth may create communities that initially don't regard the environment, which lowers the LCF. GDP in economies that gain more over a ceiling can improve environmental quality and LCF thanks to cleaner industrial technologies and environmental awareness. This U-shaped relationship between LCF and revenue is described as the "load capacity curve" (LCC) theory. Based on this, the study expands on the previous research by examining the impact of different socio-economic factors (renewable energy (REC), natural resources (NR), energy efficiency (ENE), financial globalization (FG), political globalization (PG), social globalization (SG), and environmental technology (ENP) on the LCF within LCC theory for G-20 economies. Within an economy, energy plays an important role to gain economic gains. Currently, G-20 countries are expanding their REC within the energy mix to tackle climatic issues without hurting the environment. The variance of REC for G-20 economies is depicted in Figure 1.

For instance, Saudi Arabia uses significantly less green energy than Brazil, where it accounts for 49% of total energy use (WDI, 2023). Additionally, there are differences in the ecological quality of the studied nations (see Figure 2).

Saudi Arabia's LCF value shows low ecological quality, while Brazil's LCF value suggests good ecological quality.

When implemented successfully, globalization can assist countries in creating sustainable policies that are adapted to their geographic, environmental, and economic circumstances (Abbas et al., 2024; Saqib et al., 2024). Prior studies have demonstrated that, depending on the institutional context, globalization can either improve or worsen environmental quality. There are three facets to globalization: financial, social, and political.

One of the characteristics of FG is the unification of international capital markets into a single framework. Over the past few decades, this kind of globalization has produced benefits for society in both wealthy and developing nations by making the global economy more interdependent. FG has generally been seen to promote capital flows and investment, as well as the sharing of cutting-edge technological applications, which in turn promotes cross-national growth mobilities (Ahmad et al., 2021; Mohammed et al., 2024). One can take advantage of FG to draw in more foreign-funded research and development (R&D) projects. Therefore, FG encourages economic growth, which has two consequences on environmental quality: composition and scale effects (Xu et al., 2022; Cifuentes-Faura et al., 2024). There are differing opinions about how FG affects ecological quality. According to (Awosusi et al., 2022b; Gaies et al., 2022), FG facilitates the transfer of technology and eliminates barriers to international trade and investment. As a result, output and investment levels rise because of globalization (Sinha et al., 2024). This development increases the use of energy resources, which in turn causes greater pollution in the environment. However (Wang et al., 2022; Ramzan et al., 2023), showed that FG encourages green energy and lowers barriers to green technologies. Consequently, the environment is sustained, and additional green investments are drawn to this globalization. FG encourages fiscal products that tend to support environmental quality through financing technical advancements, R&D initiatives, and renewable energy technologies.

The integration of businesses through social interactions such as ICT, travel, and migration is referred to as SG. Although the literature has examined the different aspects of SG, a thorough understanding of their combined role is lacking. In addition, there is a paucity of analysis and research on this topic, particularly when it comes to China. The literature hasn't come to a definitive conclusion about if SG is good for the environment or bad. According to (Kirikkaleli et al., 2022), SG can offer developing markets guidance on how to enhance their business environments, tourism areas, industrial operations, and administrative levels by incorporating effective techniques from more developed countries. Through digital transformation, travel, and tourism, SG fosters social interactions that put pressure on the use and depletion of finite resources. It also raises environmental awareness, supports eco-friendly technologies, and encourages the use of renewable energy sources (Wu et al., 2023). But more economic activity can also mean more carbon emission levels, which lowers environmental quality. Examples of this include outsourcing facilities and foreign direct investment (FDI).

In addition, technological, communication, and transportation advancements have contributed to the acceleration of PG in recent decades. PG may have a beneficial or bad effect on ecological performance. Transnational agreements, such as the "Paris Agreement," which attempts to reduce GHG emissions and fight climate change, are a result of PG. These agreements give nations a foundation for cooperating and addressing environmental concerns as a group. It enables the sharing of best practices and information on environmental policy between nations, which can support innovation and improved governance (Acheampong, 2022). The conflict between Russia and Ukraine that broke out in February 2022 caused energy costs to rise steadily throughout the world. For example, natural gas prices reached a record high, which drastically altered the mix of energy used in several European nations. Some nations are forced to accelerate the development of renewable energy sources, return to gas-based power plants, and restart coal power generation. Furthermore, institutional problems, government investment restrictions, and growing PG that affects global business could all have a negative effect on the environment (Kariyawasam and Jayasinghe, 2022). Studies on the connection in PG and the environment, however, are scarce. States with weak institutional governance, such as those with corruption and lax regulations, frequently experience political relations, whereas those with adequate institutional superiority have less political gaps (Kariyawasam and Jayasinghe, 2022). Most investigations concluded that globalization has an impact on the environment, including (Adebayo et al., 2022; Awosusi et al., 2023). Nonetheless, PG has a complex and wide-ranging impact on environmental quality. PG may present chances for international cooperation and coordinated action to address environmental issues. Thus, the purpose of this study is to determine whether PG protects the quality of the environment.

In three areas, the current study aims to close the research gap: Initially, it looks closely at how G-20 countries are promoting ecological quality using NRR, FG, SG, PG, energy efficiency, environmental technology, and REC. Next, we represented the ecological advancement of the tested countries using the innovative LCF within the LCC theory. The environmental supply side is overlooked by traditional proxies like carbon emissions (CO_2) (Kartal et al., 2023). Our objective is to provide a thorough empirical examination of ecological sustainability from both the supply and demand sides for the G-20 countries. Third, to ascertain the impacts of the research variables across different quantiles of LCF, we applied the recently developed moments quantile regression (MMQR) approach. The total quantile distribution can take covariance into account with this method. Furthermore, this method can produce trustworthy results while resolving endogeneity problems. Hence the research questions of this work are as follows:

How energy efficiency and subindices of globalization impact environmental quality in G-20 countries?

Is load capacity curve theory exists in the era of technological innovations?

The following is the layout of the remaining portions of this work: An overview of the empirical literature is presented in Section 2. The model's specifics, an overview of the data, and the methods used are provided in Section 3. The econometric results are discussed in Section 4. Section 5 presents the policy and conclusion at the end.

Review of literature

This part of the work analyzes the existing literature on environmental quality and the factors that impact it, including NR, GDP, ENE, ENP, REC, FG, PG, and SG.

Natural resources and environmental quality

The impact of NR on CO_2 in OECD countries from 2000 to 2018 was evaluated by Lorente et al. (2023). They showed that NR significantly and negatively impacted sustainable development. Using the MMQR model (Zhao et al., 2023) assessed the effect of NR on environment in economies with plentiful NR and concluded that NR lowers ecological quality (Sun et al., 2022) probed the impact of NR on the EF in the G-11 nations. The results validated the idea that a higher NR results in a larger EF (Jahanger et al., 2023) used the MG and AMG methodologies to track the relationship between NR and greenhouse gas emissions. It was noted that NR encourages emissions in NAFTE economies till 2018. Furthermore (Jiang et al., 2022) investigated the relationship between NR and CO2 in B&R countries between 1995–2018. They found that NR exacerbates environmental degradation (Ahmed et al., 2020) used the ARDL model to investigate the impact of NRR on EFP. The results of the study indicated that NR had a significant impact on environmental quality. In contrast (Pata and Ertugrul, 2023) investigated the impact of NR on LCF using an ARDL technique in India. The study's outcomes indicate that natural resources promote ecological progress (Wang et al., 2023) assessed the effects of NR on the LCF in 96 chosen nations using a threshold model approach. Research has shown that a high NRR results in a favorable external environment (2023) tested the relationship between NR and LCF in China using the Fourier quantile causality test, and they concluded that NR is inversely correlated with environmental quality. A quantile regression model was employed in a different work by (Guloglu et al., 2023) to assess the relationship between NR and environmental quality in OECD nations and found that NR improve environmental quality. According to the findings of (Ge and Mehmood, 2024) natural resource improves environmental quality, whereas renewable energy increases environmental quality in four quantiles. Over time, energy productivity reduces LCF.

GDP and environmental quality

Adebayo and Samour (2023) found that income causes more severe environmental degradation utilizing the NARDL approach. After examining the relationship between GDP and EF in some top emitter nations, (Shahbaz et al., 2022) concludes that income has a negative impact on the environment (Jin and Huang, 2023) investigated the relationship between income and LCF using the NARDL approach. They noticed that environmental degradation increases with GDP (Ali et al., 2023) assessed the relationship between South American country GDP and pollution. Using the MG and PMG analytical approaches, the study found that in South American countries, money increases air pollution and decreases environmental quality (Shayanmehr et al., 2023) probed the relationship between GDP and environmental degradation. The study, which used the quantile approach, found that GDP increases environmental pollution. According to (Shang et al., 2022) evaluation of the linkages between GDP and LCF in ASEAN nations and found that, GDP lowers LCF during 1980–2018. Based on a panel GMM approach, (2022) discovered that wealth correlates with more severe environmental degradation. Similar conclusions were supported by (Pata, 2021) in United States and Japan. According to (Adebayo et al., 2024) financial development, the energy transition, and advancements in information and communication technology connected to the environment all have a major impact on slowing the rise in greenhouse gas emissions, especially over the medium and long terms.

Renewable energy, energy efficiency, and environmental quality

Using the CS-ARDL technique, Zhao et al. (2023) investigated the relationship between REC and environmental quality in BRICS nations, demonstrating the positive environmental effects of green energy (Appiah et al., 2023) used the CS-ARDL method to investigate the relationship between REC and EF. They believed that by lessening the environmental impact, REC promotes favorable environmental advantages. The quantile regression model was utilized by (Baba Ali et al., 2023) to assess the relationships between REC and environmental quality for G-20 nations. As a result, they observed a growing impact of REC on environmental quality. Ofori et al. (2023) examined the relationship between RECs and CO2 in EU countries using a dynamic spatial statistical model. They believed that REC advances environmental advancement. Furthermore, (Pata and Kartal, 2023) research demonstrated that REC had no appreciable effect on environmental sustainability.

(Lei et al., 2022) investigated how China's CO2 were impacted by energy efficiency and REC. The results show that China's energy efficiency and carbon emissions are inversely correlated, suggesting that environmental stability could be enhanced by a negative shock. On the other hand, carbon emissions from sources of clean energy go down. It's obvious from this negative connotation that the nation is not yet ready to replace its present energy sources with renewable ones (Akram et al., 2022) examined how ENE, REC, and GDP affect CO_2 in MINT countries during 1990–2014. Research indicates that both EE and REC development help to reduce carbon emissions in the indicated nations, despite a variance in their development. Short-term results are higher, but long-term projections are lower due to rising countries and limited carbon emission reductions. The impact of technology, REC, and ENE on the environmental quality of OECD economies between 1990 and 2020 was studied by (Hassan et al., 2022). According to author estimates, economic expansion has a negative effect on the economic growth of the top 15 economies in the OECD, whereas renewable energy, energy efficiency, and technological innovation have favorable effects (Moosavian et al., 2024) found that 36% less fossil fuel would be consumed if the potential of nearby renewable resources was fully utilized. Additionally, implementing laws encouraging the use of renewable resources can cut annual carbon dioxide emissions.

Globalization and environmental quality

Globalization has been impacting the economic growth of the economies all over the world. In this era of digitalization, nations have collaborated in social, political, and economic sectors. These collaborations ultimately affect the climatic conditions. Globalization has three sub-indices of FG, PG, and SG. Several research studies have examined how FG affects environmental quality, and most of them hold that FG creates beneficial impacts. For instance, (Fatima et al., 2023) assessed the impact of FG on air quality in OECD nations. The outcome demonstrates that environmental quality is improved by FG. Additionally, from 1995 to 2020, (Ramzan et al., 2023) reported a negative correlation between FG and EF in the United kingdom (Akadiri et al., 2022) used time-frequency domain causation to study how FG promoted the LCF in India. According to their empirical investigation, FG lessened environmental destruction. According to Xu et al. (2022), FG lowers the LCF in Brazil. According to (Ulucak et al., 2020), there is a negative pressure from FG on environmental degradation (Danish et al., 2020) concluded that FG, by using PMG and DOLS methodologies, favorably helps to environmental sustainability in emerging economies. Using the MMQR model, Miao et al. (2022) shown a negative correlation between FG and environmental quality in emerging nations. Ahmad et al. (2021) examined the relationship between FG and EF in G7 nations using the CS-ARDL model. They concluded that FG leads to an improvement in the environment.

On the other hand, scant research revealed a declining relationship between FG and environmental quality. Wang et al. (2022), for example, used a model based on panel data to determine the impact of FG on environment in OBOR nations. They argued that the advancement of the environment is hampered by more financial globalization. Using the ARDL and NARDL techniques, Gaies et al. (2022) verified these results across OPEC MENA countries from 1980 to 2018. Political globalization, according to Paramati et al. (2017), increases environmental pollution for samples of the European Union (EU) and the G-20 nations. (Ulussever et al., 2024) indicated that ICT improves environmental quality, globalization lowers environmental quality, and income has little bearing on the Gulf countries.

Environmental technology and environmental quality

By enhancing ENE and preserving competitiveness, ENP mitigates the negative effects of GDP on the environmental quality. By striking a balance between ecological structure and economic growth, ENP, also known as green innovation assists in achieving the Sustainable Development Goals (SDGs) (Liao et al., 2023). Empirical data, however, reveals conflicting results about the relationship between environmental technology and environmental quality. Environmental technology is seen as having a positive impact on environmental sustainability, (Afshan et al., 2022; Koseoglu et al., 2022). The opposing viewpoint (Awosusi et al., 2022a; Aydin et al., 2023; Huo et al., 2023) shows results that are either positive or negligible in relation to environmental quality (Huang et al., 2023). The effects of ecological regulation on employment exhibit inhibition first and promotion second as a result of the regulations' progressive improvement. Innovation in clean technology mitigates the employment impact of environmental regulations.

Research gap

Considering the above-mentioned discussion on the available literature, it is evident that very few studies probed the impacts of globalization, energy efficiency, and technological innovations on environmental quality (LCF) in G-20 nations. Very few of them are also able to probe the LCC theory especially in G-20 countries. Therefore, no previous study has assessed how the load capacity factor under the LCC theory in G-20 countries is affected by natural resources, energy efficiency, environmental technology, renewable energy, and sub-indices of globalization. Therefore, to close this gap, various advanced approaches were utilized to assess how the targeted factors interacted with one another.

Theoretical framework, data and methodology

The current paper examined how NR, REC, economic growth, energy efficiency, environmental technology, and sub-indices of globalization contribute to or detract from the LCF in the research domains by analyzing a dataset covering the years 1990–2021. The selection of the time periods and nations was determined by the available data. These missing values in the dataset are located using the confidence interval technique. It begins with the first element and looks at each value as it moves progressively to the last element. It indicates which observations are lacking. Next, using the mean and standard error of the available observations, determine the confidence interval using the confidence interval technique. The confidence interval's median is then used to fill in the missing numbers. Additionally, the Global Footprint Network provided the LCF, the World Bank provided the REC, ENE, NR, and GDP, and the KOF Swiss economic database provided the sub-indices of globalization. The OECD data bank is the source of the ENP statistics. Renewable energy produces from clean energy resources like wind and solar energies. Natural resources are extracted to manufacture in industries. This work uses three sub-indices of globalization. Trade globalization and financial globalization, each with a 50% weighting, make up economic globalization. Personal interaction, information exchanges, and close cultural ties all contribute to social globalization, with each contributing one-third. Globalization in terms of economy, society, and politics is combined and assigned equal weights to create the Globalization Index. The factors are in line with the 2030 Agenda for Sustainable Development Goals (SDGs) and their aims. Table 1 provides further information regarding the factors used in the study.

Expanding on the work of Guloglu et al. (2023), Zhao et al. (2023a), and Ramzan et al. (2023), we have created the structure below in Eq. 1 to get a better understanding of the factors that influence LCF in the G-20 economies.

$$LCF_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP2 + \beta_3 REC_{it} + \beta_4 NR_{it} + \beta_5 ENP_{it} + \beta_6 FG_{it} + \beta_7 SG_{it} + \beta_8 PG_{it} + \beta_9 ENE_{it} + _{it} \quad (1)$$

where Table 1 appropriately defines LCF, NR, REC, GDP, GDP2, ENE, ENP, SG, PG, and FG for country i at time t. The natural logarithmic forms of the study's variables are utilized to avoid heteroscedasticity and maintain data sharpness.

Cross sectional dependence (CD) and slope homogeneity test (SH)

The panel data are expected to exhibit cross-section dependence (CD) because of growing globalization. Therefore, recognizing CD will boost the validity of the findings. Therefore, a few tests were utilized to assess the existence of the CD in panel data. First generation unit root tests, including the Im Pesaran and Shin (IPS) or Lin and Chu tests, cannot resolve CD and SH (Gu et al., 2020; Su et al., 2020). It is essential to look at the time-series characteristics of the variables before evaluating their cointegration. Tests of the unit root are essential to preventing false regression. To verify the stationarity property, we employ (Bai and Carrion-i-silvestre, 2009). Because of their benefits, unit root tests with structural breaks were initially used (Bai and Carrion-i-silvestre, 2009). A variety of unit root tests, including the (Stock et al., 1999) M-tests, are proposed by these tests. Second, under null and alternative hypotheses, the statistical technique is advised for a variety of unexplained structural improvements.

It is crucial to consider potentially distinct patterns across the cross-sections in panel data, even while taking CD into account. Assuming that the slope coefficient is homogeneous may lead to inaccurate inferences. Thus, we employed (Hashem Pesaran and

TABLE 1 Data description and sources.

Load capacity factor	LCF	Biocapacity/Ecological footprints	Global footprint network (GFN)
Renewable energy	REC	Renewable energy consumption ratio of total energy use	World data indicators (WDI), 2023
Economic growth	GDP	GDP Current US$	WDI (2023)
Economic growth squared	GDP2	Authors calculation	WDI (2023)
Natural resources	NR	Natural resources rents % of GDP	WDI (2023)
Financial globalization	FG	Financial globalization	KOF institute
Social globalization	SG	Social globalization	KOF institute
Political globalization	PG	Political globalization	KOF institute
Energy efficiency	ENE	Energy intensity	WDI (2023)
Environmental technology	ENP	Patents on environmental technology	OECD, 2023

Yamagata, 2008) example, which is stated as follows in Eqs 2, 3, to assess slope heterogeneity:

$$\tilde{\Delta}_{SH} = (N)^{\frac{1}{2}}(2k)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S} - k\right) \quad (2)$$

$$\tilde{\Delta}_{ASH} = (N)^{\frac{1}{2}}\left(2k\left(\frac{T-k-1}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S} - 2k\right)\right) \quad (3)$$

In this case, delta tilde is represented by the $\tilde{\Delta}_{SH}$, and adjusted delta tilde is indicated by the notation $\tilde{\Delta}_{ASH}$.

Co-integration test

To identify long-term relationship connections in the dataset, we used Westerlund's second-generation cointegration tests in this study. In contrast to tests from the first generation, Westerlund's test considers both SH and CD. The Eq. 4 of westerlund test is as follows:

$$\Delta Y_{it} = \tau_i d_t + \alpha_i\left(Y_{it-1} - \beta_i' X_{it-1}\right) + \sum_{j=1}^{pi} \alpha_{ij}\Delta Y_{it-j} + \sum_{j=0}^{pi} Y_{ij}\Delta X_{it-j} + \varepsilon_{it} \quad (4)$$

where the cross-sections and the period are represented, by i = 1, . . ., N and t = 1, . . ., T. The value of the error correction component is ai, the vector of parameters is si, and the determinant components are dt.

Method of momentum quantile regression (MMQR)

This work uses MMQR in accordance with Shayanmehr et al. (2023) to accomplish the goal of study to know the coefficient values within quantiles. MMQR is a methodology which links quantile regression with moment estimation. It offers a reliable and adaptable method for simulating a response variable's conditional quantiles. When working with non-normally distributed data, this approach is helpful since it provides endogeneity handling, robustness to outliers, and the capacity to examine correlations among variables at various quantiles of the dependent variable (LCF). This method is a useful tool for a variety of applications since it may detect both linear and non-linear impacts (Baba Ali et al., 2023). The conditionally quintile of $Q_Y(\tau/X)$ for random variables can be expressed as follows:

$$Y_{it} = \alpha_i + X_{it}'\beta + \sigma\left(\delta_i + Z_{it}'\gamma\right)U_{it} \quad (5)$$

The unknown components in Eq. 5 are ai, b, di, and c. Z functions as a vector of recognized transformations of notable elements. The definition of $\sigma(.)$ is: $P\left\{\sigma(\delta_i + Z_{it}'\gamma) > 0\right\} = 1$. U is a random component that is unknown.

$$Q_Y(\tau \mid X_{it}) = \left(\alpha_i + \delta_i q(\tau)\right) + X_{it}'\beta + Z_{it}'\gamma q(\tau) \quad (6)$$

In Eq. 6, The main variable's quantile distribution is shown by $Q_Y(\tau \mid X_{it})$, while the explanatory variables are shown by X_{it}'. Within the context of , Eq. 1 the empirical framework of the study is stated as follows in Eq. 7:

$$\begin{aligned} QLCF_{it}(\tau_k \mid X_{it}) = {} & \delta_i + \varphi_{1\tau}GDP_{it} + \varphi_{2\tau}GDP2_{it} + \varphi_{3\tau}REC_{it} \\ & + \varphi_{4\tau}NRR_{it} + \varphi_{5\tau}ENP_{it} + \varphi_{6\tau}FG_{it} \\ & + \varphi_{7\tau}SG_{it} + \varphi_{8\tau}PG_{it} + \varphi_{9\tau}ENE_{it} \end{aligned} \quad (7)$$

Results and discussion

Following the research by (Voumik et al., 2023), we used a set of tests as indicated in Table 2 to look at the CD among the study's components. Panel models assume that disruption terms are dimensionless, but they may also have cross-sectional correlation. Thus, it is necessary to determine if the stochastic terms can operate independently.

The findings indicate in Table 2, a correlation between the stochastic terms along cross-sections, suggesting that the panel's CD is confirmed. Panel data analysis relies heavily on slope homogeneity. According to Table 3, the findings indicate that the slope is heterogeneous, which suggests that the calculated coefficients differ and cause the slope to vary between panels.

A prerequisite for advancing with the substantive model estimation in this research is guaranteeing the stability of the

TABLE 2 Cross sectional dependence test.

	CD	PC LM	BP LM	BCC LM
LCF	12.12***	11.56***	524.67***	−1.13
	(0.000)	(0.000)	(0.000)	(0.259)
GDP	55.31***	1.24	689.24***	−2.67***
	(0.000)	(0.215)	(0.000)	(0.008)
REC	9.43***	−1.78*	446.67***	−1.78*
	(0.000)	(0.074)	(0.000)	(0.075)
NRR	24.80***	−1.16	393.64***	4.15***
	(0.000)	(0.247)	(0.000)	(0.000)
ENP	67.07***	−0.62	828.99***	−2.29**
	(0.000)	(0.537)	(0.000)	(0.022)
FG	32.16***	−2.18**	405.10***	2.62***
	(0.000)	(0.029)	(0.000)	(0.009)
SG	52.75***	−1.78*	652.43***	−1.86**
	(0.000)	(0.075)	(0.000)	(0.063)
PG	40.29***	−1.73*	526.06***	−2.69***
	(0.000)	(0.084)	(0.000)	(0.007)
ENE	11.21***	−3.23***	514.80***	6.10***
	(0.000)	(0.001)	(0.000)	(0.000)

BCC, Bias-corrected scaled; PC, pesaran scaled; BP, Breusch-Pagan LM; *, ** and *** show significance level at 10%, 5% and 1% respectively.

TABLE 3 Slope homogeneity test.

		Prob-value
Delta	−2.141**	0.032
adj	−2.690***	0.007

and * show significance at 10% and 1% respectively.

variables. Unstable variables may have an impact on the study's conclusion. In such a scenario, selecting a research model would also be impacted because it would be necessary to use a framework that can manage dataset. The unit root test is used in the study considering this (Table 4).

Prior to testing the non-stationary components at first difference, we test the level factors first. The outcome provides a sense of the components' stability over both test phases. Most of the variables are stationary at 1st difference.

Examining the long run linkages of LCF and socio-economic factors is the main goal of this test. To do this, we used the (Westerlund, 2008) test (Table 5).

The outcome shows that cointegration is present in the data. After the confirmation of co-integration among the variables, the next step is to find out the coefficient values of the variables. For this purpose, this work adopts the MMQR method. The results of the MMQR provide detailed information about the link between the LCF and globalization, economic, and environmental factors at different quantiles. In order offer a clearer understanding, we incorporate essential coefficient values into phrases as we explore these relationships below in Table 6.

The GDP coefficients over quantiles reveal that the initial economic expansion has a 3.5% negative influence on LCF at the median (50th quantile), where the coefficient is −0.035. The coefficient is −0.042 at the 90th quantile, indicating a larger adverse effect of 4.2%. The first portion of the Load Capability Curve (LCC) theory, which holds that industrialization and increased pollution during the early phases of economic development cause environmental degradation, is supported by this negative association. On the other hand, the GDP squared coefficients are constantly positive. The coefficient is 0.388 at the 50th quantile and rises to 0.513 at the 90th quantile. These figures show that GDP increases favorably with further growth, contributing 38.8% and 51.3%, respectively, to LCF. This beneficial effect supports the second component of the LCC hypothesis, which postulates that modern technology, and sustainable practices promote environmental benefits because of advanced economic growth. Our results are in line with those of (Afshan and Yaqoob, 2023) for emerging nations (Dogan and Pata, 2022), for G-7 nations, and Guloglu et al. (2023) for OECD economies. As a result, the G-20 nations ought to keep an eye on how the industrial and agricultural sectors are expanding and push them to embrace green energy.

For every quantile, the renewable energy consumption coefficients are positive and very significant. The coefficient is 0.055 at the 50th quantile, meaning that a 1% increase in the use of renewable energy sources increases LCF by 5.5%. This influence

TABLE 4 Bai and Carrion-i-silvestre, (2009) unit root test.

Level				First difference		
	Z	Pm	p	Z	Pm	p
LCF	2.02	2.59***	63.22***	−3.94***	17.32***	194.92***
GDP	6.54***	0.95	48.57**	−3.93***	20.18***	220.52***
GDP2	3.34***	2.40***	61.52***	−3.43***	14.75***	171.93***
ENP	−0.95	2.10***	58.80**	−2.94***	7.45***	106.70***
REC	−0.95	1.77***	55.87**	−3.61***	11.81***	145.63***
NRR	3.31***	3.88***	74.77***	−3.70***	16.51***	187.70***
ENE	0.36	−0.68	33.87	−2.43***	3.52***	71.52***
FG	0.55	−0.33	36.97	−3.16***	12.30***	150.06***
SG	−0.50	2.01***	58.04**	1.42	9.76***	131.65***
PG	−2.00	3.65***	72.68***	−3.14***	9.34***	123.58***

For Z and Pm, Critical values (CV) are 2.103, 1.542, and 1.190, at 1%, 5%, and 10% respectively and the CV, for P are 60.07, 47.50, and 43.09 at 1%, 5%, and 10% respectively.

TABLE 5 Westerlund Co-integration test.

Statistic	Value	Z-value	Prob-value
Gt	−3.585***	−4.178	0.000
Ga	−14.497	0.246	0.597
Pt	−12.954***	−2.670	0.004
Pa	−13.253	−0.986	0.162

***show significance 1%.

increases even more at the 90th quantile, when a coefficient of 0.061 corresponds to a 6.1% rise. This steady improvement in outcomes highlights how important renewable energy is to improve the state of the environment. These findings are like the findings of (Shayanmehr et al., 2023; Dai et al., 2024).

As a pure and endless source of energy, clean energy is essential to promoting environmental excellence. Clean energy sources, in contrast to fossil fuels, produce power without releasing greenhouse gases into the atmosphere. Lowering reliance on dirty fuels, that are significant causes of environmental pollution, allows REC to mitigate the negative effects of climate change, reduce pollution in the air and water, preserve valuable NR, and safeguard the environment. Usage of REC technologies also promote innovation in technology, creates jobs in the sector, and improves energy security, all of which lays the groundwork for a more vibrant and sustainable global energy environment. However, (Huilan et al., 2022) in Mexico disputes the results. Despite the abundance of clean energy sources in the nation, they ascribe their findings to their underutilization. Additionally (Huilan et al., 2022) noted a detrimental effect in South Africa.

Similarly, the natural resource coefficients are positive. The coefficient is 0.037 at the 50th quantile, meaning that LCF is enhanced by 3.7% for every 1% rise in the wealth of natural resources. This effect is more pronounced at the 90th quantile, where the improvement is 6.1% and the coefficient is 0.061. These findings suggest that sustainable resource use and effective management are the main drivers of improving environmental quality. This suggests that the extractive sector's earnings are likely directed toward the growth of other economic sectors at the environmental cost initiatives. As a result, even though the G-20 economies may frequently overlook the potential harm this could do to the environment. Furthermore, substantial natural resource rents which are frequently associated with sectors like mining, oil, and gas extraction can be harmful to the quality of the environment. These rents have the potential to produce financial incentives that favor resource extraction over environmentally friendly methods, which could result in overuse and environmental damage. To increase money from resources, there may be deforestation, habitat loss, water pollution, and soil degradation, which would affect local communities, ecosystems, and biodiversity. Balsalobre-Lorente et al.'s (2023b) study corroborated our findings for OECD nations, whereas Wang et al.'s (2023) analysis documented the detrimental impact of resource rents on pollution for about 208 nations. In other places (Pata and Ertugrul, 2023) our findings conflicted with.

Contrary to expectations, all quantiles have negative coefficients for the environmental technology. There is a 5.8% decrease in LCF from current environmental technology, as indicated by the coefficient of −0.058 at the 50th quantile. The negative effect is much more noticeable at the 90th quantile, where the value is −0.077, indicating a 7.7% reduction. According to these findings, the initial expenses and inefficiencies of implementing environmental measures may exceed the benefits they provide in the short run.

The relationship between LCF and financial globalization is inverse. The coefficient, which is −0.021 at the 50th quantile, shows that financial globalization has reduced LCF by 2.1%. This negative influence is most noticeable in the 90th quantile, where the value is −0.039, indicating a 3.9% reduction. These results highlight the potential environmental dangers associated with further financial integration, including resource extraction and pollution-producing industrial operations funded by foreign investors. Similar findings have been reported for Nigeria by (Iorember et al., 2020), Malaysia

TABLE 6 MMQR results.

LCF	Coefficient	Std.	Prob-value
Location			
lGDP	−0.010***	0.000	0.002
lGDP2	0.383***	0.035	0.000
lREC	0.054***	0.003	0.000
lNRR	0.036***	0.005	0.000
lENP	−0.057***	0.009	0.000
lFG	−0.020***	0.004	0.000
lSG	0.012***	0.004	0.001
lPG	0.045***	0.005	0.000
lENE	0.057***	0.015	0.000
_cons	−7.293***	0.573	0.000
scale			
lGDP	−0.021	0.000	0.241
lGDP2	0.080***	0.020	0.000
lREC	0.004**	0.002	0.020
lNRR	0.015***	0.003	0.000
lENP	−0.013**	0.005	0.013
lFG	−0.012***	0.002	0.000
lSG	−0.004*	0.002	0.061
lPG	0.020***	0.003	0.000
lENE	−0.017**	0.009	0.053
_cons	−1.059**	0.325	0.001
qtile__25			
lGDP	−0.031**	0.000	0.014
lGDP2	0.302***	0.034	0.000
lREC	0.050***	0.003	0.000
lNRR	0.021***	0.004	0.000
lENP	−0.044***	0.009	0.000
lFG	−0.008**	0.004	0.036
lSG	0.016***	0.004	0.000
lPG	0.025***	0.005	0.000
lENE	0.074***	0.015	0.000
_cons	−6.219***	0.560	0.000
qtile__5			
lGDP	−0.035***	0.000	0.002
lGDP2	0.388***	0.036	0.000
lREC	0.055***	0.003	0.000
lNRR	0.037***	0.005	0.000
lENP	−0.058***	0.009	0.000
lFG	−0.021***	0.004	0.000
lSG	0.011***	0.004	0.002
lPG	0.046***	0.005	0.000
lENE	0.056***	0.016	0.000
_cons	−7.362***	0.586	0.000
qtile__75			
lGDP	−0.040***	0.000	0.004
lGDP2	0.461***	0.045	0.000
lREC	0.058***	0.004	0.000
lNRR	0.051***	0.006	0.000
lENP	−0.069***	0.011	0.000
lFG	−0.032***	0.005	0.000
lSG	0.008*	0.005	0.098
lPG	0.065***	0.007	0.000
lENE	0.040**	0.020	0.044
_cons	−8.327***	0.741	0.000
qtile__9			
lGDP	−0.042***	0.000	0.008
lGDP2	0.513***	0.054	0.000
lREC	0.061***	0.005	0.000
lNRR	0.061***	0.007	0.000
lENP	−0.077***	0.014	0.000
lFG	−0.039***	0.006	0.000
lSG	0.005	0.006	0.356
lPG	0.078***	0.008	0.000
lENE	0.029	0.024	0.226
_cons	−9.016***	0.891	0.000

(Continued in next column)

*, ** and *** show significance level at 10%, 5%, and 1% respectively.

by (Ye et al., 2021), the OECD countries by (Jianguo et al., 2022), and Saudi Arabia by Kahouli et al. (2021).

The coefficients for social globalization are positive. According to the coefficient, which is 0.011 at the 50th quantile, LCF is improved by 1.1% for every 1% increase in social globalization. With a coefficient of 0.005, the effect is still insignificant at the 90th quantile. This suggests that while social globalization promotes international norms and information exchange, which improves the quality of the environment, its benefits may decrease in more developed regions.

Social globalization facilitates the transfer of sustainable technology between industrialized and poor nations. According to the theory, underdeveloped nations ought to gain from the technological know-how of developed ones to enhance their environmental quality and halt environmental degradation (Zhang et al., 2023). Moreover, social globalization can support sustainable activities and raise environmental consciousness. Social media platforms are among the many communication methods that can raise people's awareness of environmental problems and inspire them to act for environmental preservation. As a result, the foundation for the growth of international environmental cooperation and agreements like the Paris Agreement has been social globalization. This result is consistent with earlier studies that found that rising social globalization led to an improvement in environmental quality, such those conducted in Ghana by Acheampong (2022), Malaysia by Suki et al. (2020), and the G20 countries by Awan and Azam (2022).

Political globalization consistently yields noteworthy benefits. At the 50th quantile, the coefficient is 0.046, indicating that a 1% increase in political globalization leads to a 4.6% increase in LCF. The positive impact is even more noticeable at the 90th quantile, where it rises by 7.8% with a coefficient of 0.078. These findings demonstrate how important international cooperation and common policies are to resolving the planet's environmental issues.

Energy efficiency has a positive coefficient. With a coefficient at the 50th quantile of 0.056, an increase in energy efficiency of 1% results in an improvement in LCF of 5.6%. However, the coefficient is not statistically significant at the 90th quantile (0.029), suggesting that the benefits of energy efficiency are diminishing in more developed nations, where additional advancements in energy efficiency have little impact on environmental quality. Energy efficiency is achieved through the utilization of natural gas and other non-renewable fuels, cleaner energy production, and other techniques that encourage energy conservation as production rises rather than falls. Due to the intense actions taken by the G-20 countries for financial development and the worldwide desire for economic expansion, secondary energy sources are being used by these nations (Raihan and Tuspekova, 2022; Shahzad et al., 2022). Graphical form of results are presented as follows in Figure 2.

Conclusion and policy suggestions

The Method of Moments Quantile Regression (MMQR) results show how targeted policies are required to reconcile economic growth and environmental sustainability. Initial economic growth has a negative effect on the load capacity factor (LCF), suggesting that industrialization and urbanization exacerbate environmental degradation. However, by increasing LCF, advanced economic growth validates the concept of the Load Capability Curve (LCC). Therefore, the G-20 countries should adopt a moderate approach and implement stringent environmental regulations immediately. To reduce industrial externalities, this involves actions including incorporating environmental costs into GDP estimates, enforcing environmental rules, and aligning national policies with the Sustainable Development Goals (SDGs). These actions ensure that the advancement of the economy does not come at the expense of environmental health.

The steady increase in LCF in all quantiles that results from using renewable energy shows how crucial it is to improving environmental quality. The G-20 countries need to take some proactive measures to promote the usage of renewable energy sources. Financial incentives, tax cuts, and subsidies can make renewable energy projects more appealing. Improving financing for research and development could increase the affordability and efficiency of renewable technologies. Infrastructure spending is also essential to promote the widespread usage of renewable energy. Energy storage systems and smart grids are two instances of these investments. These actions can significantly reduce energy use's negative environmental effects.

Efficient use of natural resources has a beneficial effect on LCF, suggesting that sustainable practices enhance environmental quality. The G-20 countries should enact legislation that controls the sustainable exploitation and usage of resources. Fair and sustainable resource management is ensured when local communities are involved. It is possible to prevent the ecosystem from degrading by mandating thorough environmental impact assessments for every resource extraction activity. Through the integration of environmental preservation and resource efficiency, these measures foster sustainability over the long haul. Efficient use of natural resources has a beneficial effect on LCF, suggesting that sustainable practices enhance environmental quality. The G-20 countries should enact legislation that controls the sustainable exploitation and usage of resources. Fair and sustainable resource management is ensured when local communities are involved. It is possible to prevent the ecosystem from degrading by mandating thorough environmental impact assessments for every resource extraction activity. Through the integration of environmental preservation and resource efficiency, these measures foster sustainability over the long haul.

Current environmental technology has a negative effect on LCF, most likely due to inefficiencies or expensive initial expenses. To solve this, the G-20 countries should place a high priority on enhancing the efficiency and application of environmental technologies. Innovation grants and subsidies can reduce costs while boosting effectiveness. Working together, the public and private sectors can accelerate the development and use of cutting-edge technologies. Promoting technology transfer from developed to poor countries among the G-20 ensures a greater adoption of effective environmental technologies. You can promote long-term environmental benefits and decrease short-term negative effects by adopting these steps.

Globalization on the social and political fronts often enhances LCF by highlighting the advantages of global norms and collaboration. The G-20 should make use of globalization to improve the state of the environment. It is imperative to fortify adherence to global environmental accords, like the Paris Agreement. Collective action can be sparked by supporting global governance systems that encourage environmental sustainability and make information sharing easier. Public awareness campaigns can encourage sustainable practices and increase knowledge of global environmental challenges. These actions encourage working together to solve environmental problems.

Finally, but just as importantly, improving energy efficiency raises LCF, particularly in lower and medium quantiles, indicating a significant potential for beneficial effects on the environment. The G-20 countries ought to prioritize energy efficiency and implement stringent policies for buildings, appliances, and vehicles. Offering incentives to households and businesses to adopt energy-efficient practices and technologies can result in significant increases. By developing broad national efforts aimed at enhancing energy efficiency in all industries, sustained development may be ensured. By focusing on energy efficiency, the G-20 countries may significantly reduce their energy use and the associated environmental implications. Finally, but just as importantly, improving energy efficiency raises LCF, particularly in lower and medium quantiles, indicating a significant potential for beneficial effects on the environment. The G-20 countries ought to prioritize energy efficiency and implement stringent policies for buildings, appliances, and vehicles. Offering incentives to households and businesses to adopt energy-efficient practices and technologies can result in significant increases. By developing broad national efforts aimed at enhancing energy efficiency in all industries, sustained development may be ensured. By focusing on energy efficiency, the G-20 countries may significantly reduce their energy use and the associated environmental implications.

Policy implications

To guarantee that economic growth does not negatively impact the environment, the G-20 nations should enact strict environmental rules, including environmental costs into GDP estimates, and align policies with the Sustainable Development Goals (SDGs). Renewable energy should be supported by tax breaks, subsidies, and financial incentives in addition to more money going toward infrastructure and research and development. Legislation involving local communities and requiring environmental impact assessments is necessary to promote sustainable resource management. It is essential to improve environmental technologies through technology transfer, public-private collaborations, and innovation awards. Environmental circumstances can be improved by taking advantage of globalization through public awareness campaigns, support for governance structures, and adherence to international environmental agreements. Energy consumption and its impact on the environment can be greatly decreased by placing a high priority on energy efficiency through strict regulations, incentives, and national programs.

Limitations and future directions

Even though the MMQR research provides useful information on the variables impacting LCF, there are several limitations in this study. The study's initial reliance on aggregate data may obscure regional or national disparities. Secondly, the study's exclusive focus on G-20 countries limits the generalizability of the results to other nations with different environmental and economic circumstances. Moreover, the negative consequences of current environmental technologies highlight the need for additional research to determine the underlying causes, which may include inefficiencies or exorbitant implementation costs. Future research should look at a larger range of countries, collect more comprehensive data, and explore the specific mechanisms via which financial globalization and environmental technology affect LCF to get over these limitations. Longitudinal studies may also provide a deeper understanding of the dynamic relationships that emerge between environmental sustainability, globalization, and economic growth over time. To help decision-makers find a balance between environmental conservation and economic development, it might also be helpful to look at the role of policy interventions and their effectiveness in different contexts.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://data.worldbank.org/country.

Author contributions

ZL: Conceptualization, Data curation, Funding acquisition, Methodology, Resources, Writing–original draft, Writing–review and editing. UM: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. AN: Conceptualization, Data curation, Investigation, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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