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Natural resources heterogeneity and environmental sustainability in G20 nations: post-COP28 analysis

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This study presents the maiden empirical evidence disintegrating the impacts of natural resources on environmental sustainability into production and consumption models. For easy trackability of the empirical evidence, environmental sustainability is captured by carbon emissions and ecological footprint in selected G20 economies with ta running from 1995 to 2019. To elaborate the study's contributions, green policies comprising green energy, green technology, and green finance together with environmental tax, financial development, economic growth, and population are considered as covariates in STIRPAT embedded theoretical framework. The empirical verification anchors on second-generation estimators entailing cross-sectional autoregressive distributed lag (CS-ARDL), common correlated effects mean group autoregressive mean group (AMG), and method of moment quantile regression The fallouts from the analyses reveal that the production and consumption of natural resources based on coal and oil hinder environmental sustainability, although the former has greater effects than the latter. Interestingly, natural gas provides diverging direct and indirect impacts on both pollutants. More so, green policies and environmental taxes support promoting environmental sustainability. Additionally, two channels of causalities, including unidirectional and bidirectional nexuses, are apparent from the estimated model. The study highlights the importance of eliminating fossil fuel subsidies and making substantial investments in green policies as key recommendations for policy action.

KEYWORDS

natural resources, green policies, environmental tax, financial development, environmental sustainability

1 Introduction

The fundamental roles of natural resources in humans' economic and non-economic activities can hardly be overemphasized. The pertinence of these resources raises significant concerns about the sustainability of the global economy within the context of continuous and inevitable reliance on them (Niu et al., 2023). Among many driving factors, the global population has doubled, and GDP which has experienced an all-time quadruple increase since the 1970s, heightens the pressures on natural resource depletion (United Nations Environment Programme, 2019). Besides, sustaining the expanding global economy, and

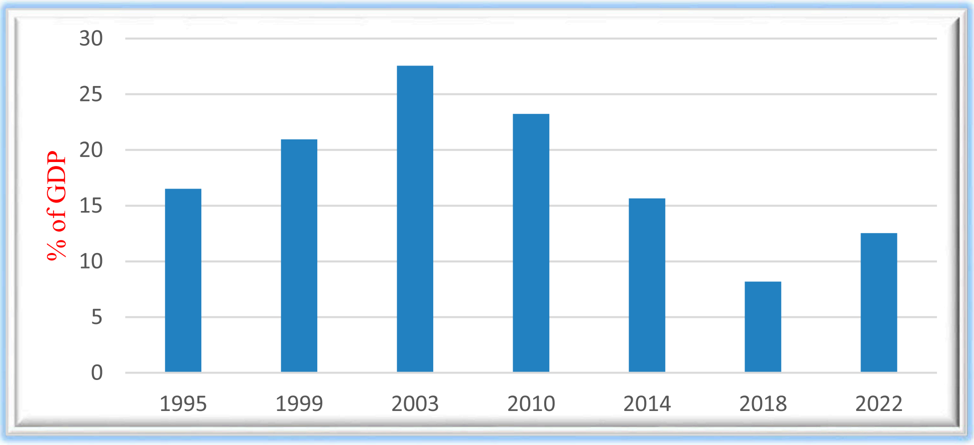

FIGURE 1
Trend in G20 natural resources rents.

ensuring continuity in human wellbeing, require extensive use of natural resources. However, the key issues of concern revolving around natural resources utilization center on their detrimental impacts on the environment, ultimately impacting individuals, their quality of life, and exacerbating inequality on both national and international levels. Empirical evidence has indicated how climate change endangers the global ecosystem and threatens the existence and stability of numerous species, expediting the decline of biodiversity by progressively modifying the ecological structure (Abbass et al., 2022; Amin et al., 2023). Consequently, protecting the environment has become a top priority for both individuals and corporations in today's modern society (Xie et al., 2024). To this end, ensuring sustainable production and consumption of natural resources has become a global responsibility for every region, nation, state, firm, and household to pursue. In specific terms, goal twelve of sustainable development goals (SDG-12) centers around responsible consumption and production with a specific focus on promoting responsible utilization of resources, enhancing sustainable infrastructure and energy efficiency, delivering indispensable services to everyone, establishing lucrative environmentally-friendly employment opportunities, and securing an elevated quality of life for all individuals (United Nations Environment Programme, 2021).

Based on the foregoing among other factors, natural resources have continued to attract the center of academic debates in the last few decades, particularly in an attempt by scholars to balance the tradeoff that exists between achieving economic growth and neutralizing the ensuing environmental complications emanating from natural resources depletion. Consequently, sustainable consumption and production become inevitable, particularly from four motivating arguments. First, the current era has seen the depletion of natural resources occurring simultaneously with the rapid growth of our population. Available evidence unveils that should the global population reach 9.8 billion by 2050, it would require nearly three Earths to sustain the natural resources necessary to maintain our current way of life (Martin, 2023). Second, throughout the previous century, the progress of economic and social development has been accompanied by the deterioration of the environment, posing a threat to the fundamental systems that sustain human life and further progress. To achieve a smooth transition, it is imperative to enhance resource efficiency through sustainable consumption and production. Third, it is crucial to note that, in the process of maintaining sustainable growth and development, natural resources must be consciously utilized while at the same time ensuring the minimization of waste and pollution throughout the production and consumption process. Available evidence has indicated the trend in natural resource depletion in the 20 economies. Based on Figure 1, it can be noted that the G20 countries experienced increasing levels of natural resources depletion from 1995 to 2003. A persistent decline is observable from 2006 down to 2018. The declining rate of natural resources in the G20 economies could be attributed to ensuing deteriorating impacts on the ecosystem. There was a slight rise from 2018 to 2022. The trend in ecological footprint in Figure 2 reveals a persistent increase from 1995 to 2006. A decline from 2006 to 2021 with a sudden rise in 2022. Consequently, it could be suggested that more conscious efforts need to be made to forestall further increases in the level of ecological footprint.

It is worth noting that achieving environmental sustainability through sustainable consumption and production of natural resources requires the interplay of certain macroeconomic variables of which green policies and environmental tax stands out. For instance, the role of green policy in maintaining carbon carbon-neutral environment has been empirically accentuated in recent times. Conceptually, green policy is perceived as any measure that supports the attainment of increased economic expansion and at the same time protects the ecosystem from deterioration (Niu et al., 2023; Wang A. et al., 2023). Basically, green policy seeks to proffer a lasting solution to resolving the dilemma created by the natural resources utilization tradeoff between increasing economic growth rate and demeaning ecological quality. Some of the key factors often identified within the framework of green policy include; green technology, green finance, and green energy which are perceived as viable in promoting economic growth at a decoupling CO_2 emission rate (Wang A. et al., 2023).

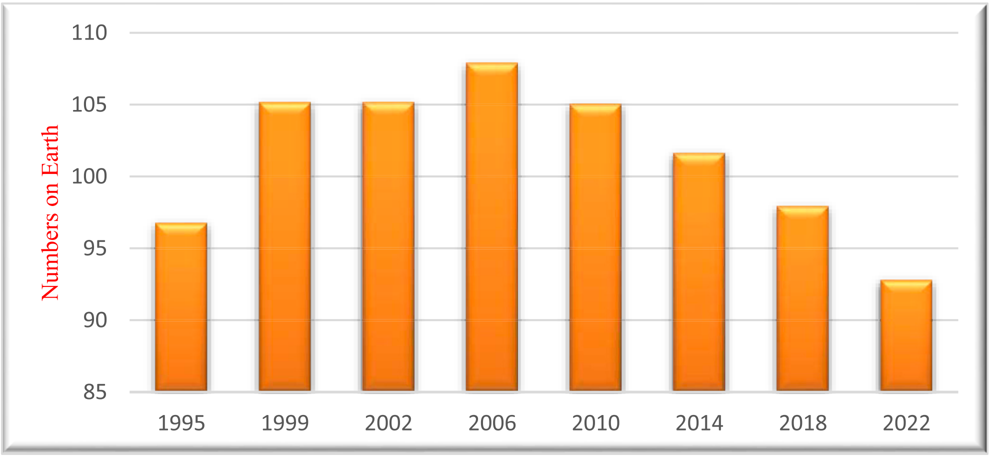

FIGURE 2
Trend in G20 ecological footprint.

Environmental tax is another factor that is germane in the process of achieving sustainable consumption and production of natural resources. Environmental also known as green taxes, or pollution taxes, are levies imposed by legislation on both businesses and individuals in order to restrict activities that cause harm to the environment (Brown, 2022). Environmental taxes come in various forms, with some targeting those who release hazardous chemicals into the environment, while others provide incentives for adopting eco-friendly practices. Environmental taxes offer numerous important advantages, including their effectiveness in protecting the environment, enhancing economic productivity, enabling the collection of state funds, and promoting transparency. By adhering to the fundamental principle of "polluters pay", these taxes play a crucial role in mitigating climate change. Moreover, environmental taxes have demonstrated their success in addressing various issues such as air quality, water pollution, and sewage treatment (Sarpong et al., 2023; Tanveer et al., 2024).

Given the exposited roles of green policies and environmental tax in the drive toward achieving environmental sustainability, it becomes empirically intuitional to assess how a combination of these indicators can be instrumental in offsetting the environmental complications arriving from natural resources depletion. Consequent to the foregoing, the current study seeks to examine the environmental effects of natural resources from the consumption and production angles in G20 nations. The empirical evidence considers the interplay of green policies (vectoring green technology, green finance, and green energy), environmental tax, and financial development. To buttress the theoretical relevance of the study, population, and economic growth are considered as a precondition for exploring the novel STIRPAT model. Specifically, the empirical analyses in this study will proffer practicable answers to the following research questions; (i) is there significant relationship between natural resources and ecological footprint in G20 economies? (ii) Are there significant differences between the consumption and production effects of natural resources on ecological footprint in G20 economies? (iii) to what extent do green policies mitigate ecological damages in the G20 economies? (iv) How effective are environmental tax and financial development in promoting ecological quality in the G20 economies?

The contributions of the current study to the extant studies can be summarized into four viewpoints. First, it is undeniable that empirical studies evaluating the effects of natural resources on the environment are quite enormous, however, the focus has often been directed toward the consumption angle of the nexus. Previous studies have been noted to provide policy implications that suggest how the adverse effects of natural resources consumption on the environment can mitigated. Others lay emphasis on the rents from natural resources. A survey of the current inquiries shows that little evidence has been found to explain how the production of natural resources affects the ecological system. Besides, to the best of our knowledge, no study has investigated how the dual of natural resources consumption and production affects environmental sustainability in G20 countries.

Second, green policies are a recent concept emerging in ecological debates with logical arguments as viable tools that can help achieve long-debated environmental sustainability. However, how these policies can be effective in achieving environmental sustainability in the presence of persistent reliance on natural resources remains a puzzle that is resolved in the literature. Moreover, environmental tax which is equally accorded credence in terms of effectiveness and efficacy of achieving carbon neutral environment is well incorporated in the current study's model. Hence, this study moves a step forward in its quest to extend the Frontier of knowledge in the literature by considering the nexuses of natural resources consumption and production, green policies, and environmental tax in the drive to sustain the G20 ecosystem. Third, the econometric model often requires a theoretical basis for justifying the proposed model to be specified and the hypotheses to be evaluated. As such, this study adapts the novel STIRPAT framework to the model explicating how the variables of interest emerge and interrelate in an environmental model specified for the G20 economies.

Fourth, to explore the best of the empirical model, the study chooses to evaluate the state hypotheses with advanced estimators that have been accorded significant levels of predictive validity and reliability in the literature. For instance, to measure the short-term and long-term effects of the independent variables, we rely on cross-sectional augmented distributed model and confirm its long-run reliability with the consideration of additional long-run estimators such as common correlated effects mean group and augmented mean group. It is pertinent to mention that the analyses in the current study undergo three phases of robustness checks comprising. One, the consideration of ecological footprint as a new dependent variable is motivated by the fact that ecological footprint is found effective and accurate in assessing the influence of both humans and human activities on the entire ecosystem. Considering ecological footprint is important due to the undeniable fact that our present consumer culture is depleting the world, its ecosystems, and its resources. This depletion is particularly evident among the "most privileged" individuals, who possess greater wealth and can afford to indulge in consumption without consistently demonstrating responsible behavior. Two, the evaluation of the impacts of the exogenous variables on environmental sustainability based on distributional and heterogenous effects following the novel quantile regression. The consideration of quantile regression is prominent due to its ability to decompose the impacts of independent variables into quantiles of six or nine components based on median values, unlike the other estimators that are based on mean values.

The empirical outcomes that emanate from the study unveil some interesting facts worthy of lauding. For instance, with the disintegration of the effects of natural resources on consumption and production, the study provides empirical evidence alluding that coal and oil deter the environment from both angles. It is however interesting to mention that natural gas provides some eye-catching facts elucidating that not all angles of natural gas are detrimental to the environment. Rather, while the production angle of natural gas pollutes the ecosystem, consumption proves supportive of achieving environmental sustainability. More so, the findings reveal the environmental relevance of green policies, environmental tax, and financial development in leading the way through decarbonization.

Examining the different ways that natural resources support or undermine environmental sustainability in the G20 countries is the main goal of this study. It is crucial to recognize some restrictions, though. For example, although the assessment took into account the effects of natural resources from the viewpoints of both production and consumption, it only paid attention to particular elements like coal, natural gas, and petroleum oil. In this approach, the cumulative effects of natural resources were not considered. Furthermore, important policy indicators such as institutional quality and other contaminants measured in the environment were not included in this analysis. Future research projects should take these restrictions into account. The roadmap to delivering the major objectives of the current study is drawn upon the following outline. Aside from the current section, section two reviews relevant studies selected in accordance with the research objectives. Section three focuses on methodology adopted in model the stated nexuses, hypotheses, and estimator techniques. Section four presents the empirical results while the conclusion, recommendations, and limitations are provided in section five.

2 Literature review

The empirical literature has experienced a significant increase in efforts aimed at investigating optimal practices for the depletion of natural resources that ensure ecological safety amid rising reliance on these resources. This study provides a review of relevant research conducted at the intersection of natural resources and environmental sustainability. Specifically, the review is divided into two subsections: (i) natural resources and environmental sustainability association, and (ii) green policy and environmental sustainability association.

2.1 Natural resources and environmental sustainability association

The significance of natural resources in the global movement towards environmental sustainability has been thoroughly examined, with many discussions highlighting their detrimental impacts on the ecosystem. Starting from the most recent order, (Khan and Hassan, 2024), evaluate the roles of natural resource rents in a sample of 11 emerging economies from 2000 to 2021. The study extends its empirical probe to the effects of high-tech exports, renewable energy, economic growth, and corruption. To ascertain the economic relevance of each exogenous variable, the study relies on Westerlund cointegration test in validating the long-term cointegration relationship between the variables under study whereas Moment of Moment Quantiles Regression (MMQREG), Augmented Mean group, Canonical Cointegration regression, Fully Modified OLS, and Dynamic OLS are employed to assess the stated hypotheses. Findings indicate natural resources rent rive significant surge in CO2 emissions thereby hindering the attainment of environmental sustainability. Besides, high-tech exports and economic growth escalate the emissions surge. Conversely, corruption and renewable energy appear to be negative predictors of CO2 emissions surge implying they both support the drive toward environmental sustainability. (Wang et al., 2024) explore how the nexuses of natural resources consumption, globalization, globalization, renewable energy use, and agricultural practices impact the ecology in China from 1990 to 2020. The study uncovered that natural resources can decrease CO_2 emissions in certain economies. Conversely, globalization and agriculture have been found to simultaneously increase CO_2 emissions. Fortunately, the utilization of renewable energy sources has proven to be a positive factor in reducing CO_2 emissions.

Furthermore, (Sadiq et al., 2024), investigate how natural resources and green finance moderate the impact of fintech on environmental sustainability in China between 2013 and 2022. The study enhances the existing model and examines the practicality of environmental regulations and government measures. Several regression-based models indicate that China's fintech development contributes to climate quality by facilitating the reduction of CO_2 emissions. However, the volatility of natural resources weakens climate sustainability, while green finance plays a positive role in mitigating this effect. Additionally, environmental laws and business structures have a negative impact on environmental quality. The improvement of climate quality largely depends on government actions. Moreover, the carbon intensity related to fintech is found to vary across different quartiles. Lastly, the impact of fintech on carbon emissions differs among various subsamples based on the COVID-19 pandemic. (Han et al., 2024). the extent to which natural resources drive zero-emissions amidst the interplay of government debt and political stability in a panel study comprising China, India, Pakistan, and Kazakhstan, utilizing cross-country data from 2001 to 2021. The study conducts longrun test by relying on Westerlund panel cointegration test which affirms the existence of a long-term equilibrium relationship between the variables. Besides, the main analyses reveal the existence of a statistically insignificant yet favorable correlation between economic growth and the transition to zero emissions. Furthermore, it was evident from the analyses that a significant and negative correlation between CO_2 emissions and political stability. The relationship between GDP and CO_2 emissions exhibits a non-linear pattern, with emissions increasing up to a certain threshold as GDP grows. More apparently, natural resources use negatively impacts the transition to zero emissions, as there exists a direct connection between natural resources and CO_2 emissions. The robustness of the empirical outcomes was confirmed through Iterated Generalized Least Squares (IGLS) analysis.

In a piece of separate evidence, Ashraf et al. (2024) investigate the correlation between natural resources and CO_2 emissions in the top ten producing countries from 2001 to 2021. The additional impacts of digital commerce, renewable energy consumption, environmental technology, and economic development are evaluated. The empirical results indicate that economic development and environmental technology have a significant impact on increasing the ecological footprint. Conversely, the utilization of renewable energy sources, digital commerce, and the availability of natural resources contribute to a reduction in the ecological footprint over time (Fan and Wang, 2024). probe the correlation between resource efficiency and green economic growth in the BRICS countries from 1990 to 2021. The results clearly demonstrate that adopting sustainable consumption and production methods encourages the formation of multi-stakeholder partnerships that promote a green economy. Furthermore, greenfield exhibits different risk and return profiles compared to traditional industries within the current private financial systems.

The assessment of the interplay of natural resources and government regulation in CO_2 emission mitigation constitutes the center of research interest for (Li et al., 2023) in China from 2008 to 2018. The key findings uncover that sturdy environmental regulation can diminish the reliance on natural resources and increase its contribution to CO_2 emissions. In addition, it is noted that in numerous regions, there exists a positive correlation between natural resources dependency and CO_2 emissions, while regions with high reliance on natural resources exhibit a negative correlation between environmental legislation and carbon dioxide emissions. Lastly, natural resources dependency may expedite certain factors. (Wang K. et al., 2023). utilizes advanced econometric statistical models to analyze the connections between natural resources, sustainable energy, human capital, and CBCE in the G7 economies from 1976 to 2020. TCSARDL estimator, the study finds that imports have a positive relationship with CBCE, while exports have a negative relationship in developed countries. To ensure the reliability of the findings, the results are further validated using the AMG and CCEMG methods (Zhou et al., 2023). analyze the impact of economic globalization, natural resources, economic growth, and distributed energy sources on CO_2 emissions in RCEP countries from 1990 to 2020 based on advanced estimators comprising Granger panel causality tests, quantile regression, and cointegration analysis. The empirical evidence demonstrates that the abundance of natural resources, economic growth, and the use of non-renewable energy sources contribute to increased CO_2 emissions, leading to environmental degradation in RCEP countries. However, these countries can mitigate their CO_2 emissions by adopting renewable energy sources and embracing economic globalization. The empirical findings from the study conducted by (Tanveer et al., 2024) reveal the deteriorating effects of fossil fuels on environmental sustainability in Pakistan.

2.2 Green policy and environmental sustainability nexus

The role of key variables such as renewable energy in the group of green energies has been empirically established in the literature. For instance, (Qamruzzaman and Karim, 2024) investigate the essential function of green policies in achieving carbon neutrality by analyzing the synergistic effects of green finance, green technology innovation, and the adoption of green energy. The emanating findings underscore the importance of green finance mechanisms in mobilizing resources for sustainable initiatives, such as energy-efficient technologies and renewable energy projects. Furthermore, the study reechoes the criticality of green technology innovation in expediting technological advancement, reducing emissions, and fostering economic growth (Qing et al., 2024). estimate the extent to which financing green initiatives and renewable energy sources promote the drive toward carbon neutrality goals and ensure sustainable economic growth in 12 provinces in China from 2000 to 2019. The study employs dynamic and fully modified ordinary least squares methodologies for analysis. Results indicate that green financing and renewable energy play significant roles in addressing challenges such as climate change and environmental degradation, thereby establishing a foundation for economic sustainability (Yang et al., 2024). examine the ecological energy transition (fossil fuels, nuclear, and renewable energy) amidst the intervening roles of urbanization, structural change, and environmental technology within the BRICS nations from 1996 to 2019. The primary findings indicate that urbanization and reliance on fossil fuels impede the BRICS' initiatives toward achieving a environmental sustainability by exacerbating carbon emissions. Conversely, nuclear energy, renewable energy, environmental technology, and structural changes contribute significantly to enhancing environmental sustainability by facilitating reductions in CO_2 emissions.

Furthermore (Han et al., 2024), employ the advanced STIRPAT model to examine the symmetrical effects of eco-digitalization, green technology, green finance, and renewable energy on environmental sustainability in China. Utilizing quarterly data spanning from the first quarter of 1995 to the fourth quarter of 2019, the research applies the ARDL model to evaluate the proposed hypotheses. The findings indicate that eco-digitalization, green technology, green finance, and renewable energy contribute to environmental sustainability in China by mitigating CO_2 emissions and reducing the ecological footprint. Conversely, the factors of wealth and urbanization are associated with an increase in pollutant levels (Wang et al., 2023a). evaluate the impact of green policies vectoring green energy, green finance, and green innovation on environmental sustainability, specifically as it relates to CO_2 emissions, ecological footprint, and PM2.5 air pollutants within the BRICS nations from 1995 to 2019, in the context of eco-digitalization and urbanization. The empirical evidence relies on second-generation estimators alongside the STIRPAT framework. The study finds that green energy, green finance, green innovation, and eco-digitalization contribute positively to environmental sustainability Conversely, urbanization and increased wealth are detrimental to environmental sustainability, as they exacerbate the identified pollutants (Abdul et al., 2022). examine how China's carbon intensity is affected by renewable energy, foreign remittances, globalization, financial development, and economic growth. The study used multiple diagnostic tests and the linear Autoregressive Distributed Lag (ARDL) approach on data spanning from 1990 to 2020. The linear ARDL methodology's results show that renewable energy contributes to lessening environmental damage. On the other hand, the decline in China's environmental conditions is a result of globalization, financial development, economic expansion, and foreign remittances. Furthermore, the results imply that renewable energy has a detrimental short- and long-term impact on environmental deterioration.

2.3 Research gaps

The appraisal of the existing body of studies reveals some lacunas that remain unfilled and perhaps could be held responsible for the apparent inconclusiveness in the literature. For instance, despite the overwhelming interest in the study of the nexus between natural resources and environmental sustainability, the consideration of the consumption and production arguments remains largely neglected. Besides, the consideration of the roles of green policies together with environmental tax and financial development is a novel idea that is scarce in the extant literature. These among others are eminent gaps that the current study fills.

3 Methodology

3.1 Scope, data, and source

The analysis of this study focuses on production and consumption effects of natural resources including coal, gas, and oil on environmental sustainability in G20 economies. The empirical evidence, based on panel data from 1995 to 2019, extrapolates to the role of green policies comprising (green energy, green technology, and green finance), environmental tax, population, and economic growth. The endogenous variable which is environmental sustainability is measured by two indicators such as CO_2 emissions and ecological footprint. The scope of the analysis from 1995 to 2019 is based on three criteria. First, the year 1995 was chosen because several important variables such as green technology, green finance, and environmental tax were not observed in the previous year. Second, 2019 is strongly selected because most explanatory variables are not available beyond 2020. Third, the estimates used in this study require the panel data to be highly balanced, which seems reasonable for the period 1995–2019. The study focuses on the G20 due to their considerable impact on three critical environmental challenges: increasing pollution and waste, the deterioration of nature and biodiversity, and the intensifying effects of climate change. These issues arise from the unsustainable production and consumption practices of G20 nations, which pose significant threats to global economies (Andersen, 2023). Besides, in 2021, global carbon dioxide emissions reached 38.0 billion tons, with around 81% originating from G20 nations. Among these, China, the United States, and the European Union were the leading contributors to CO_2 emissions (United Nations Environment Programme, 2021). Furthermore, the G20 countries have acknowledged the critical need to enhance productivity growth and improve the efficiency of natural resources utilization, particularly in response to the accelerating depletion of these resources worldwide. In this context, they have undertaken several important initiatives. A primary focus for G20 economies has been the adoption of advanced technologies and methodologies aimed at optimizing the extraction, processing, and consumption of resources (Shah et al., 2024). Considering the high level of economic development occasioned by advancement in technological innovation and advocacy for the transition to 100% renewable energy (Ibrahim, 2022), the roles of G20 in the drive for green policy initiatives cannot be overemphasized. Table 1 provides detailed information about the dataset, including variable names, units of measurement, and data sources.

3.2 Theoretical framework and strategic modeling

The present study examines the impact of natural resources on the environment of G20 economies, drawing upon the theoretical framework of Dietz and Rosa's (1997) STIRPAT model. This model takes into account the influence of multiple environmental factors, allowing for non-monotonic or uncorrelated outcomes (Qi et al., 2023). The basic model of this framework is commonly employed to analyze various aspects of environmental quality as thus:

$$I = \beta P_i^{\vartheta 1} \times A_i^{\vartheta 2} \times T_i^{\vartheta 3} \times \pi_i \quad (1)$$

In accordance with Equation 1, the variable I denotes the aggregate carbon dioxide emission and remains constant, while the index coefficients P, A, and T are expressed as follows $\sigma_1, \sigma_2, \sigma_3$. The error is denoted as π. A linear representation of this model can be expressed in Equation 2.

$$\ln I_{it} = \beta_0 + \sigma_1 (\ln P_{it}) + \sigma_2 (\ln A_{it}) + \sigma_2 (\ln T_{it}) + \pi_i \quad (2)$$

In accordance with the objectives of the present study, we adhere to the works of (Wang A., et al., 2023; Xing et al., 2023; Zhu et al., 2022) to explicate the STIRPAT model. The fundamental model posits:

TABLE 1 Details of empirical data.

Variables	Description	Sources
	Outcome Variables	
CO_2	CO_2 emissions (metric tons *per capita*)	World Development Indicators
ECF	Ecological footprint	Global Footprint Network
	Principal Explanatory Variables (Production)	
COALPR	Coal (quad Btu)	International Energy Administration
GASPR	Natural gas (quad Btu)	International Energy Administration
OILPR	Petroleum and other liquids (quad Btu)	International Energy Administration
	Principal Explanatory Variables (Consumption)	
COALCO	Coal (quad Btu)	IEA
GASCO	Natural gas (quad Btu)	IEA
OILCO	Petroleum and other liquids (quad Btu)	IEA
	Control Variables	
GTECH	Green Technology: Environment-related technologies (Number of patents)	OECD
GFINANCE	Green Finance: Climate change mitigation (Number of patents)	OECD
GENERGY	Green Energy: Solar photovoltaic (PV) energy (Number of patents)	OECD
ENVTAX	Environmental tax: Environmentally related tax revenue (% of GDP)	OECD
FDV	Financial Development: Domestic credit to private sector (% of GDP)	WDI
POP	Population (total)	WDI
GDPPC	Economic growth: GDP *per capita* (constant 2015 US$)	WDI

WDI denotes World Development Indicators, IEA represents International Energy Administration, and OECD signifies Organization For Economic Cooperation And Development.

$$SUSENV_{it} = \sigma_0 + \sigma_1 Natres_{it} + \sigma_2 Grepol_{it} + \sigma_3 Afflue_{it} + \sigma_4 Pop_{it} + \alpha_{it} \tag{3}$$

Based on Equation 3, *SUSENV* denotes CO_2 emissions, Natres stands for natural resources encompassing two variations such production and consumption. *Grepol* denotes green policies vectoring green technology (GTECH), green finance (GFINANCE), and green energy (GENERGY). Afflue denotes affluence and Pop represents population.

Equation 4 can be expanded to incorporate the full set of the indicators including other covariates such as environmental tax (EnvTax), and financial development (FDV) as thus:

$$SUSENV_{it} = \sigma_0 + \sigma_1 coalpr_{it} + \sigma_2 gaspr_{it} + \sigma_3 oilpr_{it} + \sigma_4 gtech_{it} + \sigma_5 gfinance_{it} + \sigma_6 genegy_{it} + \sigma_3 GDPPC_{it} + \sigma_4 Pop_{it} + \sigma_5 EnvTax_{it} + \sigma_6 FDV_{it} + \alpha_{it} \tag{4}$$

Equation 5 depicts the production channel model. To estimate the consumption channel effects of natural resources, we restate the model for the consumption indicators as thus:

$$SUSENV_{it} = \sigma_0 + \sigma_1 coalco_{it} + \sigma_2 gasco_{it} + \sigma_3 oilco_{it} + \sigma_4 gtech_{it} + \sigma_5 gfinance_{it} + \sigma_6 genegy_{it} + \sigma_3 GDPPC_{it} + \sigma_4 Pop_{it} + \sigma_5 EnvTax_{it} + \sigma_6 FDV_{it} + \alpha_{it} \tag{5}$$

Both *pr* and *co* are suffixes denoting production and consumption channels respectively.

3.3 A priori expectations

In the context of a specific model that encompasses a particular relationship; economic intuition typically offers a crucial elucidation of the feedback mechanism between exogenous and endogenous variables. In order to comprehend this relationship within the realm of environmental sustainability in G20 economies, it becomes imperative to grasp the reasons and mechanisms through which natural resources instigate variations in CO_2 emissions and ecological footprint. To achieve this objective, we draw upon insights derived from prior empirical studies. Beginning with natural resources, it is imperative to clarify that the depletion of available resources provides negative externalities to the environment in the form of pollution that degrades the quality of the ecosystem (Xu and Hu, 2024). For instance, the processes involved in the production of coal, oil, and natural gas emit substantial quantities of CO_2 emissions all of which do not exit the atmospheric system. This is especially true considering the fact that these economies are fossil fuel dependent (Balsalobre-Lorente et al., 2023; Ibrahim and Ajide, 2021a). The resultant effects of these emissions hinder the ecological system. Notable strands of empirical studies allude to the deteriorating effects of natural resources on the ecosystem (Akram et al., 2023; Saud et al., 2023; Xiaoman et al., 2021). Consequently, a direct nexus is anticipated thus $\frac{\delta CO_2}{\delta NATRES} < 0$.

The quantity of research substantiating the significance of environmentally friendly policies for the preservation of the environment has witnessed a substantial surge in the past few decades. The majority of these studies center their attention on the potential of green policy indicators, such as green technology, green finance, and green energy, to foster economic expansion. This correlation signifies progress in mitigating environmental issues stemming from economic activities. It has been demonstrated that the adoption of green policies effectively curtails CO_2 emissions and other associated pollutants (Nassani et al., 2021; Niu et al., 2023; Wang A., et al., 2023). Consequently, the aforementioned relationship presents the prospect of a connection between CO_2 emissions and the implementation of green initiatives $\frac{\delta CO_2}{\delta GREPOL} < 0$.

Population growth is an inherent occurrence that poses a significant obstacle to sustainable development due to the increasing demands of the population for finite resources. Furthermore, population pressure is deemed particularly detrimental to the environment as it perpetuates the ongoing depletion of existing natural resources, consequently impacting the emission of greenhouse gases in an adverse manner. Consequently, population has been empirically acknowledged as the catalyst for CO_2 emissions (Alnour et al., 2022; Chen et al., 2022; Zhang et al., 2021). Consequently, a direct relationship is expected with CO_2 emissions as thus $\frac{\delta CO_2}{\delta POP} > 0$.

The environmental effects of tax revenues have been noted to be effective in moderating the surge in ecological pollutants. Precisely, the societal expenses associated with coal are manifested in the form of environmental taxes, which are regarded as the primary policy instrument for regulating carbon emissions. The escalation in prices of carbon-emitting commodities leads to a reduction in their demand. Notable strands of empirical studies affirm the carbon-mitigating impacts of environmental tax revenue (Bigerna et al., 2023; Safi et al., 2021; Wolde-Rufael and Mulat-Weldemeskel, 2022). Consequently, we anticipate a negative association between carbon emissions and environmental tax revenue as follow $\frac{\delta CO_2}{\delta EnvTax} < 0$ s. The impact of affluence through economic growth on the environment has garnered the interest of scholars in the field of environmental studies. Notably, studies have indicated that economic growth can effectively escalate the rise in CO_2 emissions (Ahmed et al., 2022; Qi et al., 2023; Xing et al., 2023). This association is articulated as follows $\frac{\delta CO_2}{\delta GDPPC} < 0$.

The correlation between financial development and CO_2 emissions has been extensively examined, with two notable findings. The first empirical observation posits that financial development fosters higher carbon emissions by providing financial resources to organizations and government agencies, thereby stimulating increased economic activity. This heightened economic activity results in greater energy resource consumption, predominantly derived from fossil fuels, consequently exacerbating CO_2 emissions growth. Hence, a direct relationship is inferred. Conversely, financial development may enhance the accessibility of financial services for individual households to acquire energy-efficient appliances, while also motivating companies to modify their business practices. On the basis of the two arguments, two directions of effects are anticipated comprising direct and indirect as thus $\frac{\delta CO_2}{\delta FDV} < 0$ and $\frac{\delta CO_2}{\delta FDV} > 0$.

3.4 Estimation strategies

Conventional evaluation methods are employed to assess the extent to which natural resources, green policies, environmental tax, and other covariates contribute to environmental sustainability, particularly in G20 countries, with the aim of deriving the most pertinent and precise empirical findings. This examination encompasses various aspects, including the level of consistency in the slope coefficient, the presence or absence of cross-sectional dependence in the slope coefficients, the stationarity and long-term behavior of the series, the assessment of the long-term impact of external indicators on the resultant variable, and the causality of the estimated model. Recent empirical studies, such as those conducted by Akram et al. (2023), Lanre Ibrahim et al. (2022), and Shen et al. (2023), are carefully scrutinized to uncover these aspects. Figure 3 provides a visual representation of the aforementioned steps.

The criteria for selecting each method are methodical and adhere to established guidelines found in the literature. For example, assessing the nature of dependency and heterogeneity within the model via cross-sectional dependence (CSD) and slope heterogeneity tests (SHT) is essential for determining whether to employ first-generation or second-generation techniques. When both CSD and SHT are identified in the model, second-generation methods are considered the most suitable. Conversely, if these conditions are not met, first-generation techniques are regarded as appropriate. The appropriateness of second-generation methods for instance, will lead to the choice of Westerlund cointegration technique due to its robustness to handle the potential disruption that could arise from CSD and SHT. The assessment of long-term impacts is affected by prior conditions, with the cross-sectional autoregressive distributed lag (CS-ARDL), common correlated effects mean group (CCEMG), and augmented mean group (AMG) identified as the most suitable approaches. The selection methods for additional robustness analyses are similarly influenced.

When determining the suitability of data sets and estimates for regression analysis, the empirical process depicted in Figure 3 recommends the consideration of two factors. Specifically, it is advisable to conduct cross-sectional dependence tests and homogenous slope tests to ascertain whether the data is influenced by an unknown common component. The presence of the two tests necessitates the use of the second-generation estimator, which is more effective in identifying spurious series through unit root tests such as cross-sectionally augmented ADF (CADF) and cross-sectionally augmented IPS (CIPS) unit root tests. In the absence of either test, first-generation estimators such as the standard ADF and IPS unit root tests may be deemed acceptable for unit root analysis. The choice of approach (first or second order) determines the estimator to be employed in subsequent analyses. On the other hand, the existence of cross-sectional dependence and slope heterogeneity leads to the adoption of second-generation methods. In such a situation, cross-sectional autoregressive distributed lag (CSARDL) is adopted to estimate the short and long-run estimates. Among many other reasons, CSARDL estimator

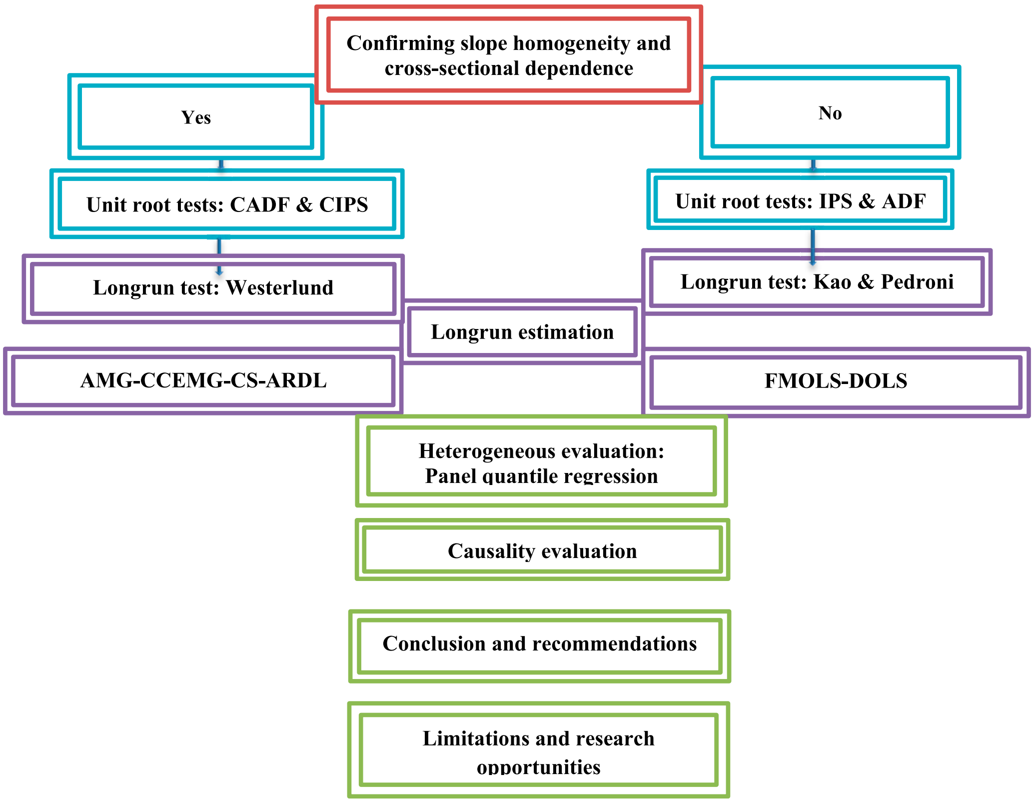

FIGURE 3
Steps involved in the empirical verification.

is capable of controlling for the econometric issues arising from cross-sectional dependence and slope heterogeneity. The ability of the estimator to simultaneously estimate the short-run and longrun estimates without losing track of the efficiency further accentuates the reason for adopting it. Furthermore, common correlated effects mean group (CCEMG), augmented mean group (AMG), and method of moment quantile regression (MMQR) are employed as robustness checks for the main estimator. These estimators efficiently subdue the inconsistency in the estimated results that could be attributed to cross-section dependence and slope heterogeneity.

3.5 Descriptive analysis

This study investigates three channels that delineate the types and features of data employed to empirically assess established objectives. Initially, the summary statistics depict the mean values of each indicator during the study period. Furthermore, normality tests are furnished to indicate whether the variables' distribution is normal or non-normal. To gain a comprehensive comprehension of the numerous environmental indicators chosen in GG20, we commence with their preliminary analyses in Table 2. The descriptive analysis reveals the mean value of 10.08 for carbon emissions in G20 economies. Regarding the indicators of natural resources, it is evident that consumption pattern in oil resources averaging 9.69 is the highest among the classes of natural resources followed by natural gas and coal with mean values of 6.15 and 4.38 respectively. The mean values in production pattern of natural resources reveal that oil with the highest value 5.07 followed by natural gas production averaging 4.65 and oil production with a mean value of 3.64. The mean values of the conduction and production patterns suggest that the G20 economies are more reliant on nonrenewable sources of energy than renewable resources. Evidence abounds justifying the fossil-dependent nature of the G20 on fossil fuels energy resources for production and other economic (Balsalobre-Lorente et al., 2023). The mean values of green policies vectoring green energy, green finance, and green technology are provided thus 166.20, 2,149.9, and 2,735 respectively with the general depiction of thriving moments of these macroeconomic indicators in G20 economies. Environmental tax averaging 1.97 suggests an evolving policy era of the environment indicators. Population, economic growth, and financial development average 1,010, 38,722, and 123 respectively. The dataset is observed to be abnormally distributed considering the values of the skewness, kurtosis, and Jarque-Bera in Table 2.

4 Presentation of findings

4.1 Preliminary findings on data interdependence, correlation, and homogenous slope coefficients

Table 3 presents the outcomes of the preliminary tests conducted with a specific focus on the dependency of the series based on Pesaran

TABLE 2 Description of empirical dataset.

	Mean	Median	Maximum	Minimum	Std. Dev	Skewness	Kurtosis	Jarque-bera	Probability
CO_2	10.08	8.54	20.47	4.46	4.70	0.83	2.26	24.10	0.00
COALCO	4.38	1.53	22.80	0.22	6.50	1.99	5.46	159.22	0.00
COALPR	3.64	0.47	24.05	0.00	7.30	2.08	5.54	173.31	0.00
GASCO	6.15	3.18	32.26	1.27	7.81	2.08	5.60	175.70	0.00
GASPR	4.65	0.67	35.19	0.00	7.84	1.99	5.91	177.83	0.00
OILCO	9.69	4.71	40.57	2.54	11.59	1.92	4.91	133.84	0.00
OILPR	5.07	0.22	31.96	0.02	6.39	1.93	6.55	200.68	0.00
GENERGY	166.20	52.17	1,443.65	1.00	263.76	2.58	10.20	572.51	0.00
GFINANCE	2,149.93	931.83	9,228.21	112.25	2,499.93	1.40	3.76	61.37	0.00
GTECH	2,735.82	1,212.48	10,555.70	173.75	2,975.87	1.23	3.28	44.88	0.00
ENVTAX	1.97	2.17	3.60	0.69	0.76	0.10	2.16	5.42	0.07
POP	1,010.00	6,100.00	3,300.00	2,900.00	8,654.00	1.69	4.39	97.66	0.00
GDPPC	38,722.7	36,378.62	60,698.01	29,265.09	7,200.265	1.015738	3.412,169	31.33069	0
FDV	123.0116	114.67	217.761	60.3499	42.13172	0.389,211	1.947,886	12.48979	0.00194

Note: CO_2, carbon emissions; COALCO, coal consumption; COALPR, coal production; GASCO, gas consumption; GASPR, gas production; OILCO, oil consumption; OILPR, oil production; GENERGY, green energy; GFINANCE, green finance; GTECH, green technology; ENVTAX, environmental tax; OPO, population; GDPPC, economic growth.

TABLE 3 Interdependence, homogeneity, and correlation analyses.

Variables	Pesaran (2004)	Pesaran (2015)	Correlation
CO_2	15.800***	15.796***	0.875
COALCO	9.130***	9.127***	0.672
COALPR	16.820***	16.823***	0.934
GASCO	6.420***	6.421***	0.715
GASPR	9.345***	9.335***	0.765
OILCO	6.840***	6.844	0.677
OILPR	5.443***	5.425***	0.687
GTECH	22.390***	22.392***	0.977
GFINANCE	22.440***	22.444***	0.980
GENERGY	21.370***	21.373***	0.933
ENVTAX	8.770***	8.766***	0.687
POP	15.639***	15.646***	0.852
GDPPC	17.270***	17.269***	0.754
FDV	9.115***	9.225***	0.603
Slope Heterogeneity	**t-statistic**	**P-values**	
Delta	9.042	0.000	
Adjusted Delta	10.965	0.000	

The estimated significance levels denoted by *, **, and *** correspond to values of 10%, 5%, and 1% respectively.

(2015) and Pesaran (2004). Based on these results, it can be inferred that the probability values are statistically significant, indicating a strong interdependence among the cross sections. The conformity of the findings to rule of thumb is further reinforced by the 1% level of significance, and this conclusion is supported by correlation coefficients ranging from 67% to 98%. This suggests that macroeconomic shocks in one of the G20 economies can have both positive and negative impacts on others. The active engagement of the G20 countries in regional and global intergovernmental organizations adds credibility to these findings. Moreover, these countries engage in trade with each other and collaborate to adopt a unified stance on certain economic matters. Interactions between countries can lead to either positive or negative effects when one country experiences macroeconomic shocks. By analyzing the delta significance and corrected delta-tilde statistics, it is evident that the result of slope homogeneity contradicts the null hypothesis of a unity slope. The fact that the political systems and ethnic composition of the G20 countries are highly diverse supports the conclusion. It is worth noting that the heterogeneity of the slope and cross-sectional CSD demonstrates that the first-generation unit root test is not appropriate for estimating the unit-roots of a series. On the other hand, empirical evidence has indicated that second-generation unit root testing is sufficient and dependable.

4.2 Stationarity test results

This work employs second-generation approaches to ascertain the stable state of the series, taking into account the dependence of the cross-section and the variability of the slope. The obtained results,

TABLE 4 Feedback of panel unit root analyses.

Variables	Cross-sectional IPS (CIPS)		Cross-sectional ADF (CADF)	
	Level	First difference	Level	First difference
CO_2	−2.759	−4.700***	−2.683	−3.940***
COALCO	−2.400	−4.261***	−2.415	−4.051***
COALPR	−1.848	−4.056***	−2.431	−3.461***
GASCO	−2.149	−5.168***	−1.459	−3.717***
GASPR	−0.901	−2.789*	−0.551	−2.855*
OILCO	−2.253	−4.732***	−2.138	−3.726***
OILPR	−0.654	−3.601***	−0.911	−2.799*
GTECH	−2.101	−4.363***	−2.074	−3.189***
GFINANCE	−1.935	−4.368***	−1.871	−3.219***
GENERGY	−1.974	−4.994***	−1.818	−3.522***
ENVTAX	−2.310	−4.425***	−1.710	−2.992**
POP	−2.454	−4.619***	−1.073	−4.278***
GDPPC	−2.192	−3.013**	−2.592	−3.090***
FDV	−2.730	−2.903**	−2.090	−3.965***

The estimated significance levels denoted by *, **, and *** correspond to values of 10%, 5%, and 1% respectively.

TABLE 5 Cointegration results.

Statistic	Values	Z-values	P-values
Gt	−3.455***	−5.164	0.000
Ga	−21.331***	−17.044	0.000
Pt	−15.154***	−6.661	0.000
Pa	−13.526***	−6.055	0.000

presented in Table 4, utilize the cross-sectionally augmented IPS (CIPS) and cross-sectionally augmented ADF (CADF) tests. Upon applying the first difference, the data reveals that all variables exhibit stationarity, indicating an I (1) order of integration. To address the two econometric inquiries raised earlier, this study conducts a panel cointegration test based on cross-sectional dependence and feedback of the slope heterogeneity test (Westerlund, 2007), offering a resolution. The group (Ga) and panel (Pa) statistics are employed to assess the likelihood of a lasting association under the assumption that no long-term relationship exists. The outcomes from Table 5 demonstrate that despite the alternative hypothesis proposing the presence of a long-term relationship, the null hypothesis is refuted. This discovery implies that a long-term relationship does indeed exist among natural resources, green policies, environmental tax, economic growth, and population in G20 economies.

4.3 Main empirical outcomes

Examining the impact of regressors on outcome variables in long-term relationships is more advantageous due to the existence of long-term relationships among the measures. This research employs a cross-sectional dependent technique (CS-ARDL) to assess both short-term and long-term associations among the dependent and independent indicators. Additionally, two supplementary estimators, CCEMG and AMG, are employed to provide further evidence for the long-term effects of CS-ARDL. As evident from the empirical outcomes provided in Table 6. It is pertinent to mention that our analysis focuses on two angles through which natural resources impact the environment which are the consumption and production angles.

Based on the outcomes presented in Table 6, it is apparent that two of the three measures of natural resources consisting of coal and oil have both short-term and long-term positive effects on CO_2 emissions. The reported carbon-inducing effects are apparent from the consumption and production channels. The AMG and CCEMG estimators provide complementing outcomes fortifying the CS-ARDL feedback. Consequently, it can be inferred that the continued growth in both coal and oil in the G20 economies will further endanger the sustainability of the environment for the present and future generations. A result of this nature indicates that a continuous dependence on oil poses substantial threats to the Group's commitment to achieving net zero emissions by 2050. Furthermore, it is quite interesting to mention that the impacts of gas on carbon emissions from both consumption and production display some significant level divergences in terms of facilitating and hindering environmental sustainability in the G20 economies. For instance, the production channel advances positive effects on CO_2 emissions implying that a rise in natural gas production leads to a corresponding increase in CO_2 emissions. Conversely, the consumption channel provides substantial support for environmental sustainability as apparent from the significantly negative coefficient of natural gas on CO_2 emissions.

TABLE 6 Feedback from Short-run and Longrun analyses based on carbon emissions model.

Variables	Endogenous variables: Carbon emissions							
	Consumption model				Production model			
	CS-ARDL		CCEMG	AMG	CS-ARDL		CCEMG	AMG
	Short-run	Longrun			Short-run	Longrun		
COAL	0.393*** (0.126)	0.239*** (0.058)	0.147* (0.068)	0.157*** (0.031)	0.261*** (0.115)	0.225*** (0.069)	0.145 (0.085)	0.084** (0.041)
GAS	−0.436* (0.194)	−0.473** (0.211)	−0.332*** (0.103)	−0.282*** (0.055)	0.273 (0.165)	0.268** (0.095)	0.188*** (0.058)	0.126*** (0.038)
OIL	0.165** (0.056)	0.231*** (0.066)	0.284*** (0.055)	0.067 (0.072)	0.096** (0.025)	0.305*** (0.058)	0.175 (0.149)	0.055** (0.024)
GTECH	−1.367** (0.552)	1.559*** (0.612)	−1.655*** (0.514)	−1.102*** (0.119)	−1.429*** (0.521)	−1.782*** (0.233)	−1.055*** (0.122)	−0.855*** (0.233)
GFINANCE	−1.381* (0.691)	−1.877*** (0.334)	−1.455*** (0.322)	−0.169 (0.135)	−1.115** (0.335)	−1.405*** (0.228)	−1.186*** (0.203)	−0.955*** (0.322)
GENERGY	−0.344*** (0.098)	−0.533*** (0.114)	−0.255 (0.145)	−0.612*** (0.095)	−0.451*** (0.122)	−0.566*** (0.085)	−0.155 (0.089)	−0.382** (0.065)
ENVTAX	−0.282* (0.148)	−0.714*** (0.233)	−0.486** (0.199)	−0.355*** (0.114)	−0.133** (0.055)	−0.645*** (0.099)	−0.255*** (0.035)	−0.143*** (0.042)
FDV	−0.497 (298)	−0.515** (0.219)	−0.319 (0.179)	−0.215** (0.069)	−0.556*** (0.173)	−0.798*** (0.125)	−0.169** (0.075)	−0.177** (0.036)
POP	0.119*** (0.035)	1.113*** (0.133)	1.168*** (0.298)	1.252*** (0.331)	1.435*** (0.316)	1.523*** (0.377)	0.686** (0.323)	1.029*** (0.154)
GDPPC	1.268*** (0.336)	1.553*** (0.255)	1.088*** (0.155)	1.105*** (0.228)	1.295*** (0.276)	1.338*** (0.115)	0.855*** (0.155)	0.552*** (0.144)
ECT (-1)	−0.613*** (0.165)				−0.573*** (0.095)			
R-square/ RMSE	0.855		0.013	0.025	0.924		0.019	

The estimated significance levels denoted by *, **, and *** correspond to values of 10%, 5%, and 1% respectively.

The feedback on the effects of green policies shows significant support for achieving sustainability targets in the G20 countries. This is obvious from the various impacts exerted by each of the green policy indicators. For instance, green technology (GTECH) is observed to significantly reduce carbon in the short and long run, and from both angles of consumption and production. Analogously, green finance (GFINANCE) and green energy (GENERGY) prove to be substantial in mitigating the surge in CO_2 emissions across the various levels of assessments as depicted earlier. In essence, the totality of green policies appears as driving factor of environmental sustainability in the G20 economies. The role of environmental tax in moderating the rise in CO_2 emissions is empirically supported by the significant and negative coefficient values in the short run and long run from both angles of consumption and production. The moderating roles of financial development are evident in the longrun suggesting that advancements in the financial sectors of the G20 economies will provide substantial support for green environment projects. The provision of financial support for the growth of renewable energy will result in significant reduction in fossil fuel consumption.

The twist of the foregoing effects is evident in the way population growth and economic growth hinder sustainability targets in the economies. Both indicators are noted to exacerbate environmental degradation by inducing significant surge in CO_2 emissions. In conclusion, all the models indicate temporary disparities, with a correction rate of 61% for the consumption model and 57% for the production model. The noteworthy adaptation rates of these two models underscore the significant adverse environmental effects caused by natural resources, particularly their rigid reliance on and incapability to adjust to policy alterations aimed at mitigating resource exhaustion.

A summary of the empirical outcomes as explicated above is presented in Figure 4. Going by the diagram, it is evident that the inducing effects of coal, petroleum oil, population, and economic growth are explicated with positive signs. The moderating impacts of natural gas, green technology, green finance, green energy, environmental tax, and financial development are exposited with negative signs.

4.4 Discussion of results

The current study provides empirical evidence to substantiate the environmental effects of natural resources from consumption and production angles in G20 countries. The empirical model allows for examining the additional roles of green policies, environmental

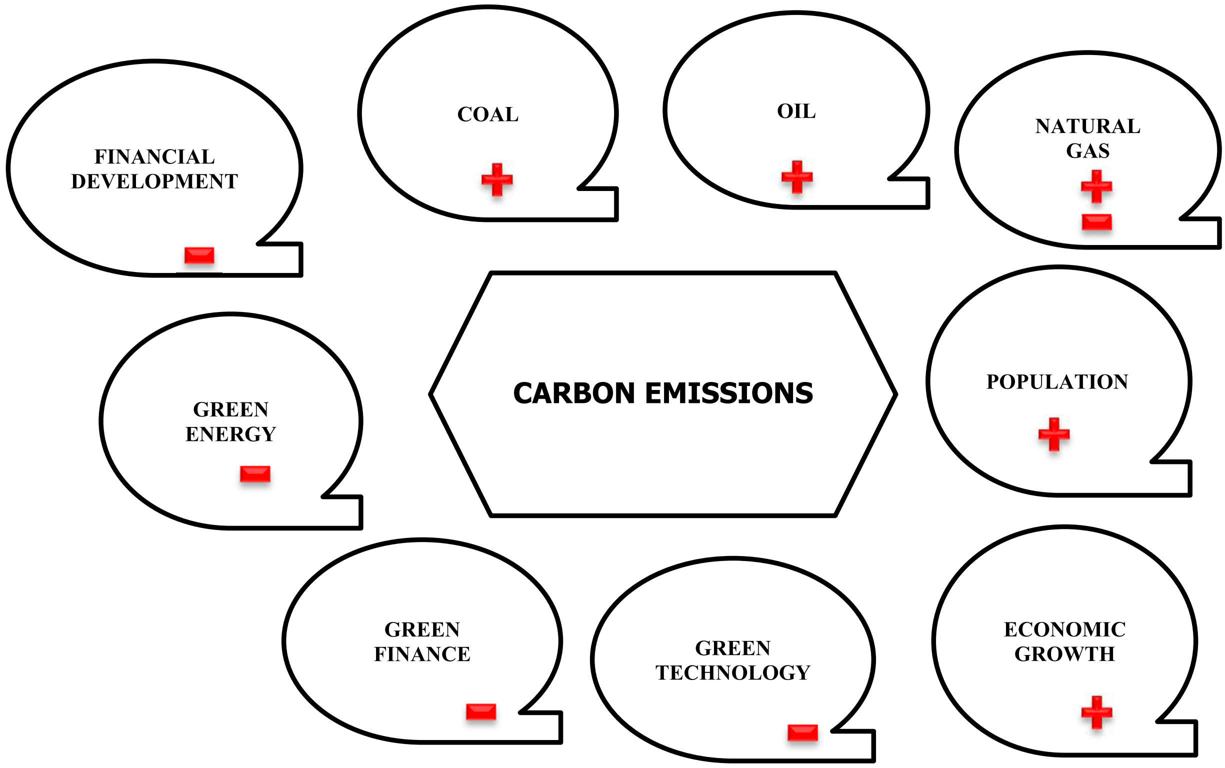

FIGURE 4
Summary of the effects of the estimated model.

tax, and financial development estimated within the STIRPAT theoretical framework. The outcomes of the Table 6 hypotheses test show that coal and oil exert positive impacts on CO_2 emissions in the short and long run. The observed carbon-generating effects are reflected in consumption and production patterns. Consequently, the continuous growth of coal and oil by the G20 economies poses an additional threat to the environmental sustainability of current and future generations. This outcome demonstrates that despite the commitment of the G20 economies to zero emissions by 2050, continuous reliance on coal and particularly petroleum products will serve as a deterrent to achieving the set goals. The escalating impacts of coal and oil on environmental pollutants hinder the strides toward sustaining the G20 environments and this has triggered renewed attention and commitments by the group of economies to phasing out these two pollution drivers. For instance, on 16 April 2023, the climate and environment ministers of the G20 nations issued a statement emphasizing the global reduction of emissions from fossil fuels, particularly coal power. They reiterated their commitment to fully or predominantly decarbonize their energy sectors by 2035, aiming to achieve zero energy systems by that time. Additionally, they vowed to accelerate the elimination of all remaining burning fossil fuels to prevent global temperatures from surpassing a 1.5-degree increase (Powering Past Coal Alliance PPCA, 2023).

Moreover, it is worth mentioning that the influence of natural gas from production angle hinders the attainment of environmental sustainability which could be exposited from two angles. First, transmission pipeline drilling is employed for the extraction of natural gas, with routine inspections conducted on wellheads and motor-driven lines to ensure efficient gas production. Compressors are utilized to regulate the pressure of the gaseous gasoline as it traverses through the transportation pipeline. The processes involved in the drilling emit some significant volumes of pollution into the atmosphere. Second, methane, which is the primary constituent of natural gas, escapes during the process of drilling wells, mining, and transporting gas via pipelines. In terms of heat retention over a hundred years, methane is three times more effective than CO_2 emissions.

On the flip side, the channel of natural gas effects on CO_2 emissions indicates it drives environmental sustainability by mitigating CO_2 emissions. The moderating effects of natural gas are evident in the roles it plays in emitting minimal pollutants in comparison to petroleum oil. The moderating impacts of natural gas consumption are evident from the notably negative coefficient of gaseous CO_2 emissions from both perspectives. A substantial strand of empirical evidence affirms the exacerbating roles of natural resources on the environment (Luo et al., 2024; Ahmad et al., 2023; Wang et al., 2023b; Xiaoman et al., 2021). Besides, studies such as (Ibrahim and Ajide, 2021b; Wang Z. et al., 2023) specifically accentuate the roles of natural gas in the promotion of environmental sustainability.

Within the G20 nations, there is unanimous backing for the attainment of sustainability objectives when discussing the effects of eco-friendly measures. The distinct influence of each green policy indicator is readily apparent. To illustrate, the empirical findings from this study demonstrated that green technology significantly diminishes CO_2 emissions both in the short and long run, encompassing aspects of production and consumption. As previously mentioned, green energy and green finance hold crucial roles in curbing peak CO_2 emissions across all levels of assessment. On the whole, it appears that the environmental sustainability of G20 economies is primarily propelled by their initiatives in the realm of green practices. Considering the aforementioned factors, available facts unveil that the G20 economies have committed to guiding the global energy market towards achieving zero emissions by 2050. This commitment aims to facilitate a technology-driven shift towards achieving net zero emissions, which will be supported by relevant policies of which green policies are not negligible (International Energy Agency, 2021). The extant studies have documented the efficacy of green policies from the varying components in promoting environmental sustainability through the mitigation of carbon emission surge particularly as it relates to green technology (Xu and Hu, 2024; Radmehr et al., 2023; Sharif et al., 2023); green finance (Qi et al., 2023; Shen et al., 2023), and green energy (Akram et al., 2023; Sharif et al., 2023).

Furthermore, the estimated models reveal that there is empirical evidence confirming the effectiveness of environmental taxes in reducing CO_2 emissions. The coefficients for both short-term and long-term effects are significant and negative when it comes to consumption and production. The implication is that an increase in carbon prices occasioned by high rates of taxes on carbon-related products will inversely result in decrease in demand for such products. The eventual result will be a significant decline in carbon emissions. Hence, we can infer that environmental taxes inversely relate to carbon emission surge. Specifically, empirical evidence from the work of Shi et al. (2022) reveals that environmental taxes exert a statistically notable impact on conventional energy usage, resource rents, and renewable energy consumption. Furthermore, they propose that environmental taxes serve as an efficacious approach for G20 nations to curtail emissions. Regarding the roles of financial development in facilitating environmental quality, results from the current study show that long-term financial developments and dampening effects play a crucial role, indicating that the financial sectors of G20 countries have a significant impact on environmental projects. Furthermore, providing financial support for the expansion of renewable energy leads to a substantial decrease in the reliance on fossil fuels. Appreciable strands of empirical studies confirm the significance of financial development to the achievement of environmental quality (Acheampong, 2019; Baloch et al., 2021; Li et al., 2022).

The inducing roles of population on carbon emissions are empirically accentuated from the estimated model for the G20 economies. This is evident from the coefficient of population that is positive and statistically significant across models. The ecological implications of population can be justified from the viewpoint of the fact that the growing population results in increased demand for basic needs of humans of which food is not negligible. This is because food is a fundamental requirement for the survival of human beings, and as the world and population continue to expand, the demand for it also rises. To meet this growing need, extensive deforestation takes place as a consequence of agricultural development. The inability of forests to counterbalance the effects of heightened CO_2 emissions leads to a rise in temperatures. A burgeoning strands of studies attested to the aggravating effects of population on the environment (Alnour et al., 2022; Chen et al., 2022; Zhang et al., 2021). The results on economic growth-carbon emissions nexus show that the former is a positive predictor of the former suggesting that a significant rise in the rate of economic expansion leads to a corresponding increase in the level of CO_2 emissions in G20 economies. Although the G20 economies are basically categorized as developed nations, the continuous dependence on fossil fuels in the majority of the economic activities contributes to the direct relationship between economic growth and environmental pollution in these countries. The majority of empirical findings have established the existence of positive nexus between economic growth and environmental pollution (Ahmad et al., 2023; Ahmed et al., 2022; Wang A. et al., 2023).

4.5 Robustness analysis

The present study extends its contributions to the extant studies by considering robustness analyses from two different angles. First, a different outcome variable is considered with a specific focus on ecological footprint. The second robustness focuses on estimating the distributional effects of the exogenous variables on environmental sustainability based on quantile regression.

4.5.1 First robustness analysis based on consideration of ecological footprint as outcome variable

To extend the empirical contributions of the current study, we conduct a robustness analysis based on two the consideration of ecological footprint as an outcome indicator and evaluation of the heterogenous effects of the exogenous indicators. The heterogeneous analyses are examined following the novel quantile regression estimator. The results of the first robustness are presented in Table 7 showing that coal, gas, and oil significantly drive ecological footprint across consumption and production models. The implication of the presented feedback is that continuous depletion of natural resources will further aggravate the ecological footprint in the G20 economies. The results of the green policies unveil that green technology (GTECH), green finance (GFINANCE), and green energy (GENERGY) moderate the surge in ecological footprint. The moderating impacts of environmental tax are empirically accentuated across the two models suggesting that an increase in carbon-related tax will bring about substantial decline in the level of ecological footprint. Financial development significantly moderates ecological footprint suggesting that the financial sector can be effective in promoting investment in green growth. Conversely, population and economic growth significantly exacerbate the environment by adding to the stock of ecological footprint. The correction to the disequilibrium with a correction rate of 36% for the consumption model and 26% for the production model.

4.5.2 Second robustness analyses based on computation of the computation of the heterogenous effects of the independent variables

The current study employs quantile regression estimator, which offers a conditional distribution of the heterogenous impacts of

TABLE 7 Feedback from Short-run and Longrun analyses based on ecological footprint model.

Variables	Endogenous variables: Ecological footprint							
	Consumption model				Production model			
	CS-ARDL		CCEMG	AMG	CS-ARDL		CCEMG	AMG
	Short-run	Longrun			Short-run	Longrun		
COAL	0.459** (0.155)	0.322*** (0.122)	0.255** (0.112)	0.208*** (0.066)	0.335** (0.133)	0.492*** (0.115)	0.288*** (0.035)	0.210*** (0.066)
GAS	−0.552*** (0.103)	−0.614*** (0.145)	−0.435** (0.155)	−0.356*** (0.104)	0.344*** (0.122)	0.355*** (0.172)	0.337*** (0.112)	0.465*** (0.138)
OIL	0.655*** (0.142)	1.755*** (0.205)	0.443*** (0.099)	0.375*** (0.105)	0.416*** (0.133)	0.339*** (0.110)	0.175 (0.149)	0.055** (0.024)
GTECH	−1.367** (0.552)	1.559*** (0.612)	−1.655*** (0.514)	−1.102*** (0.119)	−1.429*** (0.521)	−1.782*** (0.233)	−1.055*** (0.122)	−0.855*** (0.233)
GFINANCE	0.449 (0.285)	−0.644*** (0.205)	−0.535*** (0.167)	−0.466*** (0.195)	−0.236 (0.159)	−0.555*** (0.118)	−0.388*** (0.132)	−0.356** (0.175)
GENERGY	−0.113 (0.085)	−0.243** (0.116)	−0.148** (0.077)	−0.388*** (0.104)	−0.087 (0.074)	−0.124*** (0.055)	−0.119** (0.052)	−0.128** (0.066)
ENVTAX	−0.355*** (0.115)	−0.654*** (0.155)	−0.361** (0.188)	−0.444*** (0.134)	−0.219** (0.075)	−0.331*** (0.139)	−0.211*** (0.045)	−0.177*** (0.052)
FDV	−0.211 (139)	−0.492*** (0.115)	−0.255** (0.122)	−0.344** (0.075)	−0.122 (0.085)	−0.433*** (0.155)	−0.119** (0.055)	−0.236*** (0.126)
POP	1.486*** (0.156)	2.557*** (0.211)	2.086*** (0.188)	2.114*** (0.223)	1.022*** (0.114)	1.882*** (0.156)	1.553*** (0.225)	1.433*** (0.274)
GDPPC	2.355*** (0.115)	1.095*** (0.117)	1.513*** (0.098)	1.455*** (0.228)	2.568*** (0.176)	1.634*** (0.115)	1.877*** (0.105)	1.332*** (0.118)
ECT (-1)	−0.358*** (0.055)				−0.255*** (0.065)			
R-square/ RMSE	0.889		0.015	0.016	0.915		0.023	

The estimated significance levels denoted by *, **, and *** correspond to values of 10%, 5%, and 1% respectively.

regressors on the outcome variables, to enhance understanding of environmental sustainability in the G20 countries. Furthermore, the quantile regression estimates presented in Table 8 are categorized into lower, middle, and upper quantiles. Following the results, it is evident that the inducing effects of coal and oil are significant across the quantiles. The implications of the results are that from the very first stage of producing and consuming both coal and oil, their ensuing effects contribute to the aggravating nature of pollution on the environment. Conversely, natural gas proves to be a significant resistance to environmental degradation from the middle to the upper quantiles. One possible explanation of the mitigating impacts of natural gas could be given from the view that it emits less than coal and oil and equally has the potential to promote sustainability than others. Available evidence reveals that burning natural gas emits fewer pollutants and carbon dioxide (CO_2) into the atmosphere compared to burning coal or petroleum products for the same energy output. As such, developed countries like the United States have witnessed a rise in the utilization of natural gas for both automotive fuel and power generation, primarily due to its environmentally friendly combustibility (Energy Information Administration EIA, 2022).

The moderating effects of green technology (GTECH) on carbon emissions are well established from the lower to upper quantiles which are indicative of the facts that technology substantially controls the surge in environmental pollution. The feedback on green finance shows that its impacts on carbon emissions are evident in the middle and upper quantiles. The finding is intuitional on the ground that it takes a while before the moderating impacts of green projects are apparent on environmental degradation. The distributional effects of green energy are equally evident from the middle to upper quantile suggesting the rigidity in transiting from fossil fuels to renewable energy. The rate of reliance on fossil fuels usually makes it difficult for households and firms to move higher on the energy ladder to renewable energy. Environmental tax proves significant in reducing the level of carbon emissions across the three phases of the quantiles. The declining roles of financial development on carbon emissions are apparent from the middle to upper quantiles. On the contrary, population and economic growth escalate the emission surges across the three quantiles.

4.6 Analyses of the panel causality nexuses

To ascertain the extent of causality between the dependent and independent indicators in an empirical study, it is imperative to conduct a causality test, as the presence of substantial effects of regressors on the outcome variables does not necessarily indicate a

TABLE 8 Outcomes Quantile regression analyses.

Indicators	Endogenous variable: Carbon emissions					
	Lower quantiles		Middle quantiles		Upper quantiles	
	15th quantile	30th quantile	45th quantile	60th quantile	75th quantile	90th quantile
COALPR	0.094***	0.079***	0.081***	0.069***	0.063***	0.068***
	(0.014)	(0.017)	(0.013)	(0.01)	(0.007)	(0.012)
GASPR	0.013	0.023	0.032**	0.041***	0.052***	0.068
	(0.013)	(0.016)	(0.013)	(0.012)	(0.016)	(0.011)
OILPR	0.181***	0.186***	0.128***	0.095***	0.088***	0.079***
	(0.023)	(0.028)	(0.022)	(0.017)	(0.011)	(0.02)
COALCO	0.257***	0.207***	0.242***	0.263***	0.25***	0.248***
	(0.04)	(0.049)	(0.039)	(0.03)	(0.02)	(0.035)
GASCO	−0.114	−0.118	−0.161**	−0.221***	−0.235***	−0.232***
	(0.078)	(0.094)	(0.075)	(0.058)	(0.038)	(0.067)
OILCO	0.603***	0.594***	0.476***	0.477***	0.425***	0.467***
	(0.081)	(0.098)	(0.078)	(0.06)	(0.04)	(0.07)
GTECH	−0.187***	−0.198***	−0.213***	−0.371**	−0.464***	−0.483**
	(0.022)	(0.069)	(0.043)	(0.164)	(0.109)	(0.192)
GFINANCE	−0.159	−0.188	−0.245***	−0.273*	−0.388***	−0.385**
	(0.089)	(0.151)	(0.099)	(0.154)	(0.102)	(0.18)
GENERGY	−0.056	−0.062	−0.081***	−0.092***	−0.105***	−0.136***
	(0.029)	(0.037)	(0.021)	(0.026)	(0.031)	(0.049)
ENVREG	−0.509***	−0.385***	−0.415***	−0.332***	−0.299***	−0.23***
	(0.083)	(0.1)	(0.079)	(0.061)	(0.041)	(0.072)
FDV	−0.034	−0.062	−0.185**	−0.108**	−0.095***	−0.147***
	(0.064)	(0.077)	(0.061)	(0.047)	(0.031)	(0.055)
POP	0.635***	0.591***	0.589***	0.647***	0.651***	0.696***
	(0.079)	(0.095)	(0.076)	(0.058)	(0.039)	(0.068)
GDPPC	0.932***	0.752***	0.383**	0.275**	0.381***	0.284***
	(0.179)	(0.216)	(0.172)	(0.132)	(0.088)	(0.055)
_cons	23.125***	20.321***	16.946***	17.108***	18.288***	17.166***
	(1.771)	(2.138)	(1.696)	(1.307)	(0.869)	(1.532)

The estimated significance levels denoted by *, **, and *** correspond to values of 10%, 5%, and 1% respectively.

causal relationship between them. This research employs Dumitrescu Hurlin panel causality tests, which are adaptable to account for variations in slopes and cross-sectional dependence. Based on the results in Table 9, it is evident that the three indicators of natural resources have bidirectional causality with CO_2 emissions. The implication of the two-way causal nexuses is that policy measures that are directed toward halting the depletion of natural resources (coal, oil, and natural gas) will have significant impacts in reducing CO_2 emissions. For instance, attempts toward phasing out coal in recent times have seen appreciable reductions in the surging CO_2 emissions. Conversely, policy initiatives implemented with the aim of reducing CO_2 emissions may have significant impacts on minimizing the depletion rates of natural resources. In case, policy measures favor depletion of natural resources, it is most likely that CO_2 emissions will escalate.

There is a two-way causality observed between green technology (GTECH) and CO_2 emissions suggesting both have the tendency to cause each other inversely. By implication, policy measures implemented to promote green technology will see substantial decline in CO_2 emissions. For instance, the promotion of

TABLE 9 Empirical results on the causality nexuses.

Model	W-stat	Zbar-stat	Conclusion
COAL → CO2 emissions	7.886***	4.215	Bidirectional
CO2 emissions → COAL	8.143***	4.088	
GASPR → CO2 emissions	9.553***	3.422	Bidirectional
CO2 emissions →GAS	8.539***	4.033	
OILPR → CO2 emissions	6.229**	5.129	Bidirectional
CO2 emissions → OIL	5.275**	3.012	
GTECH → CO2 emissions	5.102*	2.775	Bidirectional
CO2 emissions →GTECH	8.678***	4.332	
GFINANCE → CO2 emissions	9.115***	4.025	Unidirectional
CO2 emissions → GFINANCE	2.339	1.322	
GENERGY → CO2 emissions	8.555***	5.330	Unidirectional
CO2 emissions → GENERGY	3.115	0.902	
ENVREG → CO2 emissions	4.901*	2.055	Unidirectional
CO2 emissions → ENVREG	6.009	4.883	
FDV → CO2 emissions	4.901*	2.055	Unidirectional
CO2 emissions → FDV	6.009	4.883	
POP → CO2 emissions	4.901*	2.055	Unidirectional
CO2 emissions → POP	6.009	4.883	
GDPPC → CO2 emissions	4.901*	2.055	Unidirectional
GDPPC → CO2 emissions	2.664	0.055	

The estimated significance levels denoted by *, **, and *** correspond to values of 10%, 5%, and 1% respectively. It should be noted that homogenous effects are assumed for causality nexuses of natural resources (consumption and production) in Table 9 because there are not significantly different feedbacks from both models.

research and development (R&D) may lead to the discovery of production techniques that reduce CO_2 emissions significantly. On the other hand, the drive toward reducing could result in the adoption of green technology as a tool to achieve such ecological target. There is a unidirectional causality reported in the relationship between green finance, green energy, environmental tax, financial development, economic growth, and population. This implies that policy measures directed to promote green finance, green energy, and environmental tax will have ensuing impacts in reducing CO_2 emissions. The causality in the case of population implies that any policy that triggers a rise in population growth will exacerbate the level of CO_2 emissions. The one-way causality in the nexus of economic growth with CO_2 emissions suggests that policy measures that enhance expansion in the general level of production will lead to a rise in the level of CO_2 emissions.

5 Conclusion, recommendations, global implication, and limitations

5.1 Conclusion

This research investigates the two main channels (comprising consumption and production) through which natural resources (decomposed into coal, oil, and natural gas) impact environmental sustainability vectoring CO_2 emissions and ecological footprint in G20 countries from 1995 to 2019. To position the relevance of the study at the center of the extant literature, the roles of green policies, environmental tax, financial development, population, and economic growth are carefully examined. The empirical analyses encompass series of validations specifically with the consideration of second-generation tests such as cross-sectional dependence test and slope homogeneity test to ascertain the status of the dataset in undergoing first-generation or second-generation evaluation. Upon the confirmation of cross-sectional dependence and slope heterogeneity, second-generation unit rot tests such as CIPS and CADF are adopted to assess the stationarity status of the series. The empirical results of the tests support the utilization of quantile regression, augmented group mean (AMG), common correlation effect mean (CCEMG), and cross-sectional ARDL (CS-ARDL). Given the variability of the slope and the interconnectedness of the models, panel causality tests, as proposed by Dumitrescu and Hurlin (2012), must be employed. The outcomes from the estimated consumption and production models reveal that natural resources from coal and oil sources both deter environmental sustainability by positively driving an increase CO_2 emissions and ecological footprint. The effects of natural gas are divergent depending on the angle from which the impacts are evaluated. It was evident the production channel of natural gas deteriorates the environment by driving both pollutants whereas the consumption channel improves the environment by significantly mitigating both pollutants. The components of green policies comprising green technology, green finance, and green energy significantly moderate the surge in CO_2 emissions. The pertinent roles of environmental tax in moderating the surge in CO_2 emission are never without notice following the inverse relationship between environmental tax and the two environmental pollutants. It becomes clear that increasing carbon tax discourages further consumption of carbon-related products leading to eventual reduction in the overall carbon levels. Financial development proves substantial in supporting environmental sustainability with the mitigation of CO_2 emissions and ecological footprint in G20 countries. The empirical outcomes unveil the inducing effects of population and economic growth in escalating the surge in CO_2 emissions and ecological footprint. It should be noted that the feedbacks from CS-ARDL are largely supported by the outcomes from CCEMG and AMG.

5.2 Recommendations

The policy implications enlisted below are believed to be highly fundamental in supporting the sincere endeavors to tackle environmental concerns in the G20 countries.

1. The reduction of negative environmental impacts caused by coal and oil can be achieved in the G20 nations through the elimination of substantial subsidies for fossil fuels and the implementation of higher prices and taxes on products and services related to both indicators. By adopting these strategies, there will be a substantial decrease in the consumption of coal and oil and a greater encouragement towards adopting clean and eco-friendly energy sources.
2. Investing in the various components of green policies offers the opportunity to maintain the carbon dioxide reduction advantages associated with them. A comprehensive initiative is anticipated to be launched by various G20 governments, aiming to enhance the promotion of green policies. For instance, green energy such as nuclear power could be adopted in electricity generation as alternative to coal. Given the limited progress in green policies in the G20 countries, proactive and intensified promotion efforts become imperative for the objective to be achieved as a way of contributing to the region's environmental sustainability.
3. The role of environmental tax in mitigating environmental pollutants proves effective. Hence, the governments of the various G20 countries should consciously drive policies that will specifically target increase in tax rates on carbon-related products. The proceeds from the tax can be invested into green policies such as increasing investment in green technologies through the sponsoring of research and development.
4. In order to maintain the inhibitory impact of green technology, it is imperative for the government to endorse technical advancements. Specifically, the utilization of funding and support from all G20 nations should be directed toward promoting research and development in ecological sustainability. Furthermore, it is crucial for diverse media outlets and educational establishments to collaborate in order to educate the nation about the significance of implementing ecological technologies.
5. The transition to a zero-carbon environment can be pursued and coordinated by the government through the implementation of projects that comply with green finance initiatives. A deliberate injection of national resources into green projects could be pursued by the governments of the G20 nations.
6. The government has the ability to effectively handle the influx of migrants to urban areas by focusing on the development of rural regions in a manner that entices individuals with well-paying employment prospects, standardized infrastructure, and essential social services. The completion of the capital project and the appeal for international assistance to enhance the quality of life in rural areas will greatly alleviate the strain on the capital region.

5.3 Global implications

The findings of the present study, while concentrating on the G20 economies, carry substantial global implications for both developed and developing nations. The issue of natural resources depletion, a significant contributor to the increasing global warming, is observable in countries around the world. The insights derived from this research serve as valuable reference points for nations globally to comprehend the differing impacts of each natural resources component. Furthermore, in light of the growing significance of green policies, this study has successfully enhanced the empirical understanding of each green component's role in addressing the persistent rise in greenhouse gas (GHG) emissions. Notably, the statistical significance attributed to green energy further supports the notion that a transition to 100% renewable energy will mitigate the escalating GHG emission rates. Additionally, it is important to highlight the empirical evidence demonstrating the effectiveness and critical role of green finance in fostering environmental sustainability within the G20, which serves as a clear reference for broader global applications.

5.4 Limitations and future research opportunities

The current study primarily examines the ways in which natural resources influence environmental sustainability in G20 countries. However, it is important to acknowledge certain limitations. For example, while the analysis considers the effects of natural resources from both consumption and production perspectives, it is restricted to specific components, namely, coal, natural gas, and petroleum oil. The overall impact of natural resources as a whole is not addressed in this research. The empirical evidence presented in this study is confined to the G20 economies. While it is possible to generalize findings to other economies, conducting a replication of this research for those regions would be advantageous. For instance, intergovernmental organizations such as the G7, E7, and N11 could derive substantial benefits from studies of this kind. Moreover, this research does not encompass important policy indicators, such as institutional quality and various metrics related to environmental pollutants. Future investigations could gain from addressing these gaps.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AA: Conceptualization, Methodology, Software, Supervision, Validation, Visualization, Writing–review and editing. RI: Conceptualization, Formal Analysis, Investigation, Project administration, Resources, Writing–original draft. AA: Conceptualization, Data curation, Formal Analysis, Investigation, Project administration, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abbass, K., Song, H., Khan, F., Begum, H., and Asif, M. (2022). Fresh insight through the VAR approach to investigate the effects of fiscal policy on environmental pollution in Pakistan *Environ. Sci. Pollut. Res.* 29 (16), 23001–23014. doi:10.1007/s11356-021-17438-x

Abdul, D., Wenqi, J., and Tanveer, A. (2022). Environmental stewardship: Analyzing the dynamic impact of renewable energy, foreign remittances, and globalization index on China's CO_2 emissions *Renewable Energy* 201, 418–425. doi:10.1016/j.renene.2022.10.113

Acheampong, A. O. (2019). Modelling for insight: does financial development improve environmental quality? *Energy Econ.* 83, 156–179. doi:10.1016/j.eneco.2019.06.025

Ahmad, M., Ahmed, Z., Khan, S. A., and Alvarado, R. (2023). Towards environmental sustainability in E−7 countries: assessing the roles of natural resources, economic growth, country risk, and energy transition. *Resour. Policy* 82, 103486. doi:10.1016/j.resourpol.2023.103486

Ahmed, Z., Ahmad, M., Rjoub, H., Kalugina, O. A., and Hussain, N. (2022). Economic growth, renewable energy consumption, and ecological footprint: exploring the role of environmental regulations and democracy in sustainable development. *Sustain. Dev.* 30 (4), 595–605. doi:10.1002/sd.2251

Akram, R., Ibrahim, R. L., Wang, Z., Adebayo, T. S., and Irfan, M. (2023). Neutralizing the surging emissions amidst natural resource dependence, eco-innovation, and green energy in G7 countries: insights for global environmental sustainability. *J. Environ. Manag.* 344, 118560. doi:10.1016/j.jenvman.2023.118560

Alnour, M., Ali, M., Abdalla, A., Abdelrahman, R., and Khalil, H. (2022). How do urban population growth, hydropower consumption and natural resources rent shape environmental quality in Sudan? *World Dev. Sustain.* 1, 100029. doi:10.1016/j.wds.2022.100029

Amin, N., Shabbir, M. S., Song, H., Farrukh, M. U., Iqbal, S., and Abbass, K. (2023). A step towards environmental mitigation: Do green technological innovation and institutional quality make a difference? *Technological Forecasting and Social Change* 190, 122413. doi:10.1016/j.techfore.2023.122413

Andersen, I. (2023). *The G20 is a global force for sustainability*. Available at: https://www.unep.org/news-and-stories/speech/g20-global-force-sustainability.

Ashraf, M. Z., Wei, W., Usman, M., and Mushtaq, S. (2024). How can natural resource dependence, environmental-related technologies and digital trade protect the environment: redesigning SDGs policies for sustainable environment? *Resour. Policy* 88, 104456. doi:10.1016/j.resourpol.2023.104456

Baloch, M. A., Ozturk, I., Bekun, F. V., and Khan, D. (2021). Modeling the dynamic linkage between financial development, energy innovation, and environmental quality: does globalization matter? *Bus. Strategy Environ.* 30 (1), 176–184. doi:10.1002/bse.2615

Balsalobre-Lorente, D., Sinha, A., and Murshed, M. (2023). Russia-Ukraine conflict sentiments and energy market returns in G7 countries: discovering the unexplored dynamics. *Energy Econ.* 125, 106847. doi:10.1016/j.eneco.2023.106847

Bigerna, S., D'Errico, M. C., Micheli, S., and Polinori, P. (2023). Environmental-economic efficiency for carbon neutrality: the role of eco-innovation, taxation, and globalization in OECD countries. *Appl. Econ.* 0 (0), 3568–3581. doi:10.1080/00036846.2023.2206634

Brown, J. (2022). Impact of environmental taxation on environmental sustainability in Nigeria. *Texila Int. J. Acad. Res.* 9 (3), 11–20. doi:10.21522/TIJAR.2014.09.03.Art002

Chen, H., Tackie, E. A., Ahakwa, I., Musah, M., Salakpi, A., Alfred, M., et al. (2022). Does energy consumption, economic growth, urbanization, and population growth influence carbon emissions in the BRICS? Evidence from panel models robust to cross-sectional dependence and slope heterogeneity. *Environ. Sci. Pollut. Res.* 29 (25), 37598–37616. doi:10.1007/s11356-021-17671-4

Dietz, T., and Rosa, E. A. (1997). Effects of population and affluence on CO_2 emissions *Proceedings of the National Academy of Sciences* 94 (1), 175–179.

Dumitrescu, E. I., and Hurlin, C. (2012). Testing for Granger non-causality in heterogeneous panels *Economic modelling* 29 (4), 1450–1460.

Energy Information Administration (EIA), E. I. A. (EIA) (2022). Natural gas and the environment—U.S. Energy information administration (EIA). Available at: https://www.eia.gov/energyexplained/natural-gas/natural-gas-and-the-environment.php.

Fan, L., and Wang, D. (2024). Natural resource efficiency and green economy: key takeaways on clean energy, globalization, and innovations in BRICS countries. *Resour. Policy* 88, 104382. doi:10.1016/j.resourpol.2023.104382

Han, Y., Bao, M., Niu, Y., and Rehman, J. ur. (2024). Driving towards net zero emissions: the role of natural resources, government debt and political stability. *Resour. Policy* 88, 104479. doi:10.1016/j.resourpol.2023.104479

Ibrahim, R. L. (2022). Post-COP26: Can energy consumption, resource dependence, and trade openness promote carbon neutrality? Homogeneous and heterogeneous analyses for G20 countries *Environ. Sci. Pollut. Res.* 29 (57), 86759–86770. doi:10.1007/s11356-022-21855-x

Ibrahim, R. L., and Ajide, K. B. (2021a). Nonrenewable and renewable energy consumption, trade openness, and environmental quality in G-7 countries: the conditional role of technological progress. *Environ. Sci. Pollut. Res.* 28 (33), 45212–45229. doi:10.1007/s11356-021-13926-2

Ibrahim, R. L., and Ajide, K. B. (2021b). The dynamic heterogeneous impacts of nonrenewable energy, trade openness, total natural resource rents, financial development and regulatory quality on environmental quality: evidence from BRICS economies. *Resour. Policy* 74, 102251. doi:10.1016/j.resourpol.2021.102251

International Enegy Agency, I. E. A. (2021). *Executive summary – achieving net zero electricity sectors in G7 members – analysis*. IEA. Available at: https://www.iea.org/reports/achieving-net-zero-electricity-sectors-in-g7-members/executive-summary.

Khan, Y., and Hassan, T. (2024). Promoting sustainable development: evaluating the influence of natural resources, high-tech export and corruption on CO2 emissions in developing economies. *Resour. Policy* 88, 104511. doi:10.1016/j.resourpol.2023.104511

Lanre Ibrahim, R., Bello Ajide, K., Usman, M., and Kousar, R. (2022). Heterogeneous effects of renewable energy and structural change on environmental pollution in Africa: do natural resources and environmental technologies reduce pressure on the environment? *Renew. Energy* 200, 244–256. doi:10.1016/j.renene.2022.09.134

Li, J., Dong, K., Wang, K., and Dong, X. (2023). How does natural resource dependence influence carbon emissions? The role of environmental regulation. *Resour. Policy* 80, 103268. doi:10.1016/j.resourpol.2022.103268

Li, X., Ozturk, I., Majeed, M. T., Hafeez, M., and Ullah, S. (2022). Considering the asymmetric effect of financial deepening on environmental quality in BRICS economies: policy options for the green economy. *J. Clean. Prod.* 331, 129909. doi:10.1016/j.jclepro.2021.129909

Martin (2023). Sustainable consumption and production. *U. N. Sustain. Dev.* Available at: https://www.un.org/sustainabledevelopment/sustainable-consumption-production/.

Nassani, A. A., Abro, M. M. Q., Batool, R., Shah, S. H. A., Hyder, S., and Zaman, K. (2021). Go-for-green policies: the role of finance and trade for sustainable development. *Int. J. Finance and Econ.* 26 (1), 1409–1423. doi:10.1002/ijfe.1855

Niu, X., Niu, X., Ibrahim, R. L., and Al-Faryan, M. A. S. (2023). Do the asymmetric effects of natural resource dependence and financial development amidst green policies make or mar sustainability agenda in E7 countries? *Resour. Policy* 85, 103889. doi:10.1016/j.resourpol.2023.103889

Pesaran, M. H. (2004). General diagnostic tests for cross section dependence in panels (SSRN scholarly paper 572504). *SSRN Electron. J.* doi:10.2139/ssrn.572504

Pesaran, M. H. (2015). Testing weak cross-sectional dependence in large panels. *Econ. Rev.* 34 (6–10), 1089–1117. doi:10.1080/07474938.2014.956623

Powering Past Coal Alliance (PPCA), P. P. C. A. (PPCA) (2023). G7 ministers take important steps to accelerate global coal phase-out. *PPCA*. Available at: https://poweringpastcoal.org/news/g7-ministers-take-important-steps-to-accelerate-global-coal-phase-out/.

Qamruzzaman, M., and Karim, S. (2024). Unveiling the synergy: Green finance, technological innovation, green energy, and carbon neutrality *PLOS ONE* 19 (10), e0308170. doi:10.1371/journal.pone.0308170

Qi, Y., Ibrahim, R. L., and Saleh Al-Faryan, M. A. (2023). Exploring aggregated and disaggregated environmental impacts of biofuels: do affluence, green technological innovation and green finance matter for top biofuel-abundant economies? *Energy and Environ.*, 0958305X231181673. doi:10.1177/0958305X231181673

Qing, L., Abbas, J., Najam, H., Ma, X., and Dagestani, A. A. (2024). Investment in renewable energy and green financing and their role in achieving carbon-neutrality and economic sustainability: Insights from Asian region. *Renewable Energy* 221, 119830. doi:10.1016/j.renene.2023.119830

Radmehr, R., Shayanmehr, S., Baba, E. A., Samour, A., and Adebayo, T. S. (2023). Spatial spillover effects of green technology innovation and renewable energy on ecological sustainability: new evidence and analysis. *Sustain. Dev.* 32, 1743–1761. *n/a*(n/a). doi:10.1002/sd.2738

Sadiq, M., Paramaiah, C., joseph, R., Dong, Z., Nawaz, M. A., and Shukurullaevich, N. K. (2024). Role of fintech, green finance, and natural resource rents in sustainable climate change in China. Mediating role of environmental regulations and government interventions in the pre-post COVID eras. *Resour. Policy* 88, 104494. doi:10.1016/j.resourpol.2023.104494

Safi, A., Chen, Y., Wahab, S., Zheng, L., and Rjoub, H. (2021). Does environmental taxes achieve the carbon neutrality target of G7 economies? Evaluating the importance of environmental R&D. *J. Environ. Manag.* 293, 112908. doi:10.1016/j.jenvman.2021.112908

Saud, S., Haseeb, A., Zafar, M. W., and Li, H. (2023). Articulating natural resource abundance, economic complexity, education and environmental sustainability in MENA countries: evidence from advanced panel estimation. *Resour. Policy* 80, 103261. doi:10.1016/j.resourpol.2022.103261

Shah, W. U. H., Hao, G., Yan, H., Yasmeen, R., and Xu, X. (2024). Natural resources utilization efficiency evaluation, determinant of productivity change, and production technology heterogeneity across devel-oped and developing G20 economies *Technology in Society* 77, 102507. doi:10.1016/j.techsoc.2024.102507

Sharif, A., Kocak, S., Khan, H. H. A., Uzuner, G., and Tiwari, S. (2023). Demystifying the links between green technology innovation, economic growth, and environmental tax in ASEAN-6 countries: the dynamic role of green energy and green investment. *Gondwana Res.* 115, 98–106. doi:10.1016/j.gr.2022.11.010

Shen, J., Ridwan, L. I., Raimi, L., and Al-Faryan, M. A. S. (2023). Recent developments in green hydrogen–environmental sustainability nexus amidst energy efficiency, green finance, eco-innovation, and digitalization in top hydrogen-consuming economies. *Energy and Environ.*, 0958305X2311539. doi:10.1177/0958305X231153936

Shi, J., Visas, H., Ul-Haq, J., Abbas, S., and Khanum, S. (2022). Investigating the impact of export product diversification on environmental degradation: evidence from Chinese Provinces. *Environ. Dev. Sustain.* 25, 11455–11486. doi:10.1007/s10668-022-02536-8

Sarpong, K. A., Xu, W., Gyamfi, B. A., and Ofori, E. K. (2023). A step towards carbon neutrality in E7: the role of environmental taxes, structural change, and green energy *J. Environ. Manage.* 337, 117556.

Tanveer, A., Song, H., Faheem, M., Daud, A., and Safdar, N. (2024). Navigating the asymmetric influence of financial inclusion on environmental sustainability: Dynamic role of energy consumption and human capital *Energy & Environment* 35 (6), 3087–3115.

United Nation Environment Programme, U. N. E. P. (2019). Global resources outlook global resources oulook. Available at: https://www.resourcepanel.org/reports/global-resources-outlook.

United Nations Environment Programme (2021). *Goal 12: sustainable consumption and production*. UNEP - UN Environment Programme. Available at: http://www.unep.org/explore-topics/sustainable-development-goals/why-do-sustainable-development-goals-matter/goal-12.

Wang, A., Shan, S., Ibrahim, R. L., and Omokanmi, O. J. (2023). A new look at environmental sustainability from the lens of green policies, eco-digitalization, affluence, and urbanization: empirical insights from BRICS economies. *Energy and Environ.* 35, 4195–4222. doi:10.1177/0958305X231177736

Wang, K., Rehman, M. A., Fahad, S., and Linzhao, Z. (2023). Unleashing the influence of natural resources, sustainable energy and human capital on consumption-based carbon emissions in G-7 Countries. *Resour. Policy* 81, 103384. doi:10.1016/j.resourpol.2023.103384

Wang, L., Su, C. W., Liu, J., and Dong, Y. (2024). Sustainable development or smoke? the role of natural resources, renewable energy, and agricultural practices in China. *Resour. Policy* 88, 104512. doi:10.1016/j.resourpol.2023.104512

Wang, Q., Guo, J., Li, R., and Jiang, X. (2023a). Exploring the role of nuclear energy in the energy transition: a comparative perspective of the effects of coal, oil, natural gas, renewable energy, and nuclear power on economic growth and carbon emissions. *Environ. Res.* 221, 115290. doi:10.1016/j.envres.2023.115290

Wang, Q., Sun, Z., Guo, J., and Li, R. (2023b). The more effective option to combat environmental degradation: energy efficiency vs. renewable energy vs. natural gas? *Energy* 283, 128512. doi:10.1016/j.energy.2023.128512

Wang, Z., Teng, Y.-P., Wu, S., and Chen, H. (2023). Does green finance expand China's green development space? Evidence from the ecological environment improvement perspective. *Systems* 11 (7), 369. Article 7. doi:10.3390/systems11070369

Westerlund, J. (2007). Testing for error correction in panel data. *Oxford Bulletin of Economics and statistics*. 69 (6), 709–748.

Wolde-Rufael, Y., and Mulat-Weldemeskel, E. (2022). The moderating role of environmental tax and renewable energy in CO2 emissions in Latin America and Caribbean countries: evidence from method of moments quantile regression. *Environ. Challenges* 6, 100412. doi:10.1016/j.envc.2021.100412

Xiaoman, W., Majeed, A., Vasbieva, D. G., Yameogo, C. E. W., and Hussain, N. (2021). Natural resources abundance, economic globalization, and carbon emissions: advancing sustainable development agenda. *Sustain. Dev.* 29 (5), 1037–1048. doi:10.1002/sd.2192

Xie, J., Abbass, K., and Li, D. (2024). Advancing eco-excellence: Integrating stakeholders' pressures, environmental awareness, and ethics for green innovation and performance *J. Environ. Manage.* 352, 120027. doi:10.1016/j.jenvman.2024.120027

Xing, L., Khan, Y. A., Arshed, N., and Iqbal, M. (2023). Investigating the impact of economic growth on environment degradation in developing economies through STIRPAT model approach. *Renew. Sustain. Energy Rev.* 182, 113365. doi:10.1016/j.rser.2023.113365

Xu, J., and Hu, W. (2024). How do external resources influence a firm's green innovation? A study based on absorptive capacity. *Econ. Model.* 133, 106660. doi:10.1016/j.econmod.2024.106660

Yang, F., Ibrahim, R. L., Ajide, K. B., and Al-Faryan, M. A. S. (2024). Examining the ecological effects of energy transition, environmental technology, and structural change in BRICS economies: Implications for sustainable development *Energy Sources, Part B: Economics, Planning, and Policy* 19 (1), 2419956. doi:10.1080/15567249.2024.2419956

Zhang, M., Ajide, K. B., and Ridwan, L. I. (2021). Heterogeneous dynamic impacts of nonrenewable energy, resource rents, technology, human capital, and population on environmental quality in Sub-Saharan African countries. *Environ. Dev. Sustain.* 24, 11817–11851. doi:10.1007/s10668-021-01927-7

Zhou, H., Awosusi, A. A., Dagar, V., Zhu, G., and Abbas, S. (2023). Unleashing the asymmetric effect of natural resources abundance on carbon emissions in regional comprehensive economic partnership: what role do economic globalization and disaggregating energy play? *Resour. Policy* 85, 103914. doi:10.1016/j.resourpol.2023.103914

Zhu, C., Chang, Y., Li, X., and Shan, M. (2022). Factors influencing embodied carbon emissions of China's building sector: an analysis based on extended STIRPAT modeling. *Energy Build.* 255, 111607. doi:10.1016/j.enbuild.2021.111607