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Research article

Green growth transition and carbon neutrality nexus: A comparative study on the top carbon emitters

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ABSTRACT

This is a comparative study that investigates the role of green growth, green technological innovations, agricultural eco-efficiency and trade openness on carbon neutrality in the top three carbon emitting countries, namely, China, the USA and India, using panel quantile regression with quarterly data for the time period of 2010–2022. The results reveal different findings which have important policy implications. Firstly, carbon emissions vs green growth and carbon emissions vs green technological innovation have a significant U-shaped relationship, which indicate that when green growth and green technological innovations increases, the rate of carbon emissions continues to decline up to a threshold point and start to increase thereafter. Secondly, carbon emissions vs agricultural ecoefficiency has an inverted U-shaped relationship with the carbon emissions, showing that when agriculture eco-efficiency increases the rate of carbon emissions continues to increase up to a threshold point, and starts declining afterwards. Thirdly, trade openness increases the carbon emissions resulting an increase in the environmental degradation and may hinders achieving the carbon neutrality target. The carbon emissions reduction policies such as carbon taxes, promoting green trade, promoting green growth and emission trading schemes must acknowledge and incorporate the interplay among key stakeholders to enhance their effectiveness.

1. Introduction

In the last few decades, policymakers and scientists have been paying lots of attention in developing strategies to reduce carbon emissions in the atmosphere. It is predicted that by 2035, the world carbon emissions will increase, in an alarming rate, to 42.4 billion metric tons, which is 42.7% more than the carbon emissions level experienced in 2007 (IEA, 2010). Thus, in view of this major global challenge, efforts towards reduction in carbon emissions has received the worldwide attention (Jones and Glachant, 2010). Consequently, lower carbon intensity is now one of the widely used sustainability metrics (Razmjoo et al., 2021). Carbon neutrality, or the removal of carbon dioxide from the atmosphere equal to the amount of carbon dioxide emitted, may become the primary environmental objective of the twenty-first century. Carbon neutrality also refers to balancing the produced carbon dioxide (CO_2) through carbon collection, storage, and conversion within a specific time frame. Increase in carbon emissions and other greenhouse gases thus forced many countries to achieve a certain level of carbon neutrality (Liu et al., 2022).

In 2020, the United Nations Secretary General urged all governments to "declare a climate emergency in their nations until carbon neutrality is achieved". At the end of 2050, at least more than a hundred countries have committed to achieve the carbon neutrality targets and commitments and later these number is escalated to more than one hundred and fifty countries (Chen et al., 2022). Keeping this progress in view, remaining countries are also expected to follow this trend soon.

A key to achieve sustainable and environmentally friendly growth and development is known as "green growth". It is important to focus on to achieve the win-win status in terms of environment and economic growth, so that economic growth should not be achieved on the

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expenses of environment. Therefore, it is important to concentrate the “green growth” rather than to focus on the traditional concept of GDP. To achieve the targets of carbon neutrality, many governments around the globe are trying to achieve the sustainable green growth. Green growth can also be achieved by concentrating on clean energy production by introducing technological innovations in the arena of energy and energy related production (Chien et al., 2021a,b). Low carbon emissions can also be the result of the effective production of energy and the preservation of natural resources. Green growth is a common method for reducing carbon emissions and saving energy that is employed to manage environmental deterioration (Sandberg et al., 2019). To achieve carbon neutrality targets, low carbon emissions and green growth production, the elevation and upgradation of green technological innovations are some essential ingredients (Kunapatarawong and Martínez-Ros, 2016).

Economic growth may be threatened by deteriorating environmental conditions or the loss of natural resources as there is a trade-off between economic growth and environmental sustainability. Researchers are of the opinion that increase in agricultural production is determinant of environmental degradation. Over the years China has made remarkable socio-economic progress in agricultural science and technology, but different socio-economic and environmental challenges are the main obstacles in the way of this development (Chadwick et al., 2020; Shen et al., 2020). Agricultural Eco-Efficiency (AEE) is a crucial measure to determine how the goals of sustainable economic growth and development are achieved in combination with the goals of sustainable environment (Czyżewski et al., 2019). AEE measures the ratio between material factor inputs and maximum achievable agricultural output with combination of minimum consumption and environmental resources (Pang et al., 2016). This measure considers the combined influence of agricultural production, environmental goals and the ratio between economic output and resource input. Researchers have attempted to quantify this measure in many countries including China. To meet the agricultural demands with lesser pollution emissions, measuring AEE is a helpful indicator, which in turn, helps to promote the sustainable agricultural goals (Baum and Bieńkowski, 2020). Consequently, the study of agricultural eco-efficiency in relation to carbon neutral is crucial (Morea and Gebennini, 2021).

Green technological innovations play an important role to improve the agricultural production over a period of time. Each nation pays increasingly more attention to green technological innovation for the sustainable development by maintaining resources and energy conservation, reducing environmental pollution, and prevent ecological destruction. Green technological innovation reduces carbon emissions (Obobisa et al., 2022), indirectly through upgradation in industrial structure over a period of time (Lin and Ma, 2022).

Trade expansion due to globalization has played an essential role in increased carbon emissions and the reduction in the level of environmental sustainability. Therefore, trade openness has been continuously evaluated in environmental economics and socio-economic development nexus and it is found to have significant impact on environmental degradation. Moreover, trade openness is also found to be a major determinant of globalization besides technological innovations and their transfer among countries (Zahra et al., 2022a,b). The effects of trade openness on carbon emissions are not obvious, with some studies concluding that trade simply permits the transfer of products that generate high pollution levels to other nations, hindering the development of cleaner methods and green production. On the contrary, trade openness also multiplies economic growth which may further be used to improve the efforts for environmental sustainability in future over all development process (Shahbaz et al., 2017).

This study aims to investigate the impact of green growth on carbon emissions along with other determining factors such as green technological innovations, agricultural eco-efficiency and trade openness to determine their role in achieving the target of carbon neutrality in the top three carbon emitting countries, namely, China, the USA and India. Fig. 1 shows carbon emissions of top three carbon emissions countries as compared to the carbon emissions from the whole world. These three countries are selected in this study for the following reasons. China, the USA and India emit carbon into environment more than the whole world alone and is more than double the level of carbon emissions from all G-7 countries combined (Wang et al., 2020). Their emissions originate from different sources that are industrial production in China (Liu et al., 2024), transportation and energy consumption in the USA (Zahoor et al., 2023; Zahra and Badeeb, 2022), and population-driven activities in India. Addressing emissions in these countries has a disproportionately large impact on global efforts to combat climate change and to achieve target of carbon neutrality. India, the third-largest emitter, accounts for approximately 9% of global carbon emissions and relies mainly on coal for energy, combined with agricultural and industrial growth, are key contributors to its emissions. Despite developmental challenges, India has set ambitious targets, including achieving 50% renewable energy capacity by 2030 and carbon neutrality target by 2070.

The USA and China are the two countries who are focusing to

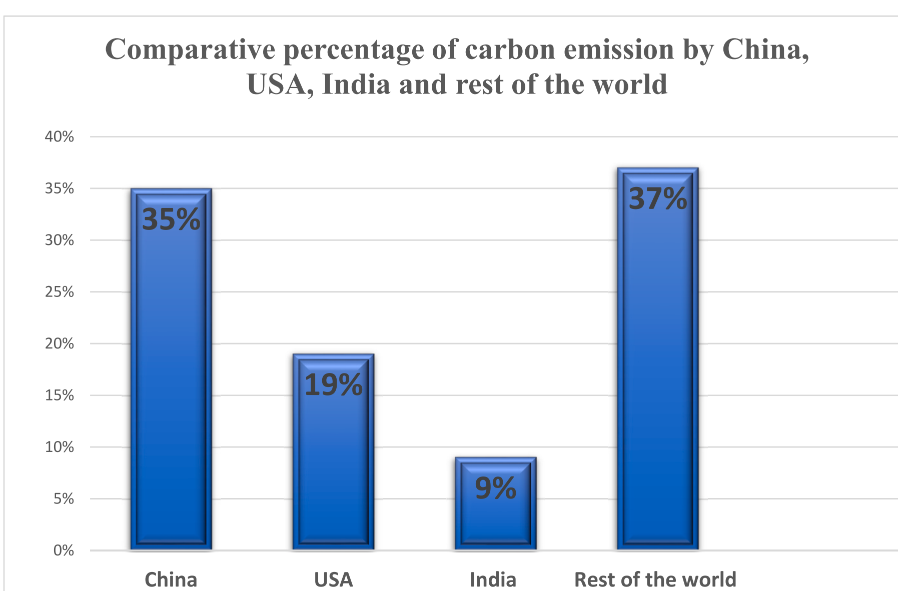

Fig. 1. World development indicator (2020).

generate the renewable energy in efforts to achieve the targets of carbon neutrality and green growth. The USA and China are both making progress in green growth, but they are doing so at different rates and in different ways (Saqib and Usman, 2023). China is heavily investing in clean energy technologies or green technological innovation, including solar, wind, and electric vehicles. 35% of electricity in China has been generated from renewable energy resources with more than 16% of energy from wind and solar energy heads in 2023. The government of China has legislated policies to reduce reliance on fossil fuels to smooth the way towards green growth transition. However, the green growth transition in China faces different challenges which include renewable energy transition, economic growth along with sustainable in global trade competition. On the other hand, US has also made a significance progress to advance environmental technology including renewable energy transition, smart grid system and waste management. US has also imposed tariffs on China green trade goods including EVs, lithium-ion batteries (a key component of renewable energy storage system) and solar cells to strengthen the domestic green technological production (Saqib and Usman, 2023). As far as the case of SDGs is concerned, both USA and China has made significant improvement to achieve the these goals (Biggeri et al., 2023), however, there is a lot of transition towards green growth is required to meet the target of carbon neutrality within the set timeframes. India, while facing developmental constraints, has set ambitious renewable energy targets, aiming for 50% of its energy capacity to come from non-fossil sources by 2030 (Pathak and Deshkar, 2023). These efforts reflect the commitment of these nations to green growth and achieving carbon neutrality goals. China and the USA are in the list of top three countries of the world who are focusing on increasing agricultural eco-efficiency by research and technology (Wang et al., 2022). India, as an agrarian economy, is also taking steps to integrate sustainable agricultural practices (Baig et al., 2023). Understanding the role of agricultural eco-efficiency in reducing emissions in these nations can provide actionable insights for other countries with significant agricultural sectors.

In 2020, these three countries accounts for more than 60% carbon emissions which effects the global environment as a whole (Ahmed and Shuai, 2022; World Bank, 2020). Lastly, as these three countries have non-homogenous characteristics, thus they contribute a big deal in the efforts of designing the relevant policies for sustainable development and alleviating environmental degradation. There is a trade-off between economic growth and environmental sustainability, necessitating the acceleration of environmentally efficient economic growth. Identifying synergies between economic and environmental objectives is crucial to minimize environmental degradation. Therefore, focusing on growth strategies that foster a positive relationship between the economy and environment is essential. By examining the interplay between green growth, green technological innovations, and agricultural eco-efficiency in China, the USA, and India, this study fills a critical gap in understanding how top emitters can transition toward sustainable and carbon neutral ecosystems. The findings are expected to inform not only their domestic policies, but also global strategies aimed to achieve the target of carbon neutrality. To our knowledge no study has empirically investigated the impact of green growth to achieve the target of carbon neutrality especially with reference to agricultural eco-efficiency, green innovations, and trade openness in top three carbon emitters of the world.

2. Literature review

The interest in environmental and climate change issues has grown during the past few years. The idea of carbon neutrality is one strategy to address climate change and environmental problems. The green energy efficiency, green construction, green technology, and other environmentally friendly agricultural production are considered the primary objectives among others to achieve the environmental goals. Therefore, achieving the goal of carbon neutrality is an appealing idea but to accept the personal responsibility at individual level to reduce the carbon footprint in daily life has the core importance to achieve this goal. Carbon neutrality is frequently portrayed as an opportunity to contribute to a solution rather than focusing on the dire consequences of the inevitable issues by global warming and climate change (Pata et al., 2023a,b). There is little research on green growth despite the strong correlation between economic growth and green growth. We discuss studies that may seem distinctly different but are related to the environment and its impact on green growth considering the lack of literature on this topic.

2.1. *Green growth and carbon neutrality*

The relationship between economic growth and carbon emissions has been investigated many times in different countries especially with reference to EKC, but these studies have presented the contradictory results in different scenarios, in different regions and countries. Some studies regarded economic growth as positive determinant of carbon emissions and some other are investigated the exact opposite results. On the other hand, some studies also found the nonlinear relationship between economic growth and carbon emissions (Ongan et al., 2021). These conflicting results about the role of economic growth in environmental sustainability has extended researchers' attention towards green growth instead of traditional economic growth. Green growth is not only helpful for environmental sustainability but also has the ability to defend the environment from negative externalities (Ahmed et al., 2022). Alam and Kabir (2013) discover that a rise in economic expansion helps to protect the environment by lowering carbon emissions. To promote environmental sustainability, the author advocates combining measures for eco-efficiency and environmental sustainability. Hao et al. (2021) also advocate that there is negative relationship between multi environmental adjusted green production and environmental degradation. Chien et al. (2021) also empirically analysed the negative relationship between environmental degradation and green growth in the USA for time span between 1970 and 2015 by applying QARDL model. On the contrary, Mikayilov et al. (2018) for Azerbaijan empirically determine the positive relationship between green growth and environmental degradation and thus found no EKC in the country. According to the authors, investments in clean technology, efficient energy use, and the promotion of labour standards are all effective ways to reduce emissions and thus promote green growth. Ardakani and Seyedaliakbar (2019) claim that if economic growth is below the turning point, carbon emissions may increase, but if it is above the turning point, environmental quality is improving, and thus economic growth has become green growth.

2.2. *Green technological innovation and carbon neutrality*

Green technology advancement has long been seen to have a significant impact on both environmental pollution and economic development (Chege and Wang, 2020; Chen and Lee, 2020; Wang and Zhu, 2020; Zhao et al., 2021). Research regarded green technological innovation as the most precise tool not only to achieve the environmental targets but also to promote renewable energy production (Rehman et al., 2024) which will ultimately lead to green growth and environmental sustainability (Ulucak, 2021).

Green technical innovation and spillover give emerging nations great chances for economic progress (Ilkay et al., 2021). Green technological Innovations also draw the positive impact on green growth. By increasing business production efficiency, technological innovation can lower product costs, hence increasing consumer demand and promoting economic growth. (Nosheen et al., 2021). Moreover, green technological innovations can be used to break the resource curse and thus helps to achieve the green growth to boost green economy (Tian et al., 2021). Technology innovation and financial development are significant variables influencing economic growth (Gao et al., 2021), thus resource use

(Zhang et al., 2021), contamination of the environment (Pata and Naimoglu, 2024), and economic expansion are closely related (Anser et al., 2020). Similarly, Meirun et al. (2021) for Singapore by applying Quantile Autoregressive Distributed Lag (QARDL) model between time span 1990 and 2018 in both short run and long run, Hsu et al. (2021) for China between 2000 and 2018 by applying Ordinary Least Square (OLS) for 20 different Chinese provinces, Anwar and Malik (2021) for G7 countries and Guo et al. (2021) by applying Augmented Mean Group (AMG) and Cross-Sectionally Augmented Autoregressive Distributed Lags (CS-ARDL) for Chinese provincial and regional data for time span between 1995 and 2017 empirically investigated that increase in green technological innovations over a specified time period causes reduction in carbon emissions and helps to achieve the target of carbon neutrality. Similarly, Bilal et al. (2021) empirically investigated the negative relationship between green technological innovations and carbon emissions for OBOR. Obobisa et al. (2022) by applying Augmented Mean Group (AMG) and Common Correlated Effects Mean Group (CCEMG) for 25 African countries for period of 18 years empirically determine that green technological innovations are negative determinant of carbon emissions.

However, there is contradiction in the empirical results about the relationship between green technological innovations and environmental sustainability. Khattak et al. (2020) suggest that the role of green technological innovations is not the same in all countries. According to them, it increases environmental degradation in India, China, Russia and South Africa whereas vice versa in Brazil. Du et al. (2019) empirically determine that green technological innovations is not a significant variable of environmental quality in less developed countries but it plays crucial role to reduce environmental degradation in developed countries. Erdoğan et al. (2020) consider green technological innovation in building sector as increasing determinant of carbon emissions and thus aggravate environmental quality.

2.3. Agricultural eco-efficiency and carbon neutrality

The growing recognition of the need for sustainable agricultural practices has led to increased interest in understanding how agricultural ecoefficiency can contribute to mitigate environmental degradation. The nexus between agricultural ecoefficiency and carbon neutrality refers to the complex and interconnected relationship between agricultural productivity, resource use efficiency, and the resulting environmental impact. Agricultural ecoefficiency aims to optimize the use of resources such as land, water, energy and inputs while minimizing negative environmental externalities, including pollution, soil degradation, water scarcity and biodiversity loss. The term "eco-efficiency" was first used in the 1970s to refer to environmental efficiency (Freeman III et al., 1973). But after 2010 it has been directly applied to agriculture as agricultural eco-efficiency (Keating et al., 2010). Eco-efficiency is a term that refers to the environmental and economic aspects of sustainable agriculture (Caiado et al., 2017). Most studies show that wealthy nations with an intense agriculture sector produce higher gross value added in their agricultural sectors with lower levels of input and are more eco-efficient (Pata et al., 2023a,b). However, being eco-efficient does not automatically equate to being environmentally sustainable (Czyżewski et al., 2019). Thus, There is evidence that farms' pro-ecological and sustainable orientations are impacted by their involvement in agri-environmental programs (Bonfiglio et al., 2017). In China, greenhouse gas emissions from agricultural output, which are frequently calculated using carbon emissions, account for 17% of all emissions, but just 7% of emissions in the US and 11% worldwide (Yang et al., 2022). Therefore; the most common and significant goals of agriculture is to achieve sustainable development and environmental sustainability (Grzelak et al., 2019). Caiado et al. (2017) advocates that agricultural sector is one of the notable one to which the concept of ecoefficiency is applied. Many researchers such as Apergis et al. (2015) and Walheer (2018) consider agricultural ecoefficiency as main determinant to further degrade the environmental quality and sustainability. Yang et al. (2022) also empirically tested the role of agricultural ecoefficiency and mention that this role has been drastically changed since recent decades because of new agricultural technology. Thus, per unit agricultural production damage to environment must be considered to achieve the targets of carbon neutrality in long run.

2.4. Trade openness and carbon neutrality

The relationship between trade openness and carbon neutrality is a subject of considerable research and debate. While trade openness can bring economic benefits such as increase in economic growth and access to international markets (Keho, 2017) but it can also have environmental consequences (Zahra et al., 2022a,b). Empirical studies on the relationship between trade openness and environmental degradation have produced the mix results. Some studies such as Tachie et al. (2020), Cole (2004) and Solarin et al. (2017) have supported the "Pollution Haven Hypothesis" suggesting that there is positive association between trade openness and carbon emissions. However other studies such as Frankel and Rose (2005) show a negative relationship, suggesting that trade openness can contribute to environmental sustainability and thus can help to achieve the target of carbon neutrality through technological advancement and cleaner production. However, some studies also show no significant relationship between trade openness and environmental degradation such as Salam and Xu (2022) empirically determine that trade openness has no significance influence on environmental degradation between BRI (Belt and Road Initiative) countries and China.

Mahmood et al. (2019) for Tunisia, Jun et al. (2020) for China, Le et al. (2016) for 98 countries of the world, Lv and Xu (2019) for 55 middle income countries, Shahbaz et al. (2017) for total 105 countries which are divided in to three sub categories as low, middle and high income countries, Munir and Ameer (2018) for 11 Asian emerging countries that are Bangladesh, Hong.

Kong, India, Indonesia, Iran, Malaysia, Pakistan, Philippines, Singapore, Sri Lanka and Thailand for time span between 1980 and 2014, Zameer et al. (2020) for India and Zhang (2018) for South Korea empirically determine that trade openness in respective areas is major determinant to boost the level of carbon emissions and thus has become the main source to aggravate the environmental degradation in long run. Amin et al. (2020) also determine that trade openness plays crucial role in increasing carbon emissions and thus may lead to deteriorate the environmental sustainability in long run.

To summarize, from the literature review of this section we identified the following four determinants of carbon neutrality, namely, green growth, green technological innovation, agricultural eco-efficiency, and trade openness. All of them have different impact on carbon emissions in different scenario and different conditions. In the following section, we use this information in modelling the carbon neutrality.

3. Theoretical framework and methodology

3.1. Theoretical framework

This study aims to investigate the impact of green growth, green technological innovations, agricultural eco-efficiency, and trade openness on carbon emissions as an endogenous variable to determine their role to achieve the target of carbon neutrality. The theoretical framework of this study is rooted in significant economic-social and environmental theories. The concept of growth should not be solely measured by financial gains but it should also considered social and environmental aspects (Elkington, 1997). The theoretical framework of green growth revolve around three P's approach that is Profit (economic aspect), People (social aspect) and Planet (environmental aspects) (Zahra and Fatima, 2024). Environmental Kuznets Curve theory investigated an inverted U-shaped relationship between economic growth and environmental degradation (Grossman, 1991). However, there is controversy among the researchers about the outcomes of EKC in different scenarios. For example, Li et al. (2023) noted an N shaped association in high income countries, an inverted U shaped pattern in upper middle income countries and U shaped in low income countries. Therefore, there is need to transfer the concentration to focus on increase in green growth rather than GDP (Zahra and Fatima, 2024). This study also incorporates green technological innovations as determinant to achieve the carbon neutrality. It plays a crucial role for green growth transition along with EKC by enhancing cleaner production and energy efficiency (Dinda, 2004). Thus "Jevons Paradox" determines the "Rebound Effect" which is considered as side effect of technological efficiency and advancement that can lead to increase in consumption or supply of resources, thus increases carbon emissions. This highlights the potential for "Rebound Effect" where efficiency gains from green technology could increase in consumption, offsetting carbon emissions reduction (Sorrell et al., 2009). The EKC hypothesis suggests that environmental degradation initially increases with economic and agricultural growth but decreases beyond a threshold as eco-efficiency improves (Grossman, 1991). This theory suggests that at low eco-efficiency levels, agricultural expansion often relies on high carbon intensive inputs but as eco-efficiency improves, better management practices, precise agricultural techniques and green technological innovations reduce carbon emissions per unit of agricultural output (Yang et al., 2022).

Although there is limited literature that explains the concept of green economic growth, different measures such as green growth index and green growth efficiency are used as proxies for green growth (Bagheri et al., 2018; Lin and Benjamin, 2017). This study uses Triple Bottom Line Approach (TBL) to provide the theoretical framework to select the proxy of green growth variable. This approach proposed by Elkington (1997), is a holistic approach that takes into account the social, economic and environmental perspectives of development. Elkington (1997) emphasizes that growth (at micro level) should not be solely measured by financial gains, but it should also consider social and environmental impact. This approach revolves around interconnected three dimensions, that are economic aspect (profit), social aspect (people) and environmental aspect (planet). Similarly, in this sphere the importance of SDGs by the UN (2015) cannot be ignored which aims to achieve target of low carbon economy, resilient society, ecosystem health and sustainable economic growth. Appendix 1 shows the interconnection of all aspects which are used to calculate the green growth index, while Table 1 shows main components of green growth index which is divided into four domains, namely, "Efficient and Sustainable Resource Use", "Natural Capital Protection", "Green Economy" and "Social Inclusion" each of these domains are further divided into sub indicators. Fig. 2 represents the interconnections of these domains for resilient society and low carbon economy.

Table 1
Indicators of green growth index.

Domains of green growth index (D)	Indicators of green growth index (I)
D1: Efficient and sustainable resource use	I1: Green energy
	I2: Efficient and sustainable use of water
	I3: Green (sustainable) land use
	I4: Efficiency of material use
D2: Natural capital protection	I5: Sustainable environnement/ environnemental quality
	I6: Greenhouse gas reduction
	I7: Protection of biodiversity and ecosystem
	I8: Cultural and social values
D3: Green Economy	I9: Green Investment
	I10: Green trade
	I11: Green employment
	I12: Green Innovation
D4: Social Inclusion	I13: Basic goods and services access
	I14: Gender equality
	I15: Social equality and equity
	I16: Social protection

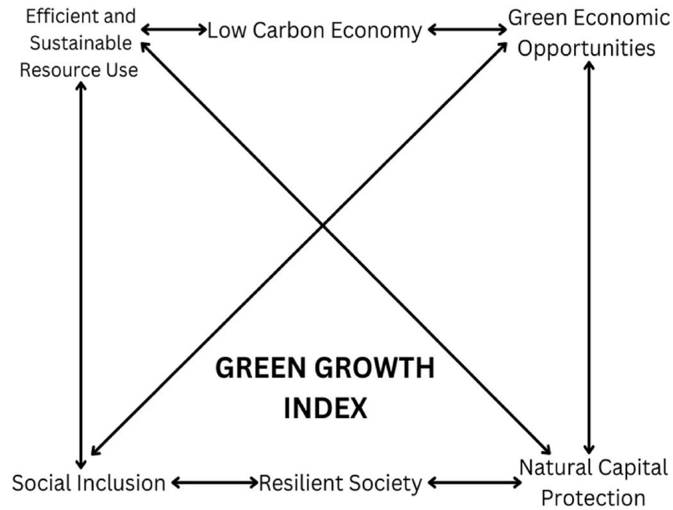

Fig. 2. Interconnection of green growth index variables.

3.2. The model

Based on the above review, we propose carbon neutrality (CN) as a function of the following variables, namely (1) Green Growth (GG), (2) Green Innovation (GI), (3) Agricultural Eco-Efficiency (AEE) and (4) Trade Openness (TO).

$$CN = f(GG, GI, AEE, TO) \tag{1}$$

We specify the functional form 1 similar to a Cobb Douglas production function in the following form:

$$CN = e^{\beta_0}\ GG^{\beta_1}\ GI^{\beta_2}\ AEE^{\beta_3}\ TO^{\beta_4} e^{\mu} \tag{2}$$

We linearize the above function by taking the natural logarithm on both sides of Equation (2), with country and time subscript added to give:

$$lCN_{it} = \beta_0 + \beta_1 lGG_{it} + \beta_2 lGI_{it} + \beta_3 lAEE_{it} + \beta_4\ lTO_{it} + \mu_{it} \tag{3}$$

where subscripts i and t refer to country and time, respectively and l refers to natural logarithm and μ_{it} is the stochastic disturbance term.

The literature review presented above also reveals the possibility of non-linear relationships, also known as EKC hypothesis between carbon neutrality (CN) and green growth index (GG), carbon neutrality and green technological innovation (GI), and carbon neutrality and agricultural eco-efficiency (AEE). Consequently, a non-linear relationship of the following form is used for the empirical estimation and further investigate the functional form of the relationship:

$$lCN_{it} = \beta_0 + \beta_{11} lGG_{it} + \beta_{12}(lGG_{it})^2 + \beta_{21} lGI_{it} + \beta_{22}(lGI_{it})^2 + \beta_{31} lAEE_{it} + \beta_{32}(lAEE_{it})^2 + \beta_4\ lTO_{it} + \mu_{it} \tag{4}$$

Where $(lGG_{it})^2$ is the square of log of green growth index (lGG_{it}), $(lGI_{it})^2$ is the square of log of green technological innovation (lGG_{it}), and $(lAEE_{it})^2$ is the square of log of agricultural ecoefficiency (lGG_{it}), of a country i at time period t.

In general, the main advantage of using quantile regression for estimation is that the method allows for understanding relationships between variables outside of the mean of the data that are non-normally distributed and that have nonlinear relationships with predictor variables. Instead of estimating the model with average effects using the OLS linear model, the quantile regression produces different effects along the distribution (quantiles) of the dependent variable (Le Cook and Manning, 2013; Uribe et al., 2020) Considering the non-linear relationships between the dependent variable (carbon neutrality, CN) and the independent variables (IGG, IGI and IAEE) by taking the whole distribution into account, quantile regression analysis is the more suitable technique for this study as well. The quantile regression enables us to study the relationship between CN and IGG, IGI and IAEE not only at the centre but also alongside the entire conditional distribution of dependent variable CN. Quantile regression is a way to find what factor influences the magnitude of the response in those points of the data which are located far from the central value and that are not necessarily found in the symmetric positions with respect to the mean. There are a number of advantages in using the quantile regression approach. Firstly, quantile regression methodology allows the understanding of relationship between outside of the mean of the data, making it useful in understanding outcomes that are non-normally distributed and that have non-linear relationship with independent variables (Le Cook, 2013). Secondly, in case of heterogeneity, the quantile approach gives a more robust picture for environmental effects because each determinant can have different impact over the distribution. Thirdly, the quantile regression shows the variation among low, moderate, and high impact of carbon determinants on carbon emissions, thus enhances the understanding of what triggers the heterogenous response, and which determinant is a valuable factor for policymakers.

The empirical analysis of this study is carried out at two level by; (1) pooling the data across three countries and estimating a panel quantile regression, and (2) using individual country data and estimate quantile regression model for each of the three countries. The first step in the panel model estimation is to test each time series for cross-sectional independence, stationarity and heterogeneity. Then panel quantile regression model is applied to investigate the role of selected variables to achieve the target of carbon neutrality in four different quantiles in quadratic model.

After pool model estimation, quantile regression is applied to each country separately. The single country analysis will provide an in-depth analysis of the relationship between dependent and independent variables under consideration in each country separately, which are very useful for policy decision making at individual country level (Selvanathan et al., 2023).

4. Data source, empirical results and discussion

We use annual time series data for the three countries, China, the USA, and India during the period of 2010–2022. The period from 2010 to 2022 was chosen for this study based on the availability of consistent and reliable data for the key variables across the countries included in the analysis. This timeframe also coincides with significant global policy shifts towards sustainability and carbon neutrality, as many countries introduced more rigorous environmental policies and green technological innovations during this period. Additionally, the 2010–2022 span ensures consistency in data availability, as earlier years had notable gaps or less reliable data especially for green growth, which would have compromised the robustness of the analysis. This period allows for a comprehensive assessment of the relationships between green growth, technological innovation, agricultural eco-efficiency, trade openness, and carbon emissions. Following Zahra and Badeeb (2022) the annual data series has been converted to quarterly timeseries data by using quadratic match sum method. Converting the data from low frequency to high frequency by using quadratic match sum approach is a recommended and widely accepted technique which helps to reduce variations in the data and thus solves the problem of seasonal variations (Cheng et al., 2012; Faisal et al., 2018; Türsoy and Faisal, 2018). The data for Carbon Neutrality (CN, CO2 emissions in kilotons), Agricultural Eco-Efficiency (AEE, Ratio of total agricultural production to total agricultural carbon emissions), Trade Openness (TO, Ratio of Imports and Exports of goods and services to GDP, all in constant 2015 US$) are taken from World Development Indicators (WDI) and data for Green Technological Innovation (number of green technological patents) is taken from OECD (OECD database), and data for Green Growth Index (GG) has been taken from Global Green Growth Institute (GGGI). Table 2 presents the definition and sources of the data. The green growth index basically evaluates the performance of a country to achieve the targets of sustainability by incorporating four domains of sustainability which are described in Table 1 in detail.

4.1. Panel estimation

Table 3 shows descriptive statistics of the panel model. The probability values show that the panel distribution is not normal, therefore, quantile regression is one of the suggested methods to apply for such distribution (L. Zheng et al., 2023).

Before we formally perform panel data estimation, we need to carry out panel unit root tests on the model variables to determine stationary and the order of integration of each variable. To select the appropriate panel unit root tests, we also need to investigate the presence or lack of cross-sectional dependency in the panel.

4.2. Cross-sectional dependence test

The null hypothesis for cross-sectional panel dependence test assumes that the series within themselves are cross sectional independent whereas the alternate hypothesis supposes cross-sectional dependency. Table 4 presents the test results for various cross-sectional dependency tests, namely, Breusch-Pagan LM, Pesaran Scaled LM, Bias-Corrected Scaled LM and Pesaran CD. The results show that the null hypothesis of cross-sectional independence should be rejected at the 1% level of significance, indicating cross sectional dependency of the variables. Based on presence of cross-sectional dependency in the data, the second-generation unit root tests are employed to check the stationarity of the variable.

4.3. Test for homogeneity

Table 5 presents the Pesaran and Yamagata (2008) test results to determine if the coefficients were homogenous, where the null hypothesis for this test is coefficients are homogenous. As can be seen that the null hypothesis of homogeneity in the slope coefficients were rejected. Based on this finding, econometric techniques that are resilient to slope heterogeneity were employed for the analysis.

4.4. Second generation unit root tests

Before we formally perform the econometric analysis, we need to carry out unit root tests on the model variables to determine the order of integration. Estimation of the model in the presence of unit roots will give spurious results thus may lead to misleading coefficient estimates (Granger and Newbold, 1974). Based on presence of cross-sectional dependency in the data and the slope coefficients are heterogenous across cross-sections, the second-generation unit root tests are employed to check the stationarity of the data. Table 6 presents unit root tests results using Pesaran-CIPS and Pesaran-CADF tests. As can be seen that all the panel variables are stationary in their level form.

Table 2
Data description and sources of data.

Symbols	Variables	Units	Sources
CN	Carbon Neutrality	CO2 emissions in kilotons	WDI
GG	Green Growth	An index	GGGI
GI	Green Technological Innovations	Number of green technological patents	OECD
AEE	Agricultural Eco-efficiency	A ratio of total agricultural production to total agricultural carbon emissions	WDI
TO	Trade Openness	Ratio of Imports and Exports of goods and services to GDP, all in constant 2015 US$	WDI

Table 3
Descriptive statistics.

Panel Model					
Mean	1,454,686	13.70	2.50	198.31	9.35
Median	123,796	14.70	2.40	141.88	9.20
Std. Dev.	851,417.8	2.10	0.35	102.83	2.35
Skewness	0.46	−1.78	0.63	0.89	0.39
Kurtosis	1.73	9.54	2.24	2.13	2.06
Jarque-Bera	15.90	360.80	13.91	25.29	9.80
Probability	0.00	0.00	0.00	0.00	0.00

Source: Authors' calculations.

Table 4
Cross sectional dependence test results.

Variables	Tests			
	Breusch-Pagan LM	Pesaran Scaled LM	Bias-Corrected Scaled LM	Pesaran CD
lCN	129. 37*** (0.0)	51.59*** (0.0)	51.56*** (0.0)	−3.61*** (0.0)
lGG	50.81*** (0.0)	19.52*** (0.0)	19.49*** (0.0)	6.30*** (0.0)
lGG²	56.15*** (0.0)	21.70*** (0.0)	21.67*** (0.0)	6.90*** (0.0)
lGI	53.75*** (0.0)	20.72*** (0.0)	20.70*** (0.0)	6.20*** (0.0)
lGI²	55.78*** (0.0)	21.51*** (0.0)	21.52*** (0.0)	6.49*** (0.0)
lAEE	140.85*** (0.0)	56.28*** (0.0)	56.25*** (0.0)	11.87*** (0.0)
lAEE²	141.41*** (0.0)	56.51*** (0.0)	56.48*** (0.0)	11.89*** (0.0)
lTO	133.66*** (0.0)	53.34*** (0.0)	53.31*** (0.0)	11.55*** (0.0)

***, **, *represent 1%,5% and 10% level of significance respectively (p-values are in parentheses).

Table 5
Pesaran-Yamagata homogeneity tests.

	Test statistics
Δ	17.95*** (0.0)
Δ Adj	19.74*** (0.0)

***, **, * represent 1%,5% and 10% level of significance respectively (p-values in parentheses).

4.5. Quantile panel regression

In the next step, we apply the panel quantile regression to determine the response of independent variables to the carbon emissions in the panel dataset formed by pooling data across the three countries. We then estimate Equation (4) (the quadratic model), where the green growth, green technological innovation and agricultural ecoefficiency variables are in quadratic form. Table 7 presents the results of panel quantile regression for Equation (4) in four selected quantiles, namely, $Q_{0.25}$, $Q_{0.50}$, $Q_{0.75}$ and $Q_{0.90}$ respectively. Fig. 3 is the graphical presentation of the quantile process of each estimated coefficient which shows the quantile trends of the carbon emissions and its determinant over a period of time. These results are discussed below:

The results presented in Table 7 reveal that green growth (GG) has a significant U-shaped relationship with carbon emissions, indicating that when green growth increases, the rate of carbon emissions continues to decline up to threshold (turning point) of 1.2 units (in log) approximately and starts to increase thereafter. Such nonlinear relationship between green growth and carbon emissions is also supported by existing literature (see, for example, Hao et al. (2021), Dong et al. (2022), Gu et al. (2023) and S. Zheng et al. (2023). Some studies (for example, see, Hickel and Kallis (2020) do not recommend promoting green growth to reduce carbon emissions in long run. Such studies recommend government should consider alternative approaches to reduce carbon emissions than prevailing green growth concepts as this is probably unwise goal to focus on. The concept of green growth based on the assumption that an absolute decoupling of GDP growth from resource utilization and carbon emissions is practical and feasible (Solow, 1973), but Hickel and Kallis (2020) recommended that it is exceedingly doubtful that complete decoupling from carbon emissions would occur at a fast enough rate to stop global warming even under optimistic policy conditions. The existing literature supports this positive association between green growth and caron emissions (see, for example, Gazheli et al. (2016), X. Zhao et al. (2023), De Haas and Popov (2023) and Mikayilov et al. (2018). At initial stage of green growth

Table 6
CIPS and CADF unit root tests.

Variables	CIPS Unit Root Test	CADF Unit Root Test	Conclusion
lCN	−2.46** (<0.05)	−2.64** (0.05)	I (0)
lGG	−2.65*** (<0.01)	−2.81** (0.03)	I (0)
lGG²	−2.86 (<0.01)	−2.79 (0.03)	I (0)
lGI	2.74*** (<0.01)	−2.98** (0.02)	I (0)
lGI²	−2.70 (<0.01)	−3.18 (0.0)	I (0)
lAEE	−2.98*** (<0.1)	−2.62* (0.06)	I (0)
lAEE²	−2.23 (<0.1)	−2.67 (0.05)	I (0)
lTO	−2.76*** (<0.01)	−2.98** (0.02)	I (0)

***, **, * represent 1%,5% and 10% level of significance respectively (p-value are in parentheses).

Table 7
Results of panel quantile regression (quadratic model).

Variables	Quantiles			
	$Q_{0.25}$	$Q_{0.50}$	$Q_{0.75}$	$Q_{0.90}$
lGG	−2.42*** (0.0)	−2.52*** (0.0)	−2.51*** (0.0)	−2.49*** (0.0)
lGG²	0.92*** (0.0)	1.05*** (0.0)	1.06*** (0.0)	1.06*** (0.0)
Turning Point lGG	1.32	1.20	1.18	1.17
lGI	−2.51* (0.10)	−4.40*** (0.0)	−5.40*** (0.0)	−5.61*** (0.0)
lGI²	1.59* (0.08)	2.58*** (0.0)	3.23*** (0.0)	3.34*** (0.0)
Turning Point lGI	0.79	0.86	0.84	0.84
lAEE	2.96 (0.15)	0.35 (0.76)	0.76 (0.22)	0.31 (0.3)
lAEE²	−0.19 (0.31)	0.05 (0.67)	0.07 (0.90)	0.05 (0.11)
Turning Point lAEE	7.79	−3.50	−5.40	−3.10
lTO	0.19 (0.14)	0.46*** (0.0)	0.49*** (0.0)	0.51*** (0.0)
Constant	3.79 (0.47)	11.08*** (0.0)	10.33*** (0.0)	11.59*** (0.0)
Pseudo- R^2	0.89	0.90	0.92	0.92

Note: The quantile regression results highlight significant variability across different quantiles, indicating heterogeneous effects of the independent variables on the dependent variable. These findings underscore the importance of considering the entire distribution of the dependent variable, rather than focusing solely on the mean.
***, **, *represent 1%,5% and 10% level of significance respectively (p-values are in parentheses).

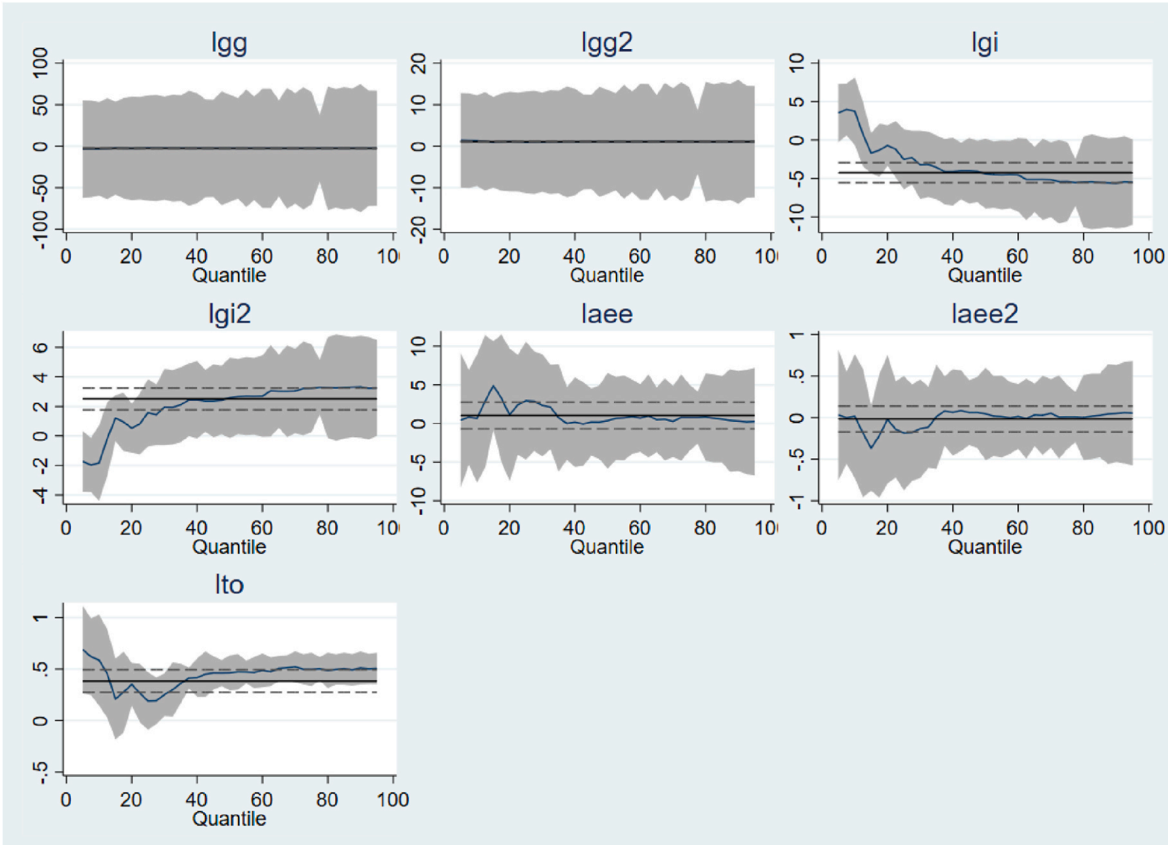

Fig. 3. Graphical presentation of panel quantile regression coefficients (quadratic Model).

transition the focus is on cleaner technologies, renewable energy transition, energy efficient practices and investment in green infrastructure. Green growth transition also enhances green energy transition, energy efficiency and strict environmental regulations to encourage green economic activities (Hao et al., 2021). The turning point represents diminishing returns on carbon emissions, and it reaches at the lowest point at U-shaped curve. After turning point carbon emissions begins to increase and reaches to resource-intensive growth which means that increase in economic growth at particular point requires significant resources depletion, which will increase carbon emissions (Huo and Peng, 2023). This phase is also called "Rebound Effect" of relationship between green growth and carbon emissions. Thus, this U-shaped relationship is divided into scale, composition and technique effects. The first stage that has also "Technique Effect" suggests that adoption of green growth techniques improves efficiency and reduces carbon emissions, which lead to initial downward trend (Mohapatra et al., 2016). After turning point, the scale and composition effects occur. This phase suggests that as green growth scale-up, carbon emissions increase due to the higher production and carbon intensity and changes in economic composition, such as shift towards green technology production can also increases carbon emissions (Liobikienė and Butkus, 2019). Thus, the impact of the green growth on carbon mission is complex, with green growth not always leading to significant emissions reduction (J. Zhao et al., 2023).

The results also reveal that green technological innovations (GI) also have a significant U-shaped relationship indicating that with increase in green technological innovations, the rate of carbon emissions continues to decline up to turning point of 0.8 units (in log) approximately and starts to increase afterwards. This U-shaped relationship between green technological innovation and carbon emissions is also supported by existing literature, (for example, see, Alnafisah et al. (2024), Chen et al. (2023)). Generally, the literature on the relationship between green technological innovation and carbon emissions is mixed. Some studies regarded the relationship as a negative while in certain scenario green technological innovations may also cause an increase in carbon emissions. This phenomenon is regarded as "Rebound Effect" or "Jevons Paradox". Chien, Anwar, et al. (2021) is in favour of "Rebound Effect", and reported that technological innovation further mitigates the carbon emissions after surpassing a threshold. This "Rebound Effect" can further be divided into three main categories, where the green innovations may further enhance the environmental degradation. The first one is called "Direct Rebound" where the green techniques reduces the cost of resources which may further increase the resource utilization, thus cause the increase in carbon emissions (Hanley et al., 2009). The second one is called "Indirect Rebound" which leads to increase in resource consumption when the cost savings from green innovations spill over into over consumption of other goods and services. For example, Greening et al. (2000) explains how reduction in cost from energy efficient green technologies may lead to increase in the consumption in other areas which can lead to increase the carbon emissions. The third aspect of this "Rebound Effect" is called "Economic Rebound", where reduction in cost because of green innovations and green production techniques can stimulate the economic growth which will further increase the carbon emissions (Lowe et al., 2024).

The results also reveal that coefficients of agricultural eco-efficiency (AEE) and its square terms are insignificant determinants of carbon emissions with the turning point of 7.79 units (in log) in first quantile, −3.50 units (in log) in second quantile, −5.40 units (in log) and −3.10 units (in log) in the last two quantiles respectively. Agricultural eco-efficiency aims to minimize environmental impacts while maximizing economic returns, and carbon emissions have a significant environmental impact on agriculture (Genstwa and Zmyślona, 2023). According to Genstwa and Zmyślona (2023) there is a trade-off between agricultural productivity and emissions efficiency, which suggests that carbon emissions efficiency will decrease with an increase in agricultural products. Carbon emissions efficiency refers to the economic benefits generated by production activities that simultaneously produce carbon emissions at the same time. The lower the carbon emissions generated per unit of economic output, the more efficient are the carbon emissions. The relationship between agricultural eco-efficiency and carbon emissions is multifaceted, involving a balance between reducing greenhouse gas (GHG) emissions and maintaining agricultural productivity. Thus, agricultural practices can influence carbon emissions and agricultural eco-efficiency. While some practices may lead to a reduction in carbon emissions and increase in agricultural eco-efficiency (Naz et al., 2021), others may not necessarily result in improved emissions efficiency in agricultural sector when compared to other sectors (Genstwa and Zmyślona, 2023). The relationship between agricultural eco-efficiency and carbon emissions is complex and multi-facets and its complexity is determined by the varying effects of different agricultural practices and the need for the careful policy formation to enhance the environmental performance of the agricultural sector (Shafiullah et al., 2021). At first stage, the efforts to increase agricultural eco-efficiency also increase agricultural output per unit of resources input. These efforts rely on carbon intensive technologies such as mechanization by fossil fuels, chemical fertilizers and pesticides and irrigation systems that require energy consumption, which ultimately increases carbon emissions (Zahra et al., 2023). After a turning point, the marginal increase in carbon emissions from agricultural eco-efficiency begins to diminish. After threshold point, agricultural innovations focus on low-carbon and sustainable practices including renewable energy consumption, organic farming and other carbon reducing practices. Therefore, it is important to have a clear and specific approach that considers the specific condition, and long-term impacts is essential for improving agricultural eco-efficiency in relation to carbon emissions (Wu et al., 2023).

Results reveals that trade openness is a positive and significant determinant of carbon emissions and thus cannot help to achieve the target of carbon neutrality. This positive relationship between trade openness and carbon emissions is also supported by the existing literature (see, for example, Erdogan (2020), Wang et al. (2024), Nathaniel and Khan (2020), Jafri et al. (2021). Trade openness increases economic growth by increasing the production (Yanikkaya, 2003) and exports which leads to increase in carbon emissions (Zahra et al., 2022a,b). Trade openness increases the volume of goods transported internationally which is also a source of carbon emissions. With increase in trade, the infrastructure requirements also increase to support trade, leads to multiply carbon emissions (Dzator et al., 2021).

4.6. Individual countries analysis

In this section, we extend our investigation at the individual country level for each of the three countries under consideration by analysing the individual country data. Table 8 presents the unit root test results for each individual country. We employed the ADF (Dickey and Fuller, 1981), and PP (Phillips and Perron, 1988) unit root tests to check the stationarity in the data.

As can be seen in Table 8, all the variables are non-stationary in level form but stationary in its first difference form, which means that all variables are integrated of order one i.e., I (1) in all three countries. As all the variables are I (1) it is important to investigate the long run relationship, cointegration, among the model variables. Table 9 shows the results for the F-Bound Cointegration tests which shows in all three countries the variables are cointegrated, thus inferring the long run relationships.

Table 10 presents the quantile regression results at the individual country level, for China, the USA, and India. The table is organized to show detailed statistical outcomes for each country, allowing for a comparative analysis across different quantiles. Columns (2) through (5) provide the estimated quantile coefficients, which illustrate how the dependent variable responds to changes in the independent variables at different points in the distribution. These coefficients are derived from quadratic models, and the turning points of these models (indicating where the relationship between the variables changes direction) are also specified. This detailed presentation helps in understanding the impacts and variations in the relationship between dependent and independent variables across different quantiles for each country studied.

Table 11 presents summary results of Tables 7 and 10, showing the shape of quadratic variables (either U-shaped or inverted U shaped) and significance of the quadratic terms in panel estimation results and individual country results for China, the USA and India and Table 12 shows the values of turning points in each quantile for both panel model

Table 8
Unit root tests for individual country.

Variables	ADF		PP		Interpretation
	t-stats	P-value	t-stats	P-value	
China					
lCN	0.65	0.99	−1.98	0.30	
ΔlCN	−1.99**	0.05	3.63***	0.00	I (1)
lGG	0.83	0.80	−0.73	0.83	
ΔlGG	−3.88***	0.0	−4.01***	0.00	I (1)
lGG^2	−0.81	0.81	−0.73	0.83	
ΔlGG^2	−3.88***	0.0	−4.01***	0.0	I (1)
lGI	−2.92	0.10	−2.83	0.07	
Δ lGI	−3.56***	0.0	−4.20***	0.00	I (1)
lGI^2	−1.94	0.32	−1.26	0.64	
$\Delta\ lGI^2$	−3.78***	0.0	−3.64***	0.0	I (1)
lAEE	−1.20	0.68	−1.74	0.72	
Δ lAEE	−3.51**	0.05	−3.51**	0.02	I (1)
$lAEE^2$	−0.99	0.74	−0.92	0.77	
$\Delta\ lAEE^2$	−3.51**	0.05	−3.64**	0.04	I (1)
lTO	−2.79	0.21	−2.31	0.43	
Δ lTO	−3.22**	0.03	−3.28**	0.03	I (1)
USA					
Variables	ADF		PP		Interpretation
	t-stats	P-value	t-stats	P-value	
lCN	−4.30***	0.0	−2.95	0.16	
ΔlCN	−5.81***	0.0	−3.89***	0.01	I (1)
lGG	−2.78	0.21	−2.25	0.45	
ΔlGG	−2.88**	0.05	−3.03**	0.04	I (1)
lGG^2	−2.78	0.2	−2.25	0.45	
ΔlGG^2	−2.87**	0.05	−3.03**	0.04	I (1)
lGI	−2.78	0.22	−2.23	0.47	
Δ lGI	−4.71***	0.00	−4.01***	0.01	I (1)
lGI^2	−3.01	0.14	−2.30	0.43	
$\Delta\ lGI^2$	−4.55***	0.0	−3.97***	0.0	I (1)
lAEE	−3.06	0.13	−3.09	0.12	
Δ lAEE	−3.48**	0.02	−3.89***	0.01	I (1)
$lAEE^2$	−3.04	0.13	−3.13	0.11	
$\Delta\ lAEE^2$	−3.51***	0.01	−3.90***	0.0	I (1)
lTO	−0.88	0.78	−0.67	0.84	
Δ lTO	−3.71***	0.01	−3.72***	0.01	I (I)
India					
Variables	ADF		PP		Interpretation
	t-stats	P-value	t-stats	P-value	
lCN	−2.43	0.36	−2.10	0.54	
ΔlCN	−2.77*	0.07	4.29***	0.0	I (1)
lGG	−4.20**	0.02	−2.60	0.30	
ΔlGG	−3.83***	0.01	−3.92**	0.02	I (1)
lGG^2	−2.65	0.30	−3.23	0.11	
ΔlGG^2	−5.57***	0.0	−4.14***	0.0	I (1)
lGI	−3.07	0.13	−3.82**	0.03	
Δ lGI	−3.86***	0.00	−4.34***	0.0	I (1)
lGI^2	−1.26	0.64	−0.48	0.88	
$\Delta\ lGI^2$	−4.00***	0.0	−4.30***	0.0	I (1)
lAEE	−2.89	0.20	−2.59	0.29	
Δ lAEE	−2.23	0.20	−3.74***	0.01	I (1)
$lAEE^2$	−2.88	0.20	−2.56	0.3	
$\Delta\ lAEE^2$	−3.08**	0.04	−3.74***	0.0	I (1)
lTO	−2.87	0.18	−3.29*	0.08	
Δ lTO	−3.31**	0.02	−3.29**	0.02	I (1)

***, **, *represent 1%,5% and 10% level of significance respectively.

Table 9
F Bound cointegration test.

F-statistic	China		The USA		India	
	72.55***		7.21***		14.43***	
K	7		7		7	
Significance level	L_0	L_1	L_0	L_1	L_0	L_1
10%	1.92	2.89	1.92	2.89	1.92	2.89
5%	2.17	3.21	2.17	3.21	2.17	3.21
2.5%	2.43	3.51	2.43	3.51	2.43	3.51
1%	2.74	3.9	2.73	3.9	2.73	3.9

***, **, * represent 1%,5% and 10% level of significance respectively.

as well as for individual country models. Results show that GG has significant U-shaped relationship with carbon emissions in panel model, in China, and in the USA. These results depict that carbon emissions decreases with each unit increase in GG and starts increasing after the threshold (turning) points. On the other hand, GG has significant U-shaped relationship with carbon emissions in first quantile while it has significant inverted U-shaped relationship with carbon emissions in the last two quantiles in India. In panel model and in India, GI has a significant U-shaped relationship with carbon emissions in all four quantiles, which depicts that with each unit increase in GI, the carbon emissions declines and starts increasing after the threshold (turning) point. On the other hand, GI has significant U-shaped relationship in China and inverted U-shaped relationship in the USA with carbon emissions in last quantile only. In the USA and India, AEE has significant inverted U-shaped relationship with carbon emissions in all quantiles. These results elaborate that carbon emissions goes up with each unit increase in AEE and goes down after the threshold (turning point) with each unit increase in AEE. On the other hand, in China AEE has significant U-shaped relationship with carbon emissions in all quantiles except second one where it has insignificant U-shaped relationship with carbon emissions. These results depict that carbon emissions declines with each unit increase in GG and then starts increasing after threshold (turning) point. On the contrary, it has insignificant inverted U-shaped relationship with carbon emissions in all four quantiles. Fig. 4 shows the graphical presentation of the quantile process for quadratic models in China, the USA and India which shows the quantile coefficients trends of the carbon emissions and its determinant over a period of time.

5. Conclusion and policy implications

This comparative study investigates the role of green growth, green technological innovations, agricultural ecoefficiency and trade openness to achieve the target of carbon neutrality in the top three carbon emitting countries, namely China, the USA and India. The empirical analysis of this study is carried out at two levels by; (1) pooling the data source across the countries and estimate a panel quantile regression, and (2) using individual country data and estimate quantile regression model for each of the three countries. The empirical study based on panel data modelling revealed three main results. Firstly, green growth and green technological innovation have a significant U-shaped relationship, indicating that when green growth and green technological innovations increases, the rate of carbon emissions continues to decline up to threshold (turning) points and start to increase thereafter. Secondly, agricultural ecoefficiency has inverted U-shaped relationship with the carbon emissions, showing that when agriculture eco-efficiency increases the rate of carbon emissions continues to increase at a decreasing rate up to the threshold (turning) point and starts declining afterwards. Thirdly, trade openness is regarded as a cause to increase the carbon emissions meaning that they increase the environmental degradation and may hinders the way to achieve the target of carbon neutrality.

There are several policy insights that can be drawn from the findings of this study. The top pollutant countries need to handle a regular

Table 10
Results of individual country quantile regression.

Variables (1)	China			
	$Q_{0.25}$ (2)	$Q_{0.50}$ (3)	$Q_{0.75}$ (4)	$Q_{0.90}$ (5)
lGG	−0.02	0.01	0.01	0.01***
	(0.32)	(0.64)	(0.14)	(0.0)
lGG^2	0.04***	0.03**	0.02***	0.02***
	(0.01)	(0.03)	(0.0)	(0.0)
	[0.25]	[-0.17]	[-0.25]	[-0.25]
lGI	1.15	0.87	−0.78	−0.93***
	(0.45)	(0.95)	(0.23)	(0.01)
lGI^2	−0.73	−0.11	0.41	0.51**
	(0.45)	(0.90)	(0.36)	(0.02)
	[0.79]	[3.96]	[0.96]	[0.92]
lAEE	8.50**	5.80*	5.22***	4.77***
	(0.04)	(0.09)	(0.0)	(0.0)
lAEE^2	−0.71**	−0.45	−0.39***	−0.34***
	(0.04)	(0.13)	(0.01)	(0.0)
	[-5.99]	[-6.45]	[-6.70]	[-7.01]
lTO	−0.13	0.28***	0.38***	0.44***
	(0.22)	(0.0)	(0.0)	(0.0)
Constant	−19.19	−12.94	−11.37**	−10.35***
	(0.11)	(0.19)	(0.03)	(0.0)
Pseudo- R^2	0.73	0.75	0.81	0.83
USA				
lGG	−0.24***	−0.19***	−2.21***	−0.24***
	(0.0)	(0.0)	(0.0)	(0.0)
lGG^2	0.60*	0.91***	0.88***	1.19***
	(0.09)	(0.0)	(0.0)	(0.0)
	[0.20]	[0.11]	[1.26]	[0.10]
lGI	−4.71	0.53	0.56	1.15***
	(0.52)	(0.23)	(0.11)	(0.0)
lGI^2	0.26	−0.27	−0.30	−0.59***
	(0.51)	(0.25)	(0.14)	(0.0)
	[9.06]	[0.98]	[0.94]	[0.98]
lAEE	8.31***	8.31***	7.28***	6.31***
	(0.0)	(0.0)	(0.0)	(0.0)
lAEE^2	−8.86***	−8.86***	−0.75***	−0.66***
	(0.0)	(0.0)	(0.0)	(0.0)
	[0.47]	[0.47]	[4.86]	[4.78]
lTO	0.13***	0.13***	0.15***	0.19***
	(0.0)	(0.0)	(0.0)	(0.0)
Constant	−7.42	−6.41*	−4.08	−2.02
	(0.23)	(0.09)	(0.16)	(0.33)
Pseudo- R^2	0.81	0.84	0.87	0.90
India				
lGG	−0.04***	0.02	0.08***	0.05***
	(0.0)	(0.38)	(0.0)	(0.0)
lGG^2	0.02***	−0.02	−0.04***	−0.03***
	(0.03)	(0.17)	(0.0)	(0.0)
	[1.00]	[0.50]	[1.00]	[0.84]
lGI	−2.07***	−3.97*** (0.0)	−4.71*** (0.0)	−2.89*** (0.0)
	(0.0)			
lGI^2	0.82***	1.88***	2.25***	1.26***
	(0.0)	(0.0)	(0.0)	(0.0)
	[1.27]	[1.06]	[1.05]	[1.15]
lAEE	40.93***	35.72***	28.13*** (0.0)	13.80*** (0.0)
	(0.0)	(0.0)		
lAEE^2	−4.12***	−3.64***	−2.89***	−1.40***
	(0.0)	(0.0)	(0.0)	(0.0)
	[4.97]	[4.91]	[4.87]	[4.93]
lTO	−0.25***	−0.07	0.20***	0.05***
	(0.0)	(0.30)	(0.0)	(0.0)
Constant	−86.38***	−72.23***	−53.21***	−19.24***
	(0.0)	(0.0)	(0.0)	(0.0)
Pseudo- R^2	0.95	0.94	0.94	0.95

Note: The quantile regression results highlight significant variability across different quantiles, indicating heterogeneous effects of the independent variables on the dependent variable in three heterogenous countries. These findings underscore the importance of considering the entire distribution of the dependent variable, rather than focusing solely on the mean.
***, **, *represent 1%,5% and 10% level of significance respectively (p-values are in parentheses and values in [] are turning points of respective quadratic terms).

Table 11
Summary results of quadratic models.

Inverted U-Shaped	Panel Model			China			The USA			India		
	lGG	*lGI*	*lAEE*	*lGG*	*lGI*	*lAEE*	*lGG*	*lGI*	*lAEE*	*lGG*	*lGI*	*lAEE*
$Q_{0.25}$			NS	–	NS	–	–	–	S	–	–	S
$Q_{0.50}$			NS	–	NS	–	–	NS	S	NS	–	S
$Q_{0.75}$			NS	–	–	–	–	NS	S	S	–	S
$Q_{0.90}$			NS	–	–	–	–	S	S	S	–	S
U-Shaped												
$Q_{0.25}$	S	S		S	–	S	S	NS	–	S	S	–
$Q_{0.50}$	S	S		S	–	NS	S	–	–	–	S	–
$Q_{0.75}$	S	S		S	NS	S	S	–	–	–	S	–
$Q_{0.90}$	S	S		S	S	S	S	–	–	–	S	–

Note: NS shows not significant, and S shows significant in respective quantiles.

Table 12
Summary results of turning points.

Quantiles	Panel Model			China			The USA			India		
	lGG	*lGI*	*lAEE*	*lGG*	*lGI*	*lAEE*	*lGG*	*lGI*	*lAEE*	*lGG*	*lGI*	*lAEE*
$Q_{0.25}$	1.32	0.79	7.79	0.25	0.79	−5.99	0.20	9.06	0.47	1.00	1.27	4.97
$Q_{0.50}$	1.20	0.86	−3.50	−0.17	3.96	−6.45	0.11	0.98	0.47	0.50	1.06	4.91
$Q_{0.75}$	1.18	0.84	−5.40	−0.25	0.96	−6.70	1.26	0.94	4.86	1.00	1.05	4.87
$Q_{0.90}$	1.17	0.84	−3.10	−0.25	0.92	−7.01	0.10	0.98	4.78	0.84	1.15	4.93

environmental degradation and need to focus on improving the green growth in favour of environmental sustainability through environmental and carbon tax policies. By innovating green growth structure, the eco-friendly policies and green technological innovations may transfer the industrial production and its structure from non-renewable energy heads to green energy sources and production. Moreover, a special concentration should be allocated to enhance the production and utilization capacity of green energy to curtail the upheaval of continuous carbon emission. Apart from this, strategies should be developed to achieve the SDG related to green growth with specified period.

Carbon tax or environmental pricing through taxation can be proved an effective tool to stimulate the green growth in favour of sustainable environment as carbon tax policy may lead investors to start investing in green projects. These policies also change the consumption patterns thus lead to green production and green output. It is also important to enhance the quality of human capital through spreading awareness about the green production techniques and environmentally friendly consumption patterns. Environmental tax has the capacity to improve the environmental sustainability of a country (Othman et al., 2020). Additionally, green trade policies should be designed and implemented to curtail the environmental burden and to enhance the environmental sustainability.

Green innovation capacities should be improved to combat the climate degradation and to multiply green economic growth. Therefore, more investment should be allocated to widen the base for research and development expenditures to polish the eco-friendly green technologies. More concentration is required to remove the financial constraints in production sector to adopt and improve green technologies which will further curtail the level of carbon

s. Thus, replacement of green technology production techniques with traditional production function is vital to improve the environmental sustainability. Finally, important suggestion is, a strict check and balance administration is required to monitor the decay effects and depreciation of green technologies so that their impact on the environment can be quantify.

At the start green technological innovations lead to reduction in carbon emissions, this is because of more efficient technologies, implementation of renewable energy sources and eco-friendly practices be adopted. Policies should focus to maximise this initial reduction phase by offering subsidies, tax incentives and early-stage green technological investment. In this situation, regulatory frameworks can promote the integration of proven low emissions technologies across various industries which ensures that the early-stage benefits are broadly realised. Policymakers can invest in infrastructure that supports green technological innovation, such as small grids for renewable energy. As green innovations mature, there may be diminishing returns, where the initial reductions in carbon emissions stabilise or slow down. It is important to introduce the evaluation mechanism to track when technologies begin reaching diminishing returns and create policies that encourage continuous of technology, ensures the reduction phase is sustained as long as possible. Some innovations may lead to higher emissions due to increased production, scaling, overuse of energy for manufacturing green tech, or a rebound effect where people consume more because technologies are perceived as eco-friendly. The policymakers should address the possible increase in emissions by introducing carbon tax that discourage over consumption, even if the technologies itself are green. Policies should mandate comprehensive lifecycle assessments for green technologies to ensure that overall emissions, from production to disposal, are minimised. Given that green innovations are often adopted globally, policymaker should collaborate internationally to set global standards or green technologies, ensuring that they are sustainable minimize their impact on rising carbon emissions in the long run.

To improve the agricultural eco-efficiency in favour of environment, the subsidies should be given to curtail the non-renewable energy consumption in agricultural sector and for replacement of renewable energy resources in this sector. The favourable impact of capital to land ratio or capital to labour ratio should be judged to improve the AEE so that sustainable environment can be promoted. The subsidies should be invested in targeted small and medium scale farms to accelerate the green capital concentration in agricultural sector but not at the expense of environment. Additionally, landfill energy (biomass) should be introduced in the agricultural sector to reduce the overall carbon footprint (Zahra et al., 2022a,b). Sustainable agricultural practices such as crop rotation, intercropping and integrated pest management should be encouraged. These practices can improve soil health, reduce erosion, and minimize the use of fertilizers and pesticides. Efficient use of water resources in agricultural sector such as drip irrigation and rainwater harvesting should be adopted. This can reduce water waste and minimize the impact of agriculture on water resources. More concentration should be given to promote agroforestry which combines agricultural

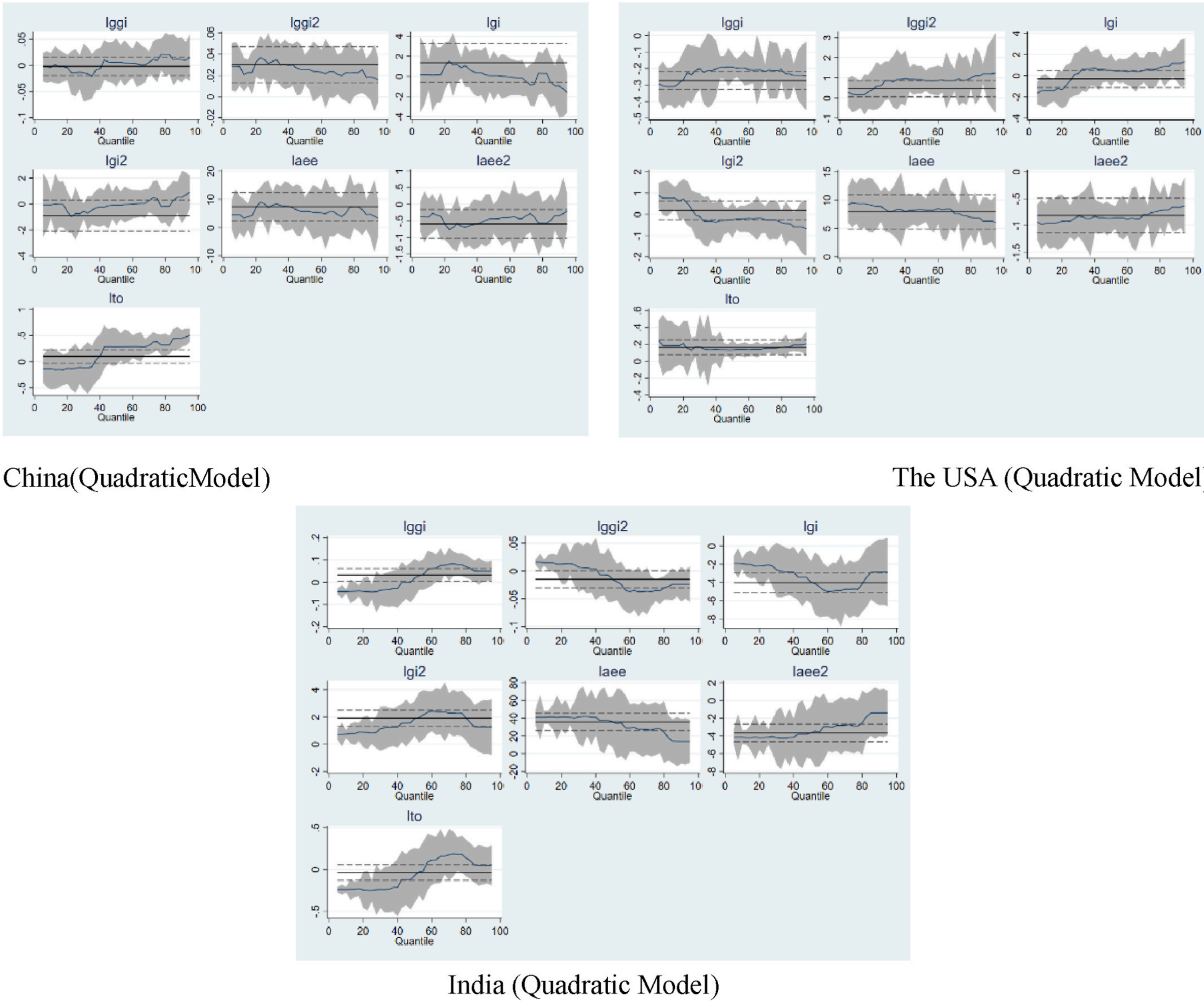

Fig. 4. Graphical presentation of the quantile regression coefficients (quadratic models).

crops and trees in the same area, to improve soil health, reduce erosion, and enhance biodiversity. Similarly, adoption of circular economy principles in agriculture, such as recycling and reusing waste products, to minimize waste and improve resource efficiency can lead agriculture to environment friendly Agri-production. Implementation and enforcement of environmental policies and regulations that promote ecoefficiency and minimize environmental degradation in agricultural production can be helpful. This can include regulations on pesticide use, water pollution, and greenhouse gas emissions.

At first, improvement in agricultural eco-efficiency may increase carbon emissions, result from investments in new technologies, the use of additional resources, or change in farming practices that initially require higher energy consumption. Policy makers can provide subsidies for renewable energy adoption in agriculture, encourage farmers to power their operations with cleaner energy sources while also adopting eco-efficient practices. Similarly, the optimal use of resources is also recommended to implement policies that promote the efficient use of inputs like water, fertilizer, and energy to minimize the initial emissions surge from agricultural activities. After a certain point of eco-efficiency is reached carbon emissions begin to stabilise and eventually decline as the practices become more efficient and effective. At the turning point, governments can introduce policies that encourage the adoption of agricultural practices that maximise eco-efficiency, such as precision farming, and organic farming. It is also important to monitor the threshold points which help to establish the regulatory frameworks that monitor the progress of agricultural eco-efficiency, help policymakers identifying when emissions are stabilise and when reductions are expected to begin. Once agricultural eco-efficiency surpasses the threshold, carbon emissions begin to decline as farming become more sustainable and resource efficient. Policy makers should focus on scaling eco-efficient practices that have proven to reduce emissions. This could involve subsidies for sustainable technologies, tax incentives for eco-friendly farming, or low-interest loans for green agricultural investments. It is suggested to encourage global cooperation to share practices and innovations in agricultural eco-efficiency, promoting reduction in emissions beyond national borders.

Similarly, trade liberalization plays its important role to stimulate the carbon footprint both in long run and in short run (Zahra et al., 2022a,b), therefore strict environmental regulatory policies should be implemented to reduce the environmental degradation in selected countries and steps should be taken to shift the trade paradigm to green trade. These top CO_2 emitters should also participate in market integration with their trading partners with necessity to promote globalization coupled with environmental sustainability. Renewable energy trade should be promoted to facilitate the trade of renewable energy technologies and products such as solar panels, wind turbines and energy efficient appliances.

6. Limitations

Apartment from these policy implications, there are certain limitations of this study. Firstly, this study is restricted to only top three carbon emitters. A similar analysis can be replicated in other countries for comparative analysis purpose, for example, developed countries versus developing countries. Secondly, energy driven carbon emissions in different sectors such as industrial and agricultural sectors can be investigated for its consequences to achieve the target of carbon neutrality, which we couldn't carry out due to data unavailability. Thirdly, this study also paves the way to determine the impact of green growth, green technological innovation and agricultural eco-efficiency with reference to other Sustainable Development Goals (SDGs) to investigate the trade-offs and synergies for future research. Fourthly, in future other novel and vital variables and econometric techniques can be included which can efficiently analysed the direct and indirect determinants towards the target of carbon neutrality. Fifthly, if long time series data available, then the choice of econometric technique can also be replaced to perform long run and short run analysis. While quantile regression is powerful to capture heterogeneous effects, it may be more complex to interpret compared to traditional mean regression models. This can make it challenging to communicate the results to policymakers. Quantile regression provides insights across different points of the distribution, but the results may not be easily generalizable to the entire population. Different quantiles may show varying effects that could complicate policy recommendations or interpretation. Sixthly this study focuses on broad economic trends, but sector-specific dynamics such as differences between manufacturing, agriculture, or energy sectors may not be fully accounted for, which potentially limit the applicability of the findings across all sectors. Future research studies could explore this approach for a more comprehensive cost-benefit analysis.

CRediT authorship contribution statement

Samia Zahra: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Eliyathamby A. Selvanathan:** Writing – review & editing, Supervision, Project administration, Methodology. **Rakesh Gupta:** Supervision. **Maneka Savithri Jayasinghe:** Supervision.

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Declaration of competing interest

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

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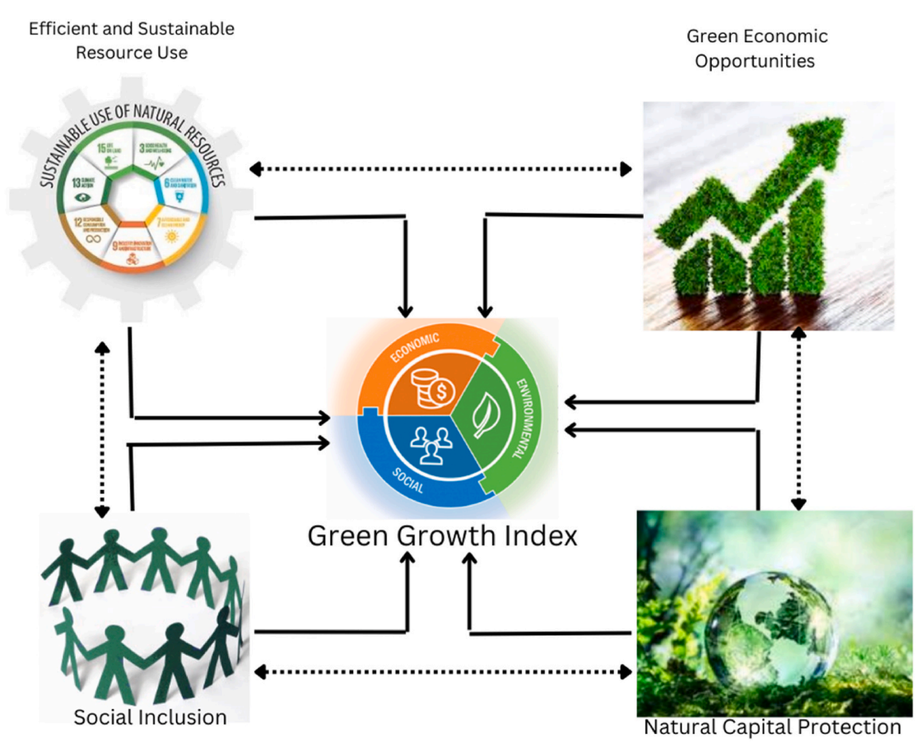
Appendix



Appendix 1The Conceptual Framework Green Growth Index

Data availability

Data will be made available on request.

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