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Reshaping China's inclusive and sustainable growth landscape through green energy innovation in the digital era

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Abstract

China faces increasing pressure to obtain inclusive and sustainable growth as it is one of the largest producers of carbon dioxide (CO_2) emissions globally. This paper aims to simplify the trend of inclusive and sustainable growth in China by focusing on the impact of green energy technology, financial development, structural transformation, digital economy and public sector corruption as the determining factors. The study adopts a sample period from 1990 to 2018. It employs advanced dynamic autoregressive distributed lag (ARDL) model techniques with counterfactual shocks and a kernel regularized least squares regression machine learning algorithm. The findings reveal that green energy technology positively and significantly affects China's inclusive and sustainable growth in the long run. However, the short-run coefficient of the dynamic ARDL model reveals an insignificant outcome. In addition, digital economy is found to be adversely affecting inclusive and sustainable growth in both the short run and long run, yet insignificantly. The role of financial development is found to be favorable in the short run, while structural transformation does not have any significant impact on inclusive and sustainable growth in either the short or long-run. Public sector corruption significantly and negatively hurts inclusive and sustainable growth in the short run. Based on the results, policy recommendations are suggested to boost green energy technology and inclusive and sustainable development in China.

Keywords Inclusive growth · Sustainability · China · Machine learning · Digital economy · Finance

Abbreviations

ACHI	Achievement index
ARDL	Autoregressive distributed lag
BRICS	Brazil, Russia, India, China and South Africa
CO2	Carbon emission
CS-ARDL	Cross-sectional autoregressive distributed lag
DEA-SBM	Data envelopment analysis-super slack-based measure
DOLS	Dynamic ordinary least squares
DYNARDL	Dynamic Autoregressive Distributed Lag
ECI	Economic complexity
EU	European Union

Extended author information available on the last page of the article

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EWM	Entropy weigh method
FD	Financial development
FMOLS	Fully modified ordinary least squares
GDP	Gross domestic product
GMM	Generalized method of moment
GTECH	Green energy technology
ICT	Information and communication technology
INSGR	Inclusive and sustainable growth/development
IV-GMM	Instrumental variable generalized method of moment
KPSS	Kwiatkowski, Phillips, Schmidt, and Shin
KRLS	Kernel regularized least squares regression
MDI	Multidimensional inclusiveness
ND-GAIN	Notre Dame Global Adaptation Initiative
PUBCOR	Public sector corruption
PVAR	Panel vector autoregression
R&D	Research and development
RE	Renewable energy
SD	Standard deviation
SDGs	Sustainable development goals
SDM	Spatial Durbin model
UN	United Nation
UNCTAD	United Nations Conference on Trade and Development
VDEM	Varieties of Democracy
WIPO	World Intellectual Property Organization

1 Introduction

Economies of the world have experienced growth and development at various times, but whether it is inclusive and sustainable remains an issue. This informs why sustainable development goal 8 (SDG 8) of sustainable development goals is dedicated to 'promoting inclusive and sustainable economic growth' on or before 2030. This is because inclusive and sustainable growth can potentially stimulate progress, create a decent job environment, and improve economic well-being. Economies generally have low environmental performance when they are in a growth trend. While they grow, they also harm the environment, which poses a barrier to sustainable development. However, developed countries with strong technological infrastructure can reverse this situation. In other words, these countries can transform their growth paths into a green, clean and sustainable structure. In doing so, not only should economic growth be cleaner, but all sectors should focus on the green transformation. Inclusive and sustainable growth refers to this progress. Kamran et al. (2023) reinforce the aforementioned assertion by conjuring that inclusive growth is an essential and sufficient condition for sustainable development. Inclusivity in growth emphasizes the social, political, and ecological aspects of economic development. However, the aforementioned aspects can only be achieved when output is sustained over time and improves the well-being of people through equality in the distribution of income and protection of the environment (Gupta & Vegelin, 2016; Pouw & Gupta, 2017). This study defines inclusive and sustainable growth within the context of the multidimensional inclusiveness (MDI) and achievement index (ACHI) proposed by Dorfell and Schuhmann

(2022). The MDI-ACHI plus defines inclusive development that is pro-human and adopts factors critical for well-being. Unlike other comprehensive indicators, this measurement also accounts for sustainable development by including CO2 emissions, in which China dominates the world region. Environmental sustainability is one of the most critical obstacles in the world right now which can critically hamper the inclusive and sustainable development of a nation.

Trade, investment and the implementation of free-market reforms in 1978 are at the center of China's economic growth strategy. Since then, the economy has been one of the fastest in terms of growth, with an annual GDP adjustment speed of about 9.5%. Chinese investment, low-cost manufacturing and export-induced growth have peaked with a serious environmental quality crisis (World Bank, 2022). Evidences in the literature generally claim that this growth has reduced environmental quality (Song et al., 2021; Wang et al., 2021; Zhao et al., 2022). The Chinese economy has continued to grow in terms of national productivity due to increased capital accumulation, improved communication systems, manufacturing machinery, and efficiency in the labor force. However, this growth has resulted in the problems of environmental degradation and pollution. According to Hu and Khan (1997), productivity gains accounted for 42% of GDP growth in China between 1979 and 1994 but were overtaken by capital accumulation in the 1990s. The Chinese manufacturing sector contribution in 2020 was about 26.6 trillion Yuan accounted for %30of the World's GDP and China is the largest manufacturing country in the world (Xin et al., 2022). In recent times, growth in China has been stimulated by factors highlighted by Wang and Giovanis (2021). These include (1) deliberately unbalancing the economy and export-led growth, (2) large-scale Afro-Chinese investments, (3) within-country migration due to industrialization, (4) the role of state and institutions in the socialization of investment, and (5) technological advancement and domestic innovations. SDG 8 can be linked explicitly with China's current economic strategies and challenges. For example, the 14th five-year plan emphasizes that apart from economic development, sustainability of growth as well as life quality is important. The plan also notes that CO2 emissions must be peaked before 2030. It emphasizes that carbon neutrality should be reached before 2060 (ADB, 2021). The Chinese policymakers plan to achieve carbon neutrality before 2060. The country incorporates carbon neutrality and peaking goals in its social as well as economic development. It also plans to build a clean energy system that will be the largest in the world. The country promotes worldwide sustainable development through multilateralism by implementing cooperation to address climate change, governance of marine pollution, and biodiversity conservation. The country, through its China's Belt and Road Initiative, (BRI) network, emphasizes green BRI by adopting green energy (UN China Mission, 2022).

Having said this, whether China has been achieving both inclusive and sustainable growth remains a puzzle. This can be especially seen in the trend of inclusive and sustainable growth of China in Fig. 1, where there appear to be some declining trends.

The trend of energy demand in manufacturing sector has been on the increase. For instance, the manufacturing sector energy consumption increased by about 7 per cent from 2.8 million tons in 2006 to 5.7 million in 2020 and CO2 emissions also rised by 3.1 per cent from 2.5 million tons to 3.6 million tons, respectively (Xin, et al., 2022). The growth in energy consumption has serious implications for the quantum of CO2 emissions and it needs to cut down. Industrialization drive has put China as the largest producer of CO2 emissions due to its consumption of coal, crude oil and power generation (Zhang et al., 2022). In 2015, the China government launched a high-powered "Made in China 2025" 10-year industrial policy. One of the policy prescriptions was to transform traditional

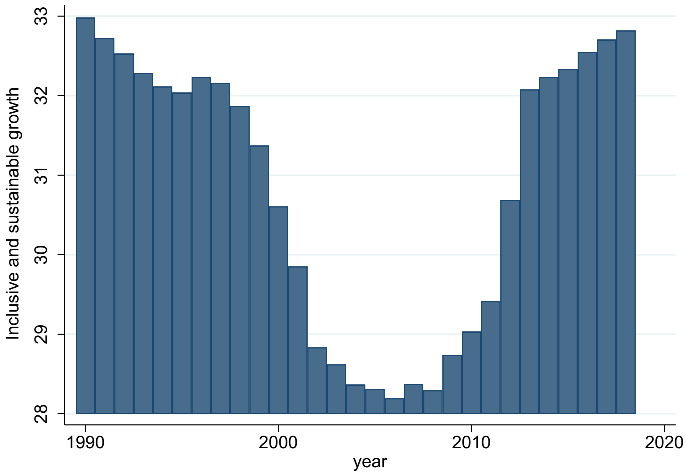

Fig. 1 Time series trend of Inclusive and Sustainable Growth in China

manufacturing industries to be environmentally friendly and reduce energy demand by 18% and carbon intensity by 40% by 2025. Thus, China's National Energy Administration has suggested a green energy technology innovation.

The China green energy technology innovation intends to deal with China's dependence on fossil fuels and its numerous environmental issues by rebalancing the economy from energy industrialization. Conceptual: This study defines green energy technology innovation within the context of renewable energy innovation. China's green energy technology is aimed at cutting down the country's carbon emissions and attaining 20% non-fossil energy as a percentage of the primary energy supply by 2030. In 2022, China's renewable energy power generation reached 2.7 trillion kWh, accounting for about 31.6% of the country's total electricity consumption, indicating an increase of 1.7%. The cumulative installed capacity of renewable energy reached 152 million kilowatts in 2022, accounting for about 76% of the country's power-generating capacity (Liu & Zhang, 2022). Figure 2 provides a time series graph for the renewable energy technology innovation in China, where it can be seen that there is an increasing trend in this innovation category.

Financial development and economic complexity are vital for the green energy technology innovation (Sun et al., 2023). For instance, green energy technology requires huge financial investment to train personnel, build infrastructure and equipment, and maintain and upgrade existing technology to minimize the costs. Besides, economic complexity measures a country's green energy technology innovation production capacity. Financial development and economic complexity are vital for inclusive and sustainable growth in China. Paun et al. (2019) suggested that financial development contributes to inclusive and sustainable growth through bank equity and harnessing funds meant for green energy technology innovation. Financial development contributes to inclusive and sustainable growth by specifically affecting savings and allocating the same to sectors that can lead to positive economic outcomes (Hunjra et al., 2022). However, economic complexity seriously impacts inclusive and sustainable growth since it entails R&D activities and promotes green energy technology innovation (Martins et al., 2021; Neagu, 2020). Hence, financial development and economic complexity can help China attain inclusive and sustainable growth by making loans available to produce green energy technology innovation and

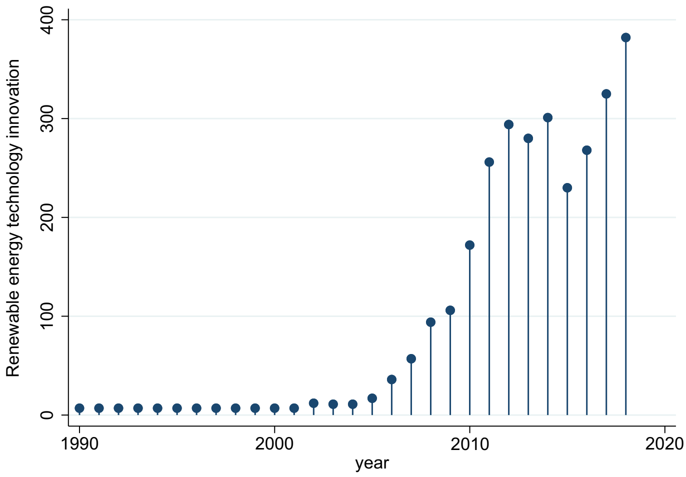

Fig. 2 Time series trend of Renewable energy technology innovation in China

expand positive impacts of green total factor productivity on growth (Abid et al., 2022; Zhou et al., 2019).

This study fills up several research gaps in literature based on the preceding debate. First, the study focuses on China because its inclusive and sustainable growth agenda presents a dual challenge. In terms of growth in GDP, the country has outpaced many major countries. For example, during 2016–2019, the country's annual average. During the times of COVID-19, in 2020, China was the only major economy in the entire world to obtain a positive growth rate of GDP of 2.3%. Its per capita GDP surpassed the USD 10000 mark. The growth rate of GDP reached 6.6%, an average higher than the global one. This tells us that other major economies achieved lower growth rates than China in the same period. According to Prasad (2023), in 2022, China's GDP was $18.3 trillion, 73% of the USA's GDP. Currently, the country's income per capita is nearly $13,000, which is 17% of US per capita income in comparison to less than 2% in 1990. During the last decade and a half, while the USA accounted for 27% of the world's economic growth, China was responsible for 35% of the nominal global growth of GDP (Prasad, 2023). While economic growth performance increases the country's GDP, air pollution and environmental degradation negatively affect public health and undermine future generations' natural resources. In historical process, China is the second largest emitter globally. However, in 2022, China is the world's leading CO_2 emitter, accounting for 30.68% of worldwide emissions (Our World in Data, 2024). As stated above, SDG 8 could contribute to sustainable development by improving economic structure. For instance, by focusing on SDG 8, China could decouple economic growth and emissions, which is critical since economic output triggers the emissions most. Therefore, China's growth and emission trajectory present opportunities and challenges for the country. While previous research has explored China's growth or emission trajectory, they have not focused on inclusive and sustainable growth at the same time which is the novelty of the paper.

Second, we considered a comprehensive novel indicator of inclusive and sustainable growth as devised by Dorffel and Schuhmann (2022). This index compares and contrasts the performance of countries with each other over time. The MDI is constructed of two subcomponents: development equity and achievement. The equity dimension includes income inequality to construct inclusive development. The authors consider it as a proxy for equity income distribution. The authors also include national distributions for health, wealth, and education. In the achievement dimension, the authors include GDP, life expectancy, savings, human capital, the productivity of labor, and employment. The authors include three aspects of the sustainability dimension. First is financial sustainability, which is captured by adjusted net savings. Second is demographic sustainability, captured by the dependency ratio, and the other is environmental sustainability, captured by carbon intensity and natural resource depletion. Therefore, compared to the existing literature, which only focuses on the equity, development, or sustainability dimensions, we focus on all three dimensions to capture a comprehensive measure of inclusive and sustainable development.

Third, the study selects specific variables that can highly influence China's inclusive and sustainable development. The first variable is green energy innovation, which has been ignored in determining China's inclusive and sustainable development. Other variables include the digital economy (ICT), financial development, and economic complexity (a proxy for the structural transformation) of the Chinese economy. We also include a unique measure of public sector corruption, which has been ignored in previous studies. To the best of these authors' knowledge, no studies have yet focused on the roles of innovation in green energy, digital economy, financial development, economic complexity, and public sector corruption in the inclusive and sustainable growth of China. Hence, this study is novel in this respect as well.

Fourth, this study applies novel methodologies to identify the relationship between green energy innovation and inclusive and sustainable development in China. First, the study checks stationary using the KPSS test, then it checks cointegration via the Pesaran Bounds test as well as the Bayer Hanck cointegration test. The Dynamic Autoregressive Distributed Lag (DYNARDL) simulation technique proposed by Jordan and Philips (2018) is used to understand the short-term and long-term implications of green innovation along with other variables on China's inclusive and sustainable development. A machine learning algorithm called Kernel Regularized Least Square Regression (KRLS) by Hainmueller and Hazlett (2014) is also employed. The dynamic ARDL simulation technique has a visual interface for estimating the possible counterfactual change in series. On the other hand, KRLS addresses classification issues without the need for strong functional form assumptions. Therefore, in contrast to previous literature, our study is unique in terms of the application of methodology.

The rest of the paper is designed as follows: the second part provides the literature review, the third part describes the data and methodology, the fourth part provides the result and discussion, and the final part concludes.

2 Literature review

Based on the variables selected for this study, subSect. 1 of this section talks about green energy and its relationship with sustainability and growth measures. SubSect. 2 provides an interaction of financial development, economic complexity, and dependent variable measures, and subSect. 3 talks about institutional quality, ICT, and growth and sustainability.

2.1 Green energy and inclusive and sustainable growth

Energy consumption concern from non-renewable sources has led to research on the use of green technology innovation and its relationship with growth and emission measures (Zheng et al., 2023). Chien et al. (2021), for example, used CS-ARDL to investigate how ecological innovation as well as two energy sources affect environmental factors. For the Asian nations, their study discovered that on both air pollution and emission measures, ecological innovation has negative influence. Along with ecological innovation, renewable energy had the same effect while nonrenewable had the opposite effect. Similarly, for Kazakhstan, Raihan and Tuspekova (2022) discovered that CO2 emission gets reduced due to technological innovation. How SDG trend was affected in G7 was examined by Yikun et al. (2022). The authors demonstrated that sustainability of the environment was enhanced by technology innovations and green growth. On the other hand, social development was also enhanced through green technology innovations.

According to Hussain et al. (2022), green technology has the capacity to increase green growth as they found for economies with higher GDP. Ahmad et al. (2023), on the other hand, showed that technological innovation has the capability to enhance sustainable development through ARDL model. Using the panel version of ARDL, Chen et al. (2023) indicated that green growth can be achieved through environment-related technologies. In another research, Zhao et al. (2024) found that green technology innovation enhances the reduction of pollution and carbon efficiency.

In one study for China, Bai et al. (2020) found that technological innovation in renewable energy has the capability to decrease carbon emissions. But, if inequality increases, this abatement effect will not be materialized. In that case, technological innovation in the renewable energy sector can positively affect carbon emissions. Using the threshold panel model, the authors showed that with respect to income inequality, the effect of renewable innovation on emissions has a threshold effect. It was mentioned that the innovation in renewable energy has no significant impact on emissions if income inequality is lower than the threshold.

In panel data for 285 Chinese cities, Dong et al. (2024) investigated how green finance affects inclusive development. Using several benchmark regressions and IV-GMM, green finance has a positive and asymmetric effect on this type of development. It has a higher promotion effect in cities where inclusive development is at the lower level.

Taking data from 2002 to 2022 for China and employing the same analysis technique of this study, Zhang et al. (2024) investigated the nexus between renewable energy innovation and CO2 emission. The authors found that long-run and short-run coefficients show a negative relationship between these variables. Using novel regression methods, Jiang et al. (2024) proved that R&D expenditure related to the clean energy sector promotes environmental quality by decreasing emissions from a consumption perspective. The study also found that green innovation is favorable for improved quality of the environment.

Lin et al., (2024a, 2024b) used methods such as PMG and Westerlund and Edgerton (2007) cointegration method for 274 cities in China. Cointegration relationship was discovered between green development and green innovation. It was found that during the long term, green innovation affects green development in a positive way. However, for the short run, green innovation was not able to influence green development. Region-wise, it was found that green innovation promotes development in the long run in central, western, and eastern regions. However, in the short run, the effect of green innovation on development was detected only in the Western part.

2.2 Financial development, economic complexity and inclusive and sustainable growth

Another strand of literature that is important to this study is financial development, economic complexity and sustainable development. In this regard, Cao et al. (2022) using spatial techniques found that local green growth is negatively affected by financial development, but surrounding provinces' green growth is positively affected by the same variable. Abid et al. (2022), however, demonstrated that financial development can help to attain sustainability of the environment.

In the study of Yu et al. (2022), it was found that environmental pollution is lowered through the mechanism of economic complexity N-11 countries. In China, Ibrahim et al. (2022) discovered inconsistent relationship between economic complexity and sustainable growth. On the other hand, Wang et al. (2022), for BRICS, discovered that economic complexity promotes green growth. Wang et al. (2023) further confirmed the result of Wang et al. (2022). The studies of Rafique (2022) and Neagu et al. (2022) indicated that economic complexity raises ecological footprint.

In a recent study, Lin et al., (2024a, 2024b) showed that green economic growth is promoted by economic complexity, which enhances capacitky of green technological innovation and facilitates industrial structure upgrading. Huang (2024) found that in BRICS, financial development has a favorable impact on green growth. They established this fact using dynamic system panel data for the 1990–2021.Lyu et al. (2024) established that green finance policy is conducive to the green development of enterprises in China. In another research, Zhang and Zhao (2024) demonstrated that green finance is good for economic development.

2.3 Institutional quality, ICT and inclusive and sustainable growth

Closely linked to the issue of inclusive and sustainable growth is the issue of corruption and information and communication technology (ICT). Tawiah et al. (2023) has termed corruption as a cultural and social epidemic which can threaten environmental quality. indicated that the relationship between corruption and green growth is negative and significant. In their paper, they used more than 100 countries to investigate how green growth can be undermined by corruption. Their findings indeed suggest that corruption is bad for green growth.

For Africa, Hope (2024) discovered that corruption hampers sustainable development and SDG objectives. For developing nations, Khan and Hassan (2024) revealed that if corruption can be controlled, then CO2 emissions can be effectively reduced. Tawiah et al. (2024) investigated the nexus between corruption and green growth for over 100 countries. They established that corruption undermines green growth. For the panel of commonwealth economies, Hwang et al. (2024) found that corruption undermines growth and indirectly decreases emissions, but its direct effect on emissions is positive. In another study, Jiang et al. (2024) discovered that decreasing political risk increases environmental quality.

On the other hand, Chen et al. (2022) examined ICT impact on green growth in China. They demonstrated that ICT has the capability to decrease emission and improve green growth. Fan et al. (2023) got a similar finding to the study of Chen et al. (2022) using the quantile autoregressive distributed lag technique. In Saudi Arabia, in the short run, Kahouli et al. (2022) found that the link between ICT and the ecological footprint is negative.

Tahsin (2022), in a similar fashion, used a panel ARDL technique on data from selected Asian countries from 1990 to 2018. The findings demonstrated that environmental pollution decreased when a reasonable level of ICT was achieved.

Lin et al., (2024a, 2024b) also demonstrated that green development could be motivated by the digital economy in Chinese cities. In contrast to green innovation, the authors discovered the positive linkage between the digital economy and green development. In the short run, in the Western region, the digital economy could not influence green development. However, in the long run, it affected the development of eastern, western, and central regions.

3 Data and methodology

3.1 Data description

This paper aims to examine the relationship between green energy technology innovation, financial development, economic complexity, financial development, ICT (proxy for digital economy) and public sector corruption in China over the period 1990–2018. The data availability is based on the data for the dependent variable, which is only available up to 2018. Equation (1) shows the empirical model for the analysis:

$$\ln INSGR_t = \beta_1 \ln GTECH_t + \beta_2 \ln FD_t + \beta_3 \ln ECI_t + \beta_4 \ln ICT_t + \beta_5 \ln PUBCOR_t + \varepsilon_t \quad (1)$$

In the above Eq. (1), INSGR is the inclusive and sustainable growth or development, GTECH refers to green energy technologies, FD is financial development, ECI is economic complexity index, ICT is information and communication technology representative of the digital economy, PUBCOR is public sector corruption, ln denotes the logarithm form and error term is represented by ε. Table 1 gives data description, period of study as well as the variables' sources.

Inclusive and sustainable growth is within the context of the Multidimensional Inclusiveness Index (MDI) and Achievement Index (ACHI) proposed by Dorfell and Schuhmann (2022). The MDI-ACHI plus defines inclusive development that is pro-human and adopts factors critical for well-being. According to Dörffel and Sebastian (2022) inclusive development is societal advancement that includes citizen empowerment through participation and fosters outcomes related to human well-being in line with the sustainability of societal foundations. As an essential component of sustainable development, we added green energy technology innovation from the WIPO database and ICT from WDI to the

Table 1 Data Description, period of study, and data sources

Data	Description	Period	Source
INSGR	Inclusive and sustainable growth	1990–2018	Dorfell and Schuhmann (2022)
GTECH	Green energy technology innovation	1990–2018	WIPO
FD	Financial development	1990–2018	IMF
ECI	Economic complexity (structural transformation)	1990–2018	Harvard's Growth Lab
ICT	Information and communication technology	1990–2018	WDI
PUBCOR	Public sector corruption	1990–2018	VDEM

empirical model. Green energy innovation is a summation of several technologies such as wind, solar, hydro, geothermal, and fuel cells. Digital economy as represented by ICT denotes the average of subscriptions of mobile phones, fixed phones, and broadband, as well as individuals having internet. The reason why studies utilize institutional quality measures is to observe the impact of the quality of institutions in the country. We selected public sector corruption as a measure of institutional quality, and this variable was collected from VDEM. By employing economic complexity, we proxied structural transformation and intend to see the impact of structural transformation on inclusive and sustainable growth. Finally, we put financial development in the empirical model to get an idea of China's financial market and economic freedom. Financial development data comes from the IMF, while economic complexity comes from the atlas of economic complexity at the growth lab of Harvard. Figure 3 provides a scatterplot matrix of the variables used in this study.

3.2 Methodology

The study applies several pre-diagnostic tests before proceeding toward the Dynamic Autoregressive distributed Lag (DYNARDL) estimation. Firstly, the KPSS unit root test is utilized in order to see the stationary properties of the variables. Then, we apply the Pesaran et al. (2001) test for cointegration and the cointegration test of Bayer and Hanck (2013). Here, by unit root, it means that the shock to the series has a permanent effect, whereas stationarity refers to the statistical property of a time series over time. If a time series is stationary, its mean, variance, and autocovariance are independent over time (Holden &

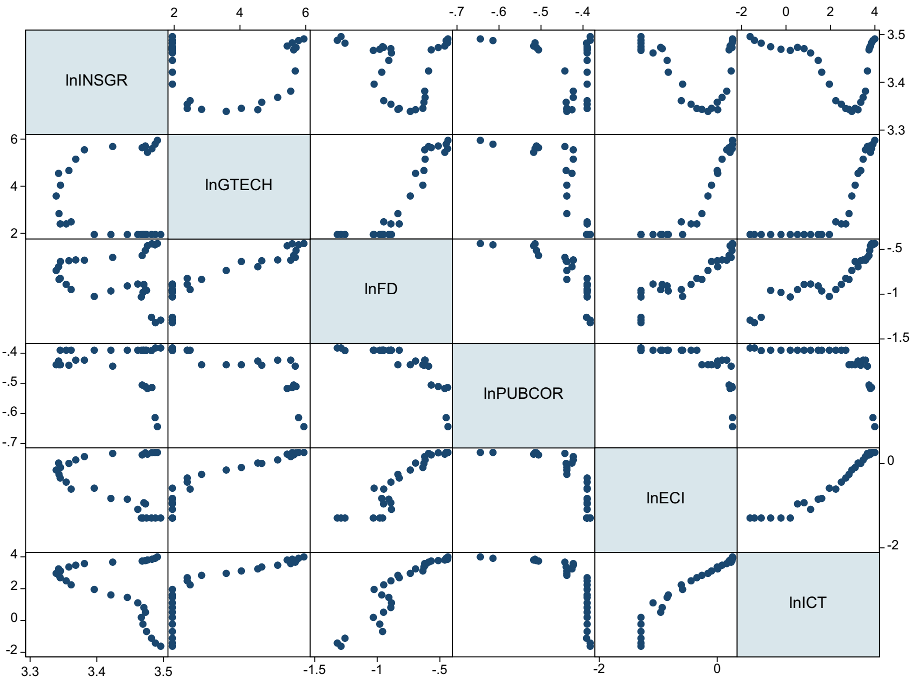

Fig. 3 Scatterplot Matrix of the variables of interest

Perman, 1994). Stationary also means mean-reverting data. On the other hand, cointegration means long-run relationships among the variables (Jalil & Rao, 2019).

Further to cointegration, we apply a novel econometric approach, the dynamic ARDL model, suggested by Jordan and Philips (2018). ARDL or Autoregressive distributed lag models are used when there is a mixture of stationery, such as I(0) and I(1). However, the dependent variable cannot be I(1), and none of the independent variables can be I(2). Here, I(0) means stationary at level, I(1) means stationary after the first differencing, and I(2) means stationary after the second differencing. In time series, if the dependent variable is estimated in the first difference or level, ARDL can test different theories. These models often have complex dynamic specifications, including lags, first differences, and lagged first differences. That is why a dynamic version of ARDL was introduced. A dynamic simulation is an alternative to hypothesis testing and conveys the results' significance via counterfactual scenarios (Jordan & Philips, 2018). In the ARDL model, given a change in a variable, the response in the dependent variable over time is simulated. These changes in x variables and associated responses in the dependent variable are called counterfactual responses. Here, it means a simulated response to a controlled shock (Jordan & Philips, 2019).

Dynamic ARDL is an advanced method that corrects the complex structure of the traditional ARDL model and enables the capture of short- and long-term relations among series. The model also utilizes stochastic simulation tests to estimate and simulate the impact of shocks in the model (Danish & Ulucak, 2022). The other advantage of this test is delivering graphically predicted findings. By using this method, short and long-term changes (positive or negative) might be graphically captured (Khan et al., 2021). Through these robust features, we utilized the dynamic ARDL model. Equation (2) shows the dynamic ARDL error correction model:

$$\begin{aligned}\Delta \mathrm{lnINSGR}_t = \beta_0 &+ \beta_1 \Delta \mathrm{lnINSGR}_{t-1} + \beta_2 \Delta \mathrm{lnGTECH}_t + \beta_3 \mathrm{LNGTECH}_{t-1} + \beta_4 \Delta \mathrm{LNFD}_t \\ &+ \beta_5 \mathrm{LNFD}_{t-1} + \beta_6 \Delta \mathrm{LNECI}_t + \beta_7 \mathrm{LNECI}_{t-1} + \beta_8 \Delta \mathrm{LNICT}_t + \beta_9 \mathrm{LNICT}_{t-1} \\ &+ \beta_{10} \Delta \mathrm{LNPUBCOR}_t + \beta_{11} \Delta \mathrm{PUBCOR}_{t-1} + \varepsilon_t\end{aligned} \tag{2}$$

Here, Δ refers to first differencing, β refers to coefficient, ln refers to logarithm, t refers to time. t-1 is one period lag, and ε is the error term.

Further, we apply the Kernel Regularized Least Square regression (KRLS) as a robustness analysis. In general, regularization methods are implemented when OLS is not possible because of a singular design matrix (Obi & Jecinta, 2023). KRLS is a machine learning algorithm by Hainmueller and Hazlett (2014). This approach allows us to estimate regression and address the classification issues without the need for strong functional form assumptions. It also provides inferences regarding the misspecification bias. This method is considered a robust estimator compared to OLS and GLM methods (Minviel & Ben Bouheni, 2022).

4 Empirical findings

Table 1 summarizes the statistics. Among the variables, the highest mean value is observed for lnGTECH (green energy technology innovation), followed by lnINSGR (inclusive and sustainable growth). The highest maximum value is observed for lnGTECH. The standard

Table 2 Descriptive statistics of the variables

	Observations	Mean	Standard deviation	Minimum	Maximum
lnINSGR	29	3.43	0.06	3.339102	3.495919
lnGTECH	29	3.47	1.65	1.94591	5.945421
lnICT	29	2.05	1.79	-1.617212	3.997703
lnFD	29	-0.80	0.25	-1.319064	-.434993
lnECI	29	-0.45	0.60	-1.292988	.2596969
lnPUBCOR	29	-0.44	0.07	-.644357	-.382726

deviations are also reported, with (lnICT Information and communication technology) having the highest standard deviation and the dependent variable having the lowest standard deviation. (Table 2)

Table 3 provides the result for the KPSS test to confirm the variables' stationary status. From the table, it can be observed that lnINSGR, lnICT, and lnPUBCOR (Public sector corruption) are I(1) while lnGTECH, lnFD (financial development), and lnECI (economic complexity /structural transformation) are I(0). This requires implementing the ARDL model. Having no I(2), dynamic ARDL model can be now applied.

In Table 4, optimal lag length criteria are provided. The Table demonstrates that lag length 1 can be selected based on the three information criteria. Now that we have determined stationarity and lag length, the cointegration test can be estimated. Table 5 provides the result for the bounds test, and Table 6 provides the Bayer Hanck Cointegration Test. The F statistics (7.4) in the bounds test is higher than the I(1) critical value at even 1%, implying the existence of cointegration. From Table 6, we can also confirm cointegration among the variables since the values of the two test statistics are higher than the critical values.

Table 3 Result of KPSS unit root test

	KPSS		
Variables	Level	First Difference	Comment
lnINSGR	0.164 *	0.093	I(1)
lnGTECH	0.132	–	I(0)
lnICT	0.187*	0.078	I(1)
lnFD	0.061	–	I(0)
lnECI	0.130	–	I(0)
lnPUBCOR	0.171*	0.135	I(1)

[*] represents 10% significance level

Table 4 Result of Optimal Lag Selection Criteria

Lag	LL	LR	df	p	FPE	AIC	HQIC	SBIC
0	89.881				8.10E-11	-6.21341	-6.12778	-5.92544
1	302.794	425.83	36	0	1.8e-16*	-19.3181	-18.7187*	-17.3024*
2	342.945	80.301*	36	0	2.00E-16	-19.6255*	-18.5124	-15.882

* sign here means optimal lag

Table 5 Result of Pesaran et al. (2001) test for Cointegration

F statistics	Critical Values	I(0)	I(1)
7.420	10%	2.578	3.858
	5%	3.125	4.608
	1%	4.537	6.370

Table 6 Result of Bayer Hanck test for Cointegration

	Test statistics	1% Critical Value	5% Critical Value	10% Critical Value
EG-JOH	55.575818	15.701	10.419	8.242
EG-JOH-Bo-BDM	110.88276	29.85	19.888	15.804

Table 7 Dynamic ARDL simulation result (Short and Long run)

Variables	Coefficient	Std. err	P>t
	Short run		
lnGTECH	-0.00778	0.011133	0.494
lnICT	-0.04373	0.038907	0.278
lnFD	0.05694	0.031472	0.089
lnECI	0.003853	0.029622	0.898
lnPUBCOR	-0.18609	0.086167	0.046
	Long run		
lnGTECH	0.018578	0.00695	0.017
lnICT	-0.00751	0.010149	0.47
lnFD	0.059403	0.036872	0.127
lnECI	-0.03901	0.043013	0.378
lnPUBCOR	0.126989	0.082955	0.145
Adj. Term	-0.18159	0.08164	0.041
Constant	0.664328	0.262077	0.022
F(11, 16) = 7.03			
R-squared = 0.8286			
Adj R-squared = 0.7107			
Simulation = 1000			
Root MSE = .00902			

After capturing cointegration, we examine short and long-term coefficients using the dynamic ARDL test. Table 7 shows the results.

According to the dynamic ARDL test results, during short run, only lnFD and lnPUBCOR have significant impacts on lnINSGR. Only lnGTECH has a significant positive impact in long run, while none of the other variables are significant. These results are discussed in the next step. Finally, we apply diagnostic tests to decide whether the findings are reliable in Table 8. The diagnostic test results show that heteroscedasticity, autocorrelation, and ARCH effects do not exist, but normality is rejected for the residual. Additionally, Figs. 4 and 5 show that the model is stable.

Table 8 Results of Diagnostic Tests

White's test for heteroscedasticity	28.00	0.4110
BGLM test for autocorrelation	0.002	0.9608
Durbin's alternative test for autocorrelation	0.002	0.9668
ARCH Test	0.549	0.4585
Skewness and kurtosis tests for normality	5.88	0.0529

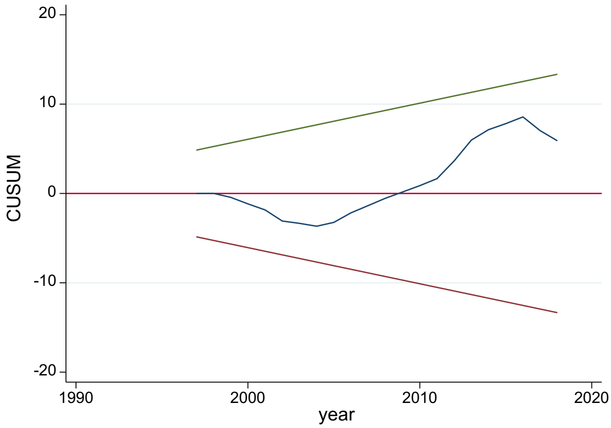

Fig. 4 CUSUM Plot for model stability

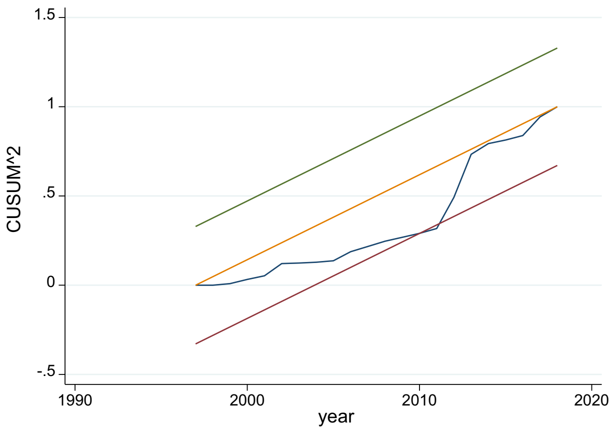

Fig. 5 CUSUM Square Plot for model stability

Since the 1980s, the negative consequences of environmental events on human development and welfare have made sustainable development the primary target (Munasingle, 2009). Sustainability policies have triggered many environmental projects contributing to the low-carbon economy model (Zhang et al., 2022). In addition, technological innovations facilitate the achievement of SDGs by supporting green growth (Yikun et al., 2022). Recently, it is seen that sustainable development policies have been tried to be put into practice in China. As the world's second-largest economy, China can use this advantage as an essential driver for sustainable development in the long run. Rodrik (2006) attributed

China's high economic growth to producing high-value-added products. In this context, our empirical results show some signals for China's inclusive sustainable growth policies.

First, green energy technology innovation contributes to inclusive sustainable development in China in the long run. As expected, green energy technology innovation promotes a low-carbon economy and enhances energy efficiency. The positive result happens because green technology innovation has the capability to decrease pollution and improve carbon efficiency and green total factor productivity (Lin et al., 2024a, 2024b; Zhao et al., 2024). Jiang et al. (2024) also found that indicators of renewable innovation, such as green innovation and R&D of clean energy, help decrease consumption side emissions and improve sustainable development. The positive result corresponds to the neoclassical growth theory, where technological change is considered to be the main driver behind economic growth. It also corresponds to the national innovation system as advanced by institutional and evolutionary explanations of economic growth at the national level. Romer's endogenous theory also emphasized this fact (Sredojević et al., 2016). The short-term insignificant result and the long-term significant result could be because of the fact that green innovations may provide low returns in the short term, but they become profitable investments by reducing compliance costs of regulation in the long term (Aldieri et al., 2021). Another essential advantage of green innovations is that they do not hurt environmental protection while boosting economic growth (Aggeri, 1999). The negative result in the short run can be explained by the findings from Bai et al. (2020), who discovered that renewable energy innovation can increase emissions in high-income inequality intervals. The short-run insignificant result can also be explained by the fact that the effect of green innovation on green development varies by region in China, where several regions show an insignificant effect of green innovation on green development (Lin et al., 2024a, 2024b).

A positive impact of structural transformation on inclusive and sustainable development can also be observed in the short run. However, the effect is insignificant. The positive result is because structural transformation profoundly relates to sustainable development (Dinda, 2004). The most important factors affecting the economic complexity index are the diversification of exports, the ability to export high-tech products, research and development (R&D) expenditures, and human capital (Yalta & Yalta, 2021; Zhu & Li, 2017). Therefore, promoting these will boost economic complexity, and economic complexity will significantly affect development. In the long run, we found that the effect of economic complexity is insignificant and negative on lnINSGR.

Public sector corruption can be seen to have negative effects on the inclusive green growth of China in the short run but insignificant effects in the long run. Specifically, a 1% increase in public corruption lowers inclusive and sustainable development in China by 0.19%. This finding is supported by several theories and empirical literature. This negative result supports the 'sand the wheels' theory, which states that corruption is bad for economic development, and contradicts the "grease the wheels" theory, which mentions that corruption is good for development (Nur-tegin & Jakee, 2020). For African economies, Hope (2024) found a similar result where corruption undermined the achievement of SDGs or overall sustainable development. Since inclusive and sustainable growth emphasizes environmental sustainability, it can be seen from empirical literature that corruption also has the capacity to decrease environmental sustainability by increasing CO2 emissions (Hwang et al., 2024; Khan & Hassan, 2024). In another study of 100 global countries, Tawiah et al.(2024) also supported our conclusion by stating that green growth is undermined by corruption.

Digital economy indicator ICT is found to have a negative effect on lnINSGR. However, the effect is insignificant. Many studies found that ICT may be helpful in achieving sustainable growth (Jayaprakash & Radhakrishna Pillai, 2022; Latif et al., 2017; Nchofoung & Asongu, 2022). However, according to our empirical results, ICT is not helpful for China's inclusive, sustainable development path. Contrary to this finding, Chen et al. (2022) found that ICT enhances environmental sustainability and green growth.

In our result, we capture the insignificant impact of financial development on inclusive, sustainable development in the long run, but it is significant and positive in the short run. The support for short-run results can be found in Huang (2024), who discovered that financial development favorably affects green growth for BRICS economies. Also, Zhang and Zhao (2024) mentioned that green finance is favorable to China's economic development. This result contradicts the finding of Cao et al. (2022), who discovered that financial development has a negative effect on the local green growth of Chinese provinces. Economists like Robert Lucas contradicted our finding that finance is good for development. He mentioned that it is an over-stressed determinant of growth (Levine, 2005). However, our result agrees with Schumpeter's theory (1911), in which he mentions the growth-inducing impact of a developed financial sector (Eschenbach, 2004).

Figures 6, 7, 8, 9, and 10 present the counterfactual shocks obtained from the DYNARDL model. These figures are obtained by applying 1000 simulations to the parameter vector in the DYNARDL model. These plots denote the change in sustainable, inclusive growth due to a one-standard-deviation positive and negative shock of independent variables.

In Table 9, we present the result of the machine learning algorithm called Kernel Regularized Least Square (KRLS) regression result. The table shows the average marginal effect and three quartiles of marginal effects. The model has a predictive power of 0.99, meaning that the independent variables can explain almost 99% of variations in inclusive and sustainable growth. The average result of lnGTECH matches with the short-run finding from DYNARDL, while the higher quantile result shows similarity to the long-run result. In contrast to DYNARDL, the effect of ICT is significant, but the sign matches. Both financial development and economic complexity have positive effects on lnINSGR. The result of FD matches that of DYNARDL, but ECI's effect only matches the short-run result. Finally, the effect of PUBCOR on INSGR is negative, which matches the outcome of DYNARDL.

5 Conclusion and policy implications

This study aims to understand how green energy technology affects inclusive and sustainable growth or development in China, considering the period from 1990 to 2018. Besides green energy technology innovation, the study considers financial development, economic complexity, digital economy or information and communication technology infrastructure, and public sector corruption as control variables. The study first performs several pre-diagnostic tests to confirm the use of dynamic ARDL. These pre-diagnostic tests include the KPSS unit root test, optimal lag criteria selection, Bounds test, and Bayer Hanck cointegration techniques. The study then performs dynamic ARDL to estimate short and long-run coefficients and the KRLS machine learning method to understand average and quantile marginal effects.

The findings from the unit root test confirm that variables are a mixture of I(0) and I(1), which allows us to proceed with the cointegration approach. The two cointegration tests

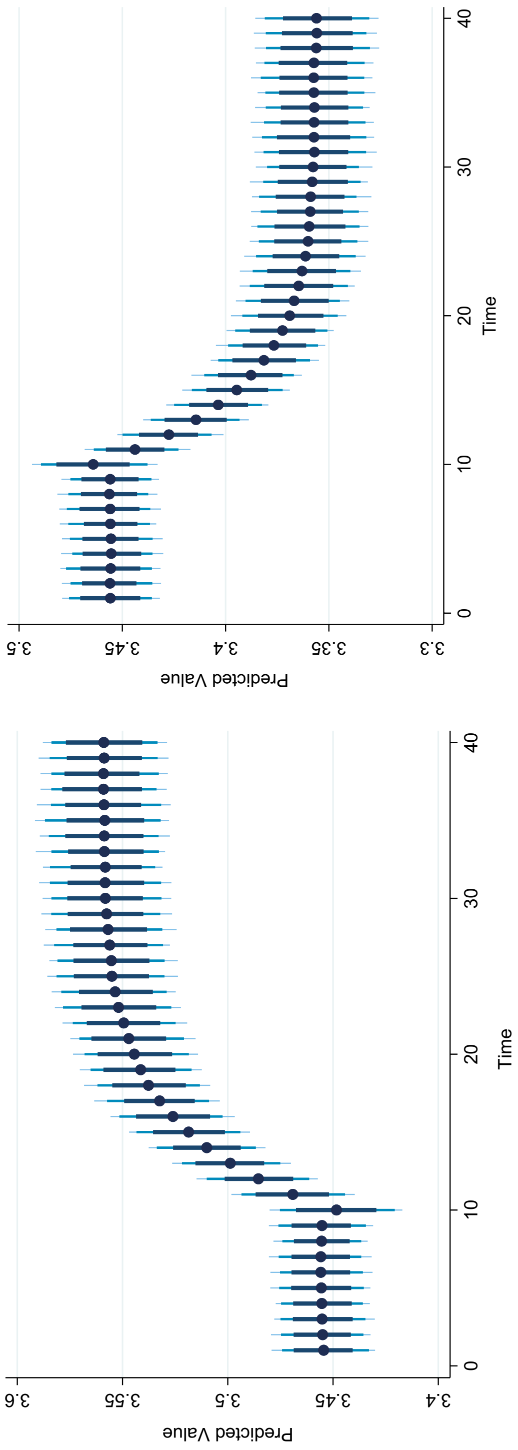

Fig. 6 Positive and negative SD shock to lnGTECH

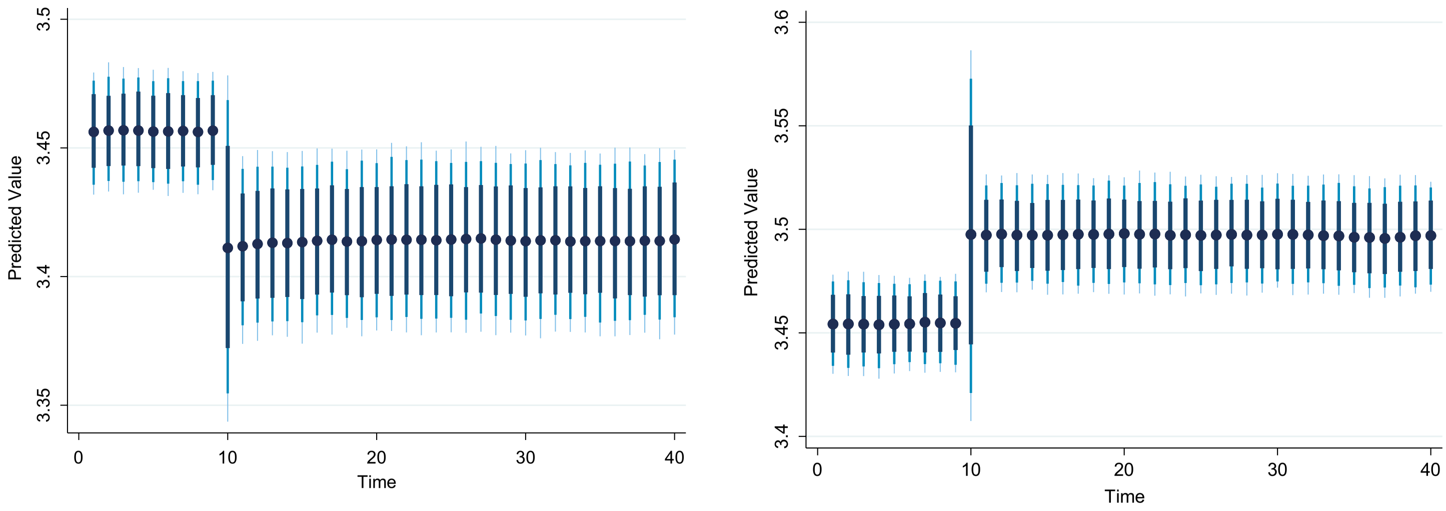

Fig. 7 Positive and negative SD shock to lnICT

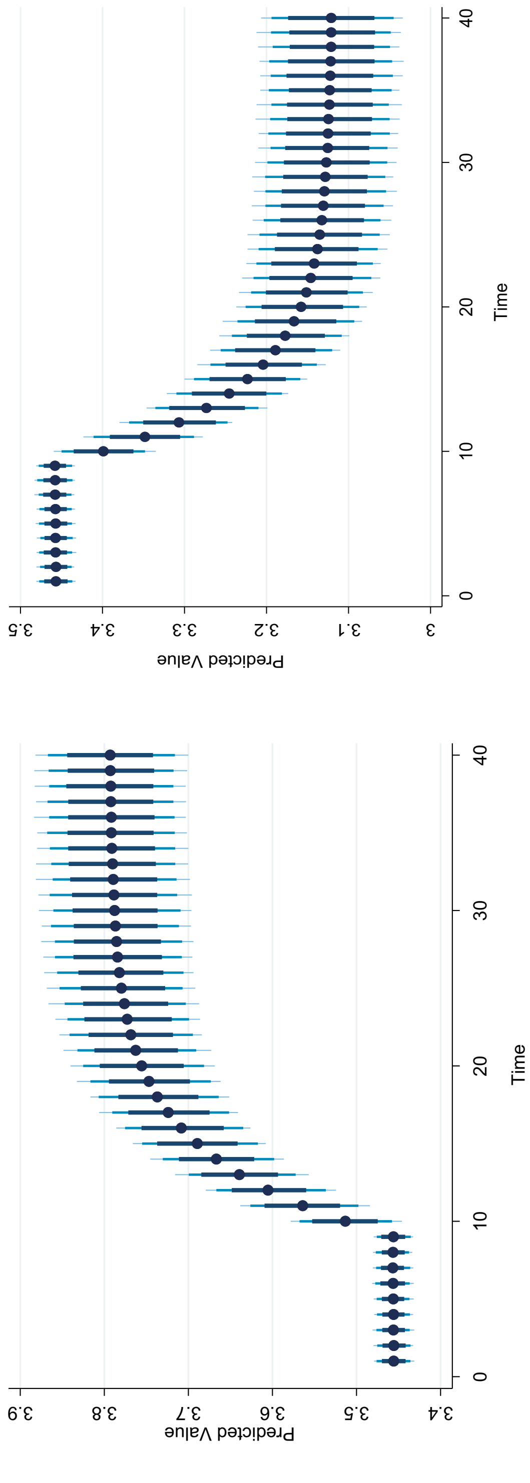

Fig. 8 Positive and negative SD shock to lnFD a

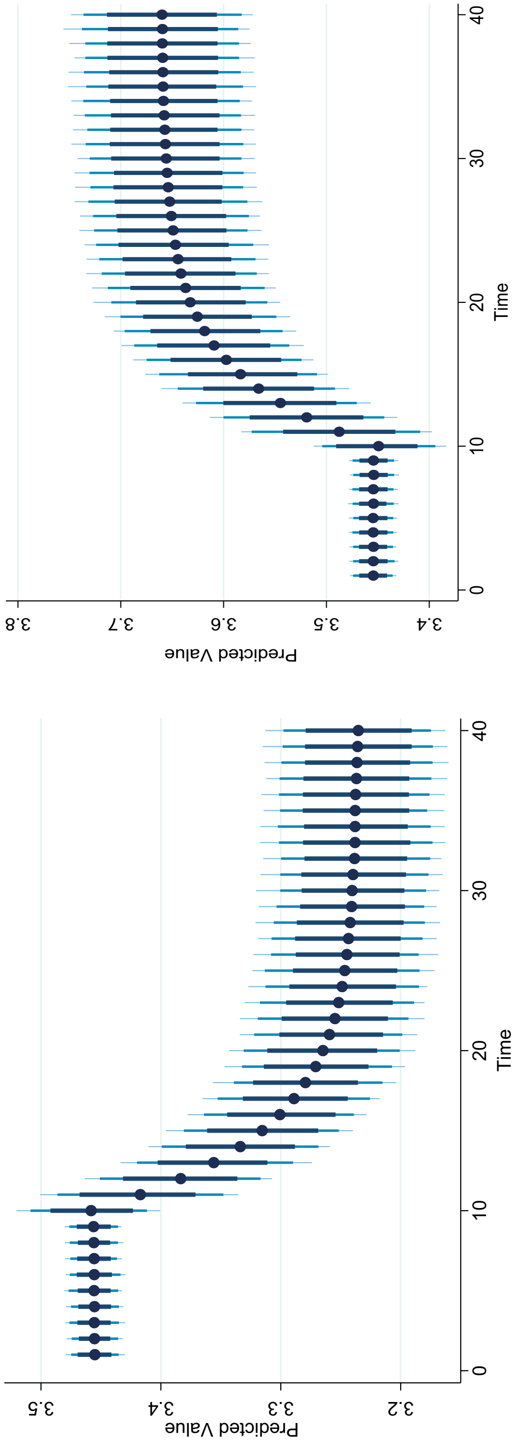

Fig. 9 Positive and negative SD shock to lnECI

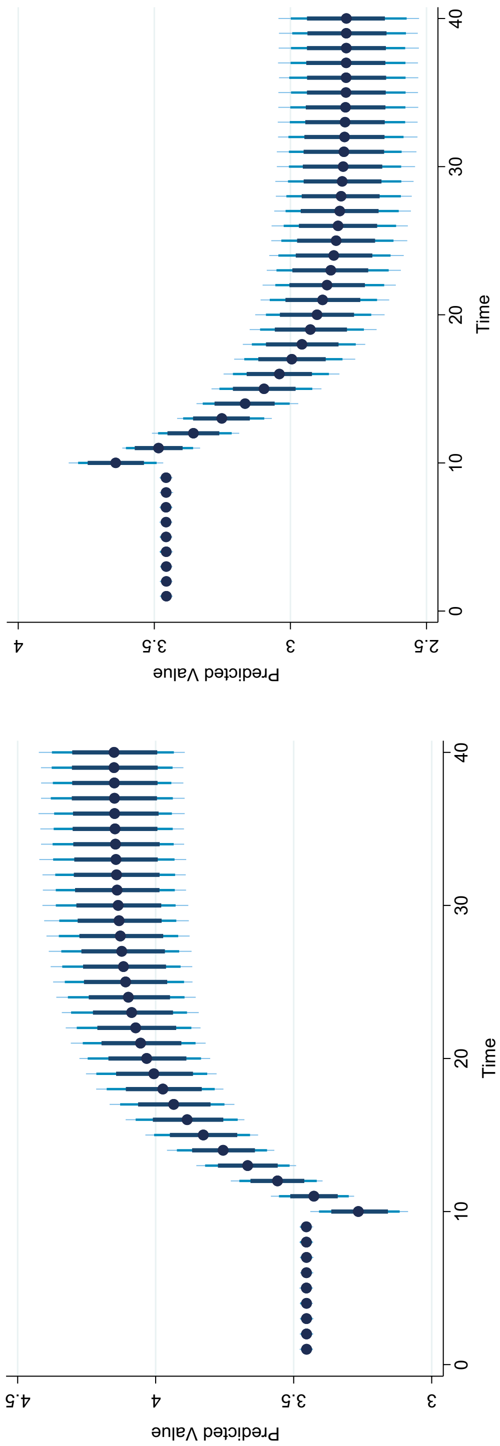

Fig. 10 Positive and negative SD shock to lnPUBCOR

Table 9 Result of Kernel Regularized Least Square Regression (KRLS) as robustness

Variables	Avg	SE	P>t	P25	P50	P75
lnGTECH	-0.00228	0.001707	0.194	-0.02171	-0.0044	0.019413
lnICT	-0.01077	0.001347	0	-0.02544	-0.00636	0.002484
lnFD	0.050694	0.013181	0.001	0.014884	0.04386	0.084618
lnECI	0.001346	0.004861	0.784	-0.03056	0.018354	0.034287
lnPUBCOR	-0.24643	0.039365	0	-0.64542	-0.03098	0.042835
Lambda = .05587						
Tolerance = .029						
Sigma = 5						
Eff. df = 10.97						
R2 = .9914						
Looloss = .03614						

then confirm the long-run association among the variables. From the short-run coefficient of DYNARDL, it was revealed that financial development and public sector corruption significantly affected the inclusive and sustainable growth in China. Specifically, financial development had a positive impact, while public sector corruption had a negative effect. In the long run, only green energy technology innovation had a positive impact on inclusive and sustainable growth. The effects of digital economy or ICT and economic complexity were found to be insignificant in both the short and long run. However, ICT had negative effects, while economic complexity had varying effects depending on the time structure (short run vs long run).

Based on these findings, several policy implications can be suggested for China. First of all, if the country wants to achieve both inclusive and green growth, it must invest significantly in green energy technology in the long run. While the short-run result shows an insignificant impact, the effect can be reversed if there is a significant investment in renewable energy technology. Banks can provide households and businesses with loans to access these technologies. The government can provide subsidies and different incentives for adopting these technologies so that producers feel interested in investing in these technologies. UNCTAD (2023) states that the cost of capital is the main barrier to implementing green energy technology. In this regard, de-risking investments in these technologies are needed. Three specific policy aspects, public investment, private investment, and regulation are needed. Regarding regulation, grid access priority, access to land, industry structure, license, and permit system are important. Incentives and risk-decreasing measures fall under private investment, while public investment includes direct investment by the state in generation capacities via PPPs and public enterprises and R&D. Tax incentives, feed tariffs, auctions, and financial incentives (e.g., direct subsidies, subsidized loans) should be emphasized. Other tools, such as renewable portfolio standards or quotas, renewable energy certificates, and guarantee schemes, can also help. China's investment in green energy technology will make energy consumption cleaner, create more employment opportunities, and promote inclusive economic growth while advancing environmental sustainability.

Since economic complexity has a short-run positive impact but a long-run negative impact, it may be stated that it is not good for long-term sustainable growth. Hence, a green structural transformation is required, which will facilitate the transformation of the economy into a green economy. The same can be said for the ICT sector, which must invest heavily in climate-friendly ICT products. Trade of polluted-related ICT products should be limited, and environmentally friendly ICT should be traded and produced to reduce inequality and conserve the environment. Since financial development positively affects the development pattern, China must continue on its path in developing its financial sector. It must continue to develop carbon–neutral bonds, green bonds, green loans, and sustainable finance policies (Sheng and Geng, 2023). Moreover, the government should try to limit public sector corruption to proceed toward achieving its carbon neutrality goals and obtain sustainable development.

The study has some limitations. For example, it was only concerned with China, but future studies may consider comparing the sustainability and inclusiveness benefits of green or renewable technology innovation in China with other countries. More machine learning methods can be adopted to compare the performance across the models.

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Data availability The data are available from the corresponding author on reasonable request.

Declarations

Conflict of interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

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