Received: 22 April 2022 | Revised: 25 May 2022 | Accepted: 29 May 2022

https://doi.org/10.56946/jeee.v1i1.351

Journal of Environmental and Energy Economics

Research Article

The influence of Information and Communication Technologies, Renewable Energies and Urbanization toward Environmental Sustainability in China

Asif Raihan[1*], Mohammad Ridwan[2], Tipon Tanchangya[3], Junaid Rahman[3], Shakil Ahmad[4]

[1]Institute of Climate Change, Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia.
[2]Department of Economics, Noakhali Science and Technology University, Noakhali 3814, Bangladesh.
[3]Department of Finance, University of Chittagong, Chittagong 4331, Bangladesh.
[4]School of International Trade and Economics, University of International Business and Economics, Beijing, China.

*Corresponding author: asifraihan666@gmail.com, ORCID ID: 0000-0001-9757-9730

Abstract
The smart cities strategy is crucial to safeguarding the environment, which is possible with the help of renewable energy and information and communication technologies (ICTs). Therefore, this research investigates the effect of ICT, green energy or renewable energy, urbanization, and economic growth (GDP) on environmental sustainability in China. The study employed the autoregressive distributed lag (ARDL) method to analyze the data. The findings demonstrate that ICT and renewable energy have an adverse and significant effect on carbon dioxide (CO_2) emissions in the country. It states that the rise of ICT and renewable energy increases the quality of the environment. On the other hand, urbanization and economic growth have a positive and significant impact on CO_2 emissions. The result argues that large-scale urbanization decreases the quality of the environment. The research recommends that ICT diffusion, renewable energy consumption, smart urbanization, and a low-carbon economy strategy assist in achieving environmental sustainability goals.

Keywords: Urbanization; carbon emissions, ICT, renewable energy, low-carbon economy, environmental sustainability.

Introduction

Nowadays, for sustainable economic development and industrialization, urbanization is playing an important role regardless of location [1]. Urbanization also helps businesses and individuals gain data and information, decrease operational expenses, and gain profit from native machines or technologies [2]. Moreover, alongside the improvement of urbanization, urban people cluster in specific locations, which advances in urban areas because of the availability of diversified commodities, large labor pools, and better public services [3]. Better public buildings help increase productive business. The procedures of urbanization lack municipal policies, which have several negative effects on the economy, significant expenses related to urbanization, and adverse environmental and sustainable effects [4]. A large portion of most people's income goes toward urban expenses, which lowers living standards in cities [5]. Moreover, the rise in CO_2 emissions within big cities adversely affects business progress [6]. To reduce the negative influences of urbanization, progressive countries and those with good municipal policies might shift more responsibilities to cities [7].

Under this circumstance, it is crucial to create the “smart cities” strategy. The “smart cities” strategy depends upon ICTs and smart transportation networks with a view to decreasing CO_2 emissions [8]. The Internet of Things (IoT), smart technologies, and automation are all made possible by ICT, which in turn makes people's lives and jobs easier (and less harmful) to the environment [9]. For this reason, smart cities require an important level of ICT acceptance. Only ICTs and emerging technologies do not provide sustainable economic development without adverse impacts on the ecology [10]. The consumption of resources and the related energy costs have negative effects on environmental quality in the creation and implementation of ICT infrastructure and devices, as well as in recycling materials [11]. Therefore, empirical research is essential to understand the several environmental impacts of ICT in metropolitan areas. Nevertheless, few studies have examined ICT, urbanization, and ecological damage [12]. Additionally, earlier research focused on the impacts of renewable energy, ICT, and economic development on environmental sustainability without addressing urban ICT [13]. Additionally, some studies have found a positive effect of ICT on ecological sustainability in urban areas [14]. Although the inherent urban aspects of different countries were not explicitly considered in this earlier research, urban costs were still expressly integrated into urban public transportation services.

This research's main objective is to scrutinize the influences of ICT, urbanization, renewable energy, and GDP on environmental sustainability in China. Nevertheless, the popular slogan "high pollution, high emissions, and low efficiency" is created to ensure economic development, whereas it is a challenge to save the environment through assimilating pollutants and impacts China in monetary terms. Over the last 40 years, more than 600 million people have shifted from villages to urban areas. However, China is one of the top-listed countries where most of the people live in cities. A report argued that about 300 million people will surprisingly relocate from village to village within the next three decades. It has now become a big concern that numerous illnesses have arisen due to urbanization. These problems created a number of barriers to the process of safe and sustainable urbanization. China has been playing a leadership role in developing smart cities for ten years in the world by implementing smart cities in the country. Hence, the researchers of this study have selected China to find out some of the following questions: (i) Are new innovations helpful for the ecosystem? (ii) Does the environmental impact of ICT grow as more projects use new technology and pollutants? (iii) Does the beginning of ICT with urbanisation have a good effect on the atmosphere?

The researchers in this study are motivated to conduct research on this topic. For the first time, the urbanization and modernization of societies have an important effect on the environment. Exploring the impact of urbanization and digitalization on environmental sustainability can be helpful for identifying the particular effects of these changes. And they can also help develop new policies to decrease the negative environmental effects. Secondly, nowadays, sustainable development is one of the burning issues in the world. Exploring the impact of urbanization and digitalization on a sustainable environment can offer important results that help policymakers ensure sustainable economic growth. Thirdly, digitalization and urbanization are the drivers of economic growth in most countries. So, exploring the effect of these factors on a sustainable environment can assist the governing bodies in ensuring economic growth without adverse influence on the environment. Lastly, urbanization and digitalization on environmental sustainability can play a role in increasing public awareness. This can support policies and motivate policymakers to take proper initiatives to reduce the adverse environmental impact.

Apart from these, this research would add great value to the existing literature. Firstly, for example, in recent years, China has taken proper strides through funding for new devices and ICT-oriented solutions with a view to decreasing its environmental adverse impact. Under this circumstance, this study provides insights into the literature by examining the impact of ICT on environmental sustainability in China from 1995 to 2020. Secondly, with the support of different technologies, China has created a positive scenario for urbanization. In this way, this study investigates the impact of urbanization on the environment, particularly on various CO_2 emissions. Thirdly, though prior studies focused on long-term analysis, this current research uses both short- and long-term analysis. Finally, the researchers of this study provide significant policy suggestions based on the findings in the cases of ICT diffusion, renewable energy consumption, smart urbanization, and a zero-carbon economy process that can unfold the gates for other countries so that they can work in the same lines in order to safeguard their environment.

Literature Review

Generally, urbanization is considered one of the environmental sustainable factors that contributes to promoting clean technologies, power efficiency, inventiveness, and environmental awareness [15]. The ecological digitalization theory of urbanization suggests that the higher the digitalization, the more enhanced power efficiency, green innovation, sustainable awareness, and essential change in the economy that promote the environment [16]. Therefore, creating cities in a sustainable manner is essentially what "smart urbanisation" is all about. There is very little literature based on the effects of smart urbanization on environmental sustainability.

Nevertheless, a number of studies have looked at the way conventional urbanisation affects environmental performance. Prastiyo and Hardyastuti [17] investigated the impact of urbanization, manufacturing, and agriculture on carbon pollution in Indonesia. They found a significant impact of the independent variables on carbon pollution. Sufyanullah et al. [18] found the inverse impact of urbanization on carbon pollution by using a cross-country study.

Zhou et al. [19] investigated how China's growing cities affect the country's carbon footprint. The contribution of their study was to explore how the supporting-structure processes of urbanization impact carbon footprint patterns. They found that the degree of CO_2 emissions changes from period to period and among urbanization systems. Hanif [20] discovered that urbanisation significantly affects CO_2 emissions in the context of nations in sub-Saharan Africa, using data from 1995 to 2015. Between 2002 and 2017, Dong et al. [21] included characteristics such industrialization, urbanisation, ecological protection, and economic growth in their research. They found that carbon emissions have an adverse impact on urban health. Mahmood et al. [22] used data from 1968 to 2014 to investigate the correlation between urbanisation and CO_2 emissions within the Saudi Arabian environment. They reported that the CO_2 footprint is boosted by urbanization. The study argued that the increase in urbanization presses on production activities where nonrenewable energy is used, releasing more carbon into the environment.

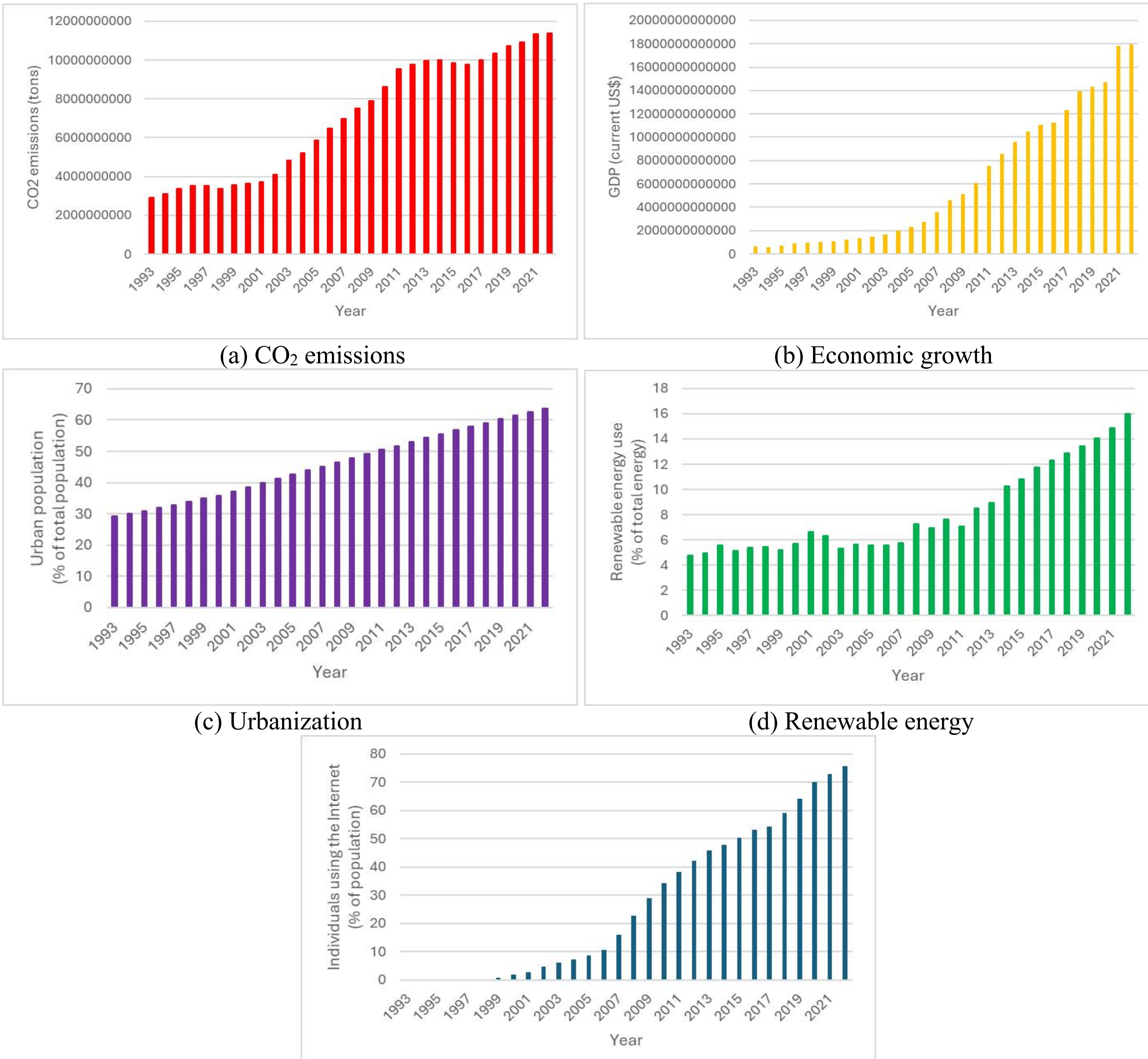
A study was executed regarding the association between ICT and CO_2 footprint by Chen et al. [23]. They found ICT has made a great contribution to increasing environmental sustainability, which plays a crucial role in social change. Lahouel et al. [24] found ICT has beneficial characteristics for reducing CO_2 emissions. Based on the emerging and industrialized countries, Awan et al. [25] found heterogeneous effect of online shopping on emissions. They argued that though internet usage mitigates CO_2 emissions in developed countries, online purchases have little negative impact on emissions in undeveloped countries. They suggest the main cause is the slow internet, which causes heterogeneous effects. Moreover, urbanization, nonrenewable power, and trade liberalization are the driving forces of economic development, which increase environmental inequality in both developed and undeveloped countries.

In addition to assisting in the reduction of CO_2 emissions, ICT has a favourable and substantial impact on economic growth in ASEAN nations, claim Lee and Brahmasrene [26]. Zafar et al. [27] reported that ICT contributes a positive role to emissions due to its energy-efficient production and low consumption of energy. Moreover, conducting a study between carbon emissions and ICT and considering 44 sub-Saharan countries, Asongu et al. [28] found that ICT has a significant impact on the CO_2 footprint, but the levels of environmental degradation decrease when ICT increases. By using the STRIPAT framework and province data, Zhang and Liu [29] conclude that ICT sectors help to decrease the CO_2 footprint in China. According to Salahuddin et al. [30], they investigated a relationship between internet usage and CO_2 emissions in the OECD countries' context. The findings of their study show their long-term impact on each other. In addition, numerous studies have found that renewable energy can reduce CO_2 emissions all over the world. However, in spite of the numerous studies available on the energy-economy-environment nexus, there is still an empirical research gap between urbanization, ICT, and environmental quality. Therefore, the literature review of this study highlights the comprehensive association of ICT and urbanization with environmental sustainability in China.

Methodology

Implications for China's CO_2 emissions from ICT, renewable energy, urbanization, and GDP growth were examined in this research. The study spanned the years 1993–2022, and it made use of the ARDL approach. Data on renewable energy and emissions of CO_2 were obtained from Our World in statistics, while the data on urbanization, information and communication technology, and GDP originated from the World Development Indicators (WDI). The yearly patterns of the variables are shown in Figure 1. Data normality was ensured by transforming the variables into natural logarithms.

The chosen variables offer a comprehensive view of the multifaceted factors influencing China's CO_2 emissions. Urbanization data is crucial as urban expansion significantly impacts energy consumption and transportation, directly influencing emissions. ICT represent a modernizing economy, but its relationship with emissions is complex, necessitating examination. Renewable energy data is vital due to its potential to mitigate emissions, highlighting the importance of sustainable energy sources. GDP growth serves as a proxy for economic activity, which typically correlates with emissions, but its impact can vary based on factors like technology efficiency. By incorporating these variables, the study captures the intertwined dynamics of economic development, technological advancement, and environmental concerns, providing valuable insights for policymakers and stakeholders aiming for sustainable emission reduction strategies in China.



(a) CO_2 emissions

(b) Economic growth

(c) Urbanization

(d) Renewable energy

(e) ICT

Figure 1. Annual trends of the variables.

This study utilizes the following econometric model to explore the relationship between variables:

$$LC_t = \tau_0 + \tau_1 LI_t + \tau_2 LU_t + \tau_3 LY_t + \tau_4 LR_t + \varepsilon_t \quad (1)$$

Where, LC_t, LI_t, LU_t, LY_t, and LR_t are the logarithmic form of CO_2 emissions, ICT, urbanization, economic growth, and renewable energy consumption at time t.

Stationarity tests are essential in time series analysis for several reasons. Primarily, they assure the dependability of statistical studies by assessing whether the data has stable statistical features across time. Stationarity refers to the condition where the average, spread, and pattern of correlation in a series stay consistent throughout time. This is crucial for generating precise predictions and reaching reliable conclusions [31]. Furthermore, stationarity enables the use of different time series models that make assumptions about consistent statistical characteristics. Recognizing non-stationarity alerts professionals to the need of making data transformations or model modifications in order to achieve stationarity, hence enhancing the precision of predictions and mitigating the possibility of misleading outcomes [32]. Conducting stationarity tests is essential for guaranteeing the strength and efficiency of time series analysis in identifying underlying trends and producing accurate predictions [33]. This study employed the Augmented Dickey-Fuller (ADF) test [34], the Dickey-Fuller generalized least squares (DF-GLS) test [35], and the Phillips-Perron (P-P) test [36] to observe stationarity.

The study employed ARDL approach [37] to observe long-term cointegration among the variables. The ARDL technique has several benefits in econometric analysis, especially for modeling dynamic connections between variables. An important advantage of the ARDL method is its versatility in including both short-term and long-term dynamics within a unified framework. ARDL, unlike standard time series approaches that only consider short-term connections or cointegration analysis that primarily focuses on long-term equilibrium relationships, enables the simultaneous investigation of both short and long-term impacts. This feature is especially helpful in empirical research, since it allows for the examination of how the connections between variables may change over time. In addition, the ARDL technique does not need strict assumptions about the sequence of integration or the existence of cointegration. This makes it suitable for analyzing a broad variety of time series data without the need for substantial preliminary testing. This adaptability streamlines the process of creating models and minimizes the likelihood of errors in model definition. ARDL models are very resistant to several types of non-stationarity, making them well-suited for studying economic and financial data that often display intricate patterns of persistence and volatility. The ARDL technique is a valuable tool for researchers to analyze the dynamic interactions between variables in a concise and adaptable way. This approach improves the correctness and dependability of empirical econometric investigations.

We utilised the ARDL method to find out whether the variables are related over the long run. Exceeding the maximum limit specified by Pesaran et al. [37] would result in the null hypothesis of no cointegration being rejected. If the F test result falls within the boundary limits, it indicates the presence of a possible bias. Our study supports the null hypothesis, indicating a lack of cooperation among the variables. Thankfully, the result of the F test is below the lower threshold, which strengthens our results. Furthermore, the long-run estimate model is shown below, illustrating the creation of a long -run association between the variables being examined:

$$\Delta LC_t = \tau_0 + \tau_1 LC_{t-1} + \tau_2 LI_t + \tau_3 LU_t + \tau_4 LY_t + \tau_5 LR_t + \sum_{i=1}^{q} \alpha_1 \Delta LC_{t-i} + \sum_{i=1}^{q} \alpha_2 \Delta LI_{t-i} + \sum_{i=1}^{q} \alpha_3 \Delta LU_{t-i} + \sum_{i=1}^{q} \alpha_4 \Delta LY_{t-i} + \sum_{i=1}^{q} \alpha_5 \Delta LR_{t-i} + \varepsilon_t \quad (2)$$

Finding a long-term relationship between the study parameters is the first step in making a short-term model prediction. Also called the error correction model (ECM), the following equation depicts the short-run model.

$$\Delta LC_t = \tau_0 + \tau_1 LC_{t-1} + \tau_2 LI_t + \tau_3 LU_t + \tau_4 LY_t + \tau_5 LR_t + \sum_{i=1}^{q} \alpha_1 \Delta LC_{t-i} + \sum_{i=1}^{q} \alpha_2 \Delta LI_{t-i} + \sum_{i=1}^{q} \alpha_3 \Delta LU_{t-i} + \sum_{i=1}^{q} \alpha_4 \Delta LY_{t-i} + \sum_{i=1}^{q} \alpha_5 \Delta LR_{t-i} + \theta ECM_{t-1} + \varepsilon_t \quad (3)$$

In this case, the error correction coefficient (θ) is a crucial component of the model that is being estimated. The provided value shows the adjustment speed parameter, which indicates the rate of convergence to a long-term equilibrium for the series.

Results and Discussion

The descriptive statistical findings of the variables are shown in Table 1. The data shows that all variables, with the exception of LR, have a negative skewness. Most of those characteristics follow a normal distribution, as seen by the sleekness scores, which are close to zero. With kurtosis values below 3, every one of these series exhibits platykurtic behavior. It can guarantee that all of the variables follow a normal distribution, according to the Jarque-Bera probability. Moreover, Table 2 presents the correlation analysis between the variables. The correlation matrix shows that all the variables are positively correlated with each other.

Table 1. Summary statistics of the variables.

Variables	LC	LI	LU	LY	LR
Mean	22.571	1.3869	3.7986	28.916	2.0249
Median	22.703	2.9453	3.8257	29.027	1.9133
Maximum	23.157	4.3256	4.1520	30.519	2.7738
Minimum	21.795	-8.6875	3.3708	27.059	1.5598
Skewness	-0.2859	-0.4386	-0.2113	-0.1054	0.5974
Kurtosis	1.4302	1.9431	1.7454	1.5113	1.8828
Jarque-Bera	2.4890	1.1459	2.1903	2.8256	2.3443
Probability	0.1747	0.2348	0.3345	0.2435	0.1878

Table 2. Correlation matrix of the variables

	LC	LI	LU	LY	LR
LC	1.0000				
LI	0.8663	1.0000			
LU	0.9822	0.8955	1.0000		
LY	0.9878	0.8613	0.9935	1.0000	
LR	0.8579	0.6908	0.9103	0.9186	1.0000

Table 3 displays the outcomes of doing unit root tests using the ADF, DF-GLS, and P-P tests. The variables initially did not show stationarity, but once their initial differences were taken into account in all three unit root tests, they became stationary. This change demonstrates how crucial differencing is for establishing statistical stability for the variables. Now that we have reached stationarity, we may go on with our analysis using the ARDL framework. In order to fully grasp the dynamics of the variables across time, this framework permits investigation of both the short-term and long-term interactions among them. Verifying that the variables are stationary allows us to conduct trustworthy econometric modeling, which in turn allows us to extract useful conclusions and make educated judgments.

Table 3. Findings of stationarity test.

Variables	ADF		DF-GLS		P-P	
	Log levels	Log first difference	Log levels	Log first difference	Log levels	Log first difference
LC	-1.142	-3.609***	-0.3012	-3.6587***	-1.1643	-3.5560***
LI	-0.254	-3.709***	-0.1256	-3.3863***	-0.2491	-4.709***
LU	-0.254	-3.254***	-0.2202	-3.2756***	-0.4695	-4.1256***
LY	-1.092	-3.411***	-0.6378	-3.4119***	-0.7079	-5.1254***
LR	-0.488	-6.260***	-0.8433	-6.3760***	-1.3872	-6.2988***

***P<0.01

In order to thoroughly evaluate the long-run cointegration among the variables, the research used the ARDL-bound testing approach, as shown in Table 4. Notably, cointegration is found in the data, which means that the variables that are being studied have a significant and long-lasting link. The model's F statistic of 8.08, which exceeds the upper critical values defined by the ARDL framework, provides support for this discovery. The strength of the found correlation is supported by this statistic's significance, which implies that the variables are genuinely linked over a long time. When we find that the variables are cointegrated, it means that when we modify one variable, other variables will change in a predictable way over time. The fundamental dynamics and interconnections of the system being studied may be better comprehended with this knowledge. Researchers, practitioners, and policymakers may use these results to better understand the factors at play, anticipate trends, and develop ways to deal with them.

Table 4. Findings of ARDL bound test

Test statistic	Value	Significance level	I(0)	I(1)
F-statistic	8.0801	10%	2.37	3.20
K	4	5%	2.79	3.67
		2.5%	3.15	4.08
		1%	3.65	4.66

Table 5 presents the findings of the ARDL model, with estimates for both the long-run and short-run associations. The results demonstrate a clear and substantial negative association between ICT and CO_2 emissions, both in the long-term and short-term. An increase of 1% in ICT might lead to a reduction in CO_2 emissions by 0.03% in the near term and 0.04% in the long run. This indicates that advancements in information and communication technology (ICT) have a tendency to decrease CO_2 emissions in China, hence showcasing the beneficial impact of ICT on promoting environmentally sustainable practices over an extended period of time. Urbanization in China is strongly correlated with CO_2 emissions, both in the long-term and short-term. Urbanization in China leads to a short-term rise of 1.22% and a long-term increase of 1.69% in CO_2 levels. Nevertheless, research has shown a strong and favorable correlation between GDP and CO_2 emissions. An increase of 1% in GDP would result in a long-term rise in CO_2 emissions of 0.61% and a short-term increase of 0.40%. At these levels of CO_2 intensity, a rise in GDP leads to higher CO emissions, highlighting the detrimental impact of GDP development on long-term environmental sustainability in China. Renewable energy consumption in China has been shown to decrease CO_2 emissions, affirming the beneficial impact of renewables on environmental sustainability in the area. The findings suggest that a mere 1% rise in the use of renewable energy will lead to a reduction of 0.55% in CO_2 emissions in the near term and 0.70% in the long term.

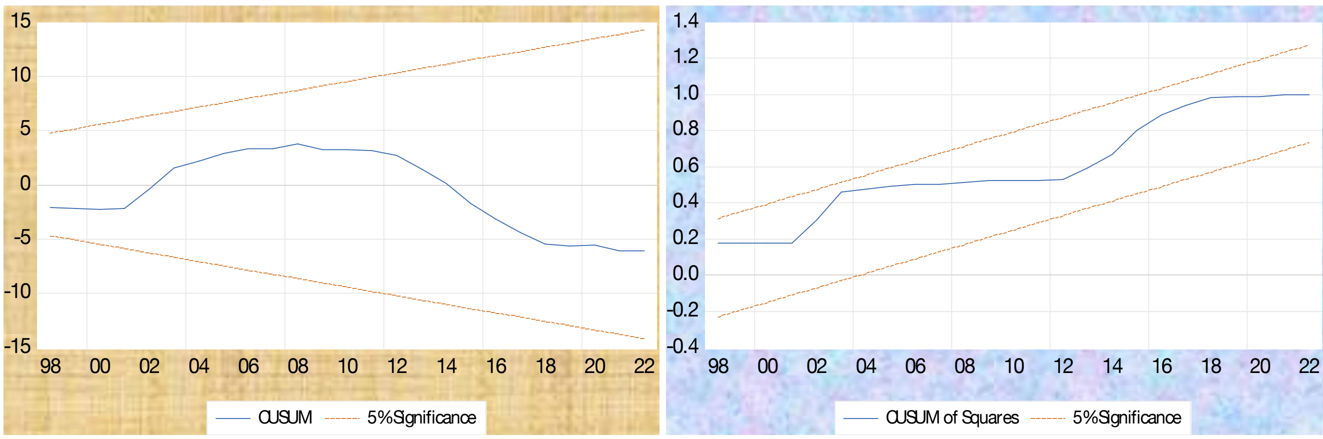
Table 5. Findings of ARDL long-run and short-run estimation

Variables	Long-run			Short-run		
	Coefficient	t-Statistic	p-value	Coefficient	t-Statistic	p-value
LI	-0.041***	-6.964	0.0013	0.0277***	-4.4907	0.0004
LU	1.6860***	5.145	0.0041	1.2228***	3.1367	0.0043
LY	0.6149***	8.4177	0.0003	0.4024***	6.2207	0.0000
LR	0.6999***	-7.2057	0.0006	0.5528***	-9.2427	0.0000
C	7.448	1.6079	0.1075	-	-	-
ECM (-1)	-	-	-	-0.5971***	-3.6015	0.0000
R^2	0.9948					
Adjusted R^2	0.9940					

***P<0.01

There is a 1% level of statistical significance that is indicated by the estimated Error Correction Model (ECM). It also reveals a downward trend, which might mean that this year we are correcting long-run equilibrium aberrations via channels like the agriculture sector, trade openness, economic development, and renewable energy projects at a pace of 59.71%. Further, the long-run estimate shows that the regression model is quite accurate with

R2 values of 0.9948 and 0.9940, respectively. Clearly, the independent variables explain almost all (99%) of the variance in the dependent variable's change. Figure 2 shows the results of the Cumulative Sum (CUSUM) and Cumulative Sum of Squares (CUSUMSQ) analyses run on the recursive regression residuals used to assess the model's reliability. At the 5% level of significance, the statistical line remains within the crucial boundaries, confirming that the ARDL model's predicted coefficients are stable. This validation strengthens the model's credibility by faithfully depicting the underlying patterns and relationships between the variables; as a result, it provides valuable insights for academics and decision-makers.



(a) CUSUM plot (b) CUSUMSQ plot

Figure 2. The results of CUSUM and CUSUMSQ tests

Likewise, additional diagnostic tests were performed to confirm the reliability of the ARDL model used in this study. The diagnostic evaluations, as shown in Table 6, included the assessment of serial correlation and heteroscedasticity. The comprehensive diagnostic analysis indicates that the residuals adhere to a normal distribution, confirming the precision of the model's specification. Furthermore, the lack of serial correlation or heteroscedasticity strengthens the dependability of the ARDL model, instilling trust in its capacity to accurately reflect the fundamental connections between the variables.

Table 6. Findings of Diagnostic test

Diagnostic tests	Coefficient	p-value	Decision
Jarque-Bera test	1.379	0.501	Normal residual distribution
Breusch-Godfrey LM test	0.552	0.583	No serial correlation exists
Breusch-Pagan-Godfrey test	1.203	0.292	No heteroscedasticity exists
Ramsey RESET test	0.133	0.895	The model is properly specified

The findings of the study show that ICT has affected CO_2 emissions negatively and significantly. It demonstrates that advancements in ICT sectors are reducing the CO_2 footprint in China, which reveals the favorable effect of ICT on environmental sustainability. The study's outcomes are supported by several previous studies that examined and reported that ICT improves environmental quality [38-40]. ICT is a significant tool that uses less energy and promotes economic growth. ICT can be used in industrial production to reduce the use of raw materials, which use less energy, and reduce detrimental emissions. Moreover, ICT promotes paperless work, which is useful for the environment. Two ICT-oriented businesses, like teleconferences and integrated point-of-sale platforms, are essential for environmental strain. The development and increase of online-based education reduce environmental degradation. Reliance on digital purchases reduces the pressure on transportation, ultimately reducing CO_2 emissions [41]. Due to distant sensing and having mechanisms for CO_2 emissions, ICT can promote a sustainable environment [42]. On the other hand, a few other studies contradict our results. This research argues that ICT infrastructure generates waste that is detrimental to the environment [43].

Furthermore, this study shows that economic growth has a negative relationship with the environment. It states that to increase the GDP, people use more energy that releases CO_2 into nature. The results are aligned with several previous studies [44-47]. To mitigate the adverse impact of global warming and climate change [48-52], humans can use renewable energy and allocate budgets to produce green power [53]. Moreover, this study found a negative relationship between renewable energy consumption and CO_2 emissions in China, indicating that increased consumption of renewable energies would help to cut China's emissions. The finding is supported by previous studies [54-57].

The study also reports that urbanization has a positive contribution to increasing CO_2 in China. Due to social and economic change, urbanization plays an important role. But urbanization boosts CO_2 footprint due to being heavily dependent on energy [58]. Some prior studies state that urbanization increases the use of energy, promotes the CO_2 footprint, and deteriorates ecological balance [59-64]. Moreover, the consumption of power in homes, transportation, and industry in urban areas releases CO_2 into the environment. Power, heat, and transportation are factors of urbanization used inside and outside of industries that are responsible for CO_2 pollution. Urban people use gadgets that are energy-intensive, resulting in increased wealth and costs that ultimately contribute to an increased CO_2 footprint. In contrast, few studies demonstrate that urbanization decreases environmental inequality through funding for R&D and sustainable technologies. In addition, urbanization motivates people to utilize energy-saving technology that is essential to protecting the environment.

Conclusions and Policy Implications

Urbanization has both positive and negative impacts. For example, fast urbanization facilitates the lives of humans all around the world. In contrast, it is considered one of the most vital sources of environmental degradation. Therefore, the smart cities" strategy is crucial to safeguarding the environment, which is possible with the help of renewable energy, ICTs, and sustainable transportation systems. ICTs can convert a city from a normal system to a smart one that makes and ensures the quality of life of urban people without putting pressure on the environment. Therefore, this research investigates the effect of ICT, green energy or renewable energy, urbanization, and economic growth (GDP) on environmental sustainability in China. The study employed the ARDL method to analyze the data. The findings demonstrate that ICT and renewable energy have an adverse and significant effect on CO_2 emissions in the country. It states that the rise of ICT and renewable energy increases the quality of the environment. On the other hand, urbanization and economic growth have a positive and significant impact on CO_2 emissions. The result argues that large-scale urbanization decreases the quality of the environment. Moreover, the research found that economic growth pollutes the environmental quality due to increasing CO_2 emissions in nature, while focusing on the consumption of renewable power can enhance environmental sustainability by reducing carbon footprints.

The results of the study offer crucial policy proposals. The study ensured the favorable effect of ICT in reducing environmental degradation. Therefore, policymakers in China should penetrate the ICT system in every sector of the country. This could be a significant initiative toward the digitalization of the economy by shifting to a light economy. The findings of the study state that urbanization has a negative impact on environmental sustainability. Hence, penetrating ICT in the urbanization system can help shift normal cities into smart cities, which would play a great role in establishing a sustainable future. China should adopt a renewable energy structure to implement urbanization, which would reduce its carbon footprint. Therefore, it is now essential to update industrial procedures and technical advancements in urban areas to attain a zero-carbon emissions environment.

It is high time for the Chinese government to focus on and foster environmental sustainability by ensuring a zero-carbon economy. It is also essential for such infrastructure to reshape the management system of urban areas and reduce carbon emissions. The study recommends that the business industry use environmentally friendly technology while developing any infrastructure. In this case, the Chinese government should come forward to adopt and implement low-carbon emissions initiatives and enforce supervision. Finally, financial aid and incentive policies should be provided in the construction industry.

The governing body of China should invest in sustainable ICTs, including cloud computing and virtualization. This step will reduce the use of energy in the sector. The Chinese government should launch a circular economy model. This model has efficient quality to efficiently use resources and manage waste properly. This initiative would be helpful for reducing the environmental degradation impact of smart city technology. China should enhance public awareness regarding the environmental effects of smart city technology and the significance of long-term urban development by organizing public education campaigns and encouraging urban community involvement. To ensure green smart technology, the Chinese government should partner with both public and private organizations. These collaborations will bring resources and knowledge that are essential to fostering sustainable development. China should develop, renew, and enforce environment-related regulations in order to utilize smart city technology and urban areas' development projects. The Chinese government should concentrate on the generation and consumption of sustainable energy to implement smart cities. This would help to lessen the dependency on nonrenewable energy and reduce CO_2 emissions. To ensure smart city development, the government should also pay attention to public transportation, walking, and cycling, which would reduce the dependency on private transportation.

The study's limitations are comparatively narrow since it focuses on the effect of urbanization and the digital era on environmental sustainability. However, future research can focus on other countries and examine the effects of other relevant variables, like social and cultural. Since the research uses secondary data, future research can be conducted on primary data. Data collection methods can be followed, such as surveys or interviews, to get in-depth information. The study has data-based related limitations on environmental sustainability and urbanization in the Chinese context. So, for better analysis, future researchers could collect good data regarding environmental sustainability and urbanization. Future studies could investigate the same issues to get a more holistic understanding of the effect of urbanization and digitalization on sustainable environments.

Funding: Not applicable (N/A).
Acknowledgement: Not applicable (N/A).
Conflict of interest: Author declares no conflict of interest.
Authors' contributions: The study's inception and structural framework were meticulously constructed by Asif Raihan. The coordination of material procurement, collecting data, and thorough analysis was carried out by a multifaceted group consisting of Tipon Tanchangya, Shakil Ahmad, Junaid Rahman, and Asif Raihan. The first version of the manuscript was influenced by the scholarly expertise of Mohammad Ridwan, whereas Asif Raihan contributed his own scholarly insights to earlier iterations. The culmination of a collaborative endeavor was the manuscript's refinement, which received unanimous assent from all authors upon reaching its pinnacle of excellence.
Data availability statement: The data on CO_2 emissions and renewable energy were collected from Our World in Data, while the data on urbanization, ICT, and GDP were retrieved from the World Development Indicators (WDI).

References

1. Sahoo, M., & Sethi, N. (2020). Impact of industrialization, urbanization, and financial development on energy consumption: Empirical evidence from India. *Journal of public affairs*, *20*(3), e2089.
2. Li, X., Hui, E. C. M., Lang, W., Zheng, S., & Qin, X. (2020). Transition from factor-driven to innovation-driven urbanization in China: A study of manufacturing industry automation in Dongguan City. *China Economic Review*, *59*, 101382.
3. Liu, Y., Zhang, X., Pan, X., Ma, X., & Tang, M. (2020). The spatial integration and coordinated industrial development of urban agglomerations in the Yangtze River Economic Belt, China. *Cities*, *104*, 102801.
4. Yu, B. (2021). Ecological effects of new-type urbanization in China. *Renewable and Sustainable Energy Reviews*, *135*, 110239.
5. Rodríguez-Pose, A., & Storper, M. (2020). Housing, urban growth and inequalities: The limits to deregulation and upzoning in reducing economic and spatial inequality. *Urban Studies*, *57*(2), 223-248.
6. Ramelli, S., Ossola, E., & Rancan, M. (2021). Stock price effects of climate activism: Evidence from the first Global Climate Strike. *Journal of Corporate Finance, 69*, 102018.
7. Hong, T., Yu, N., Mao, Z., & Zhang, S. (2021). Government-driven urbanisation and its impact on regional economic growth in China. *Cities*, *117*, 103299.

8. Stępniak, C., Jelonek, D., Wyrwicka, M., & Chomiak-Orsa, I. (2021). Integration of the infrastructure of systems used in smart cities for the planning of transport and communication systems in cities. *Energies*, *14*(11), 3069.
9. Alsamhi, S. H., Ma, O., Ansari, M. S., & Meng, Q. (2019). Greening internet of things for greener and smarter cities: a survey and future prospects. *Telecommunication Systems*, *72*, 609-632.
10. Fernández-Portillo, A., Almodóvar-González, M., Coca-Pérez, J. L., & Jiménez-Naranjo, H. V. (2019). Is sustainable economic development possible thanks to the deployment of ICT?. *Sustainability*, *11*(22), 6307.
11. Oláh, J., Aburumman, N., Popp, J., Khan, M. A., Haddad, H., & Kitukutha, N. (2020). Impact of Industry 4.0 on environmental sustainability. *Sustainability*, *12*(11), 4674.
12. Zhong, S., Xin, C., Shen, H., & Chen, X. (2021). Effects of land urbanization and internet penetration on environmental sustainability: A cross-regional study of China. *Environmental Science and Pollution Research*, *28*, 66751-66771.
13. Vasylieva, T., Lyulyov, O., Bilan, Y., & Streimikiene, D. (2019). Sustainable economic development and greenhouse gas emissions: The dynamic impact of renewable energy consumption, GDP, and corruption. *Energies*, *12*(17), 3289.
14. Ahmed, Z., Nathaniel, S. P., & Shahbaz, M. (2021). The criticality of information and communication technology and human capital in environmental sustainability: evidence from Latin American and Caribbean countries. *Journal of Cleaner Production*, *286*, 125529.
15. Rani, S., Mishra, R. K., Usman, M., Kataria, A., Kumar, P., Bhambri, P., & Mishra, A. K. (2021). Amalgamation of advanced technologies for sustainable development of smart city environment: A review. *IEEE Access*, *9*, 150060-150087.
16. Balogun, A. L., Marks, D., Sharma, R., Shekhar, H., Balmes, C., Maheng, D., ... & Salehi, P. (2020). Assessing the potentials of digitalization as a tool for climate change adaptation and sustainable development in urban centres. *Sustainable Cities and Society*, *53*, 101888.
17. Prastiyo, S. E., Irham, Hardyastuti, S., & Jamhari, F. (2020). How agriculture, manufacture, and urbanization induced carbon emission? The case of Indonesia. *Environmental Science and Pollution Research, 27*(33), 42092-42103.
18. Sufyanullah, K., Ahmad, K. A., & Ali, M. A. S. (2022). Does emission of carbon dioxide is impacted by urbanization? An empirical study of urbanization, energy consumption, economic growth and carbon emissions-Using ARDL bound testing approach. *Energy Policy, 164*, 112908.
19. Zhou, C., Wang, S., & Wang, J. (2019). Examining the influences of urbanization on carbon dioxide emissions in the Yangtze River Delta, China: Kuznets curve relationship. *Science of the Total Environment, 675*, 472-482.
20. Hanif, I. (2018). Impact of economic growth, nonrenewable and renewable energy consumption, and urbanization on carbon emissions in Sub-Saharan Africa. *Environmental Science and Pollution Research, 25*(15), 15057-15067.
21. Dong, H., Xue, M., Xiao, Y., & Liu, Y. (2021). Do carbon emissions impact the health of residents? Considering China's industrialization and urbanization. *Science of the total environment, 758*, 143688.
22. Mahmood, H., Alkhateeb, T. T. Y., & Furqan, M. (2020). Industrialization, urbanization and CO_2 emissions in Saudi Arabia: Asymmetry analysis. *Energy Reports, 6*, 1553-1560.
23. Chen, J., Rojniruttikul, N., Kun, L. Y., & Ullah, S. (2022). Management of green economic infrastructure and environmental sustainability in one belt and road enitiative economies. *Environmental Science and Pollution Research, 29*(24), 36326-36336.
24. Lahouel, B. B., Taleb, L., Zaied, Y. B., & Managi, S. (2021). Does ICT change the relationship between total factor productivity and CO_2 emissions? Evidence based on a nonlinear model. *Energy Economics, 101*, 105406.
25. Awan, A., Abbasi, K. R., Rej, S., Bandyopadhyay, A., & Lv, K. (2022). The impact of renewable energy, internet use and foreign direct investment on carbon dioxide emissions: A method of moments quantile analysis. *Renewable Energy, 189*, 454-466.
26. Lee, J. W., & Brahmasrene, T. (2014). ICT, CO_2 emissions and economic growth: evidence from a panel of ASEAN. *Global Economic Review, 43*(2), 93-109.

27. Zafar, M. W., Zaidi, S. A. H., Mansoor, S., Sinha, A., & Qin, Q. (2022). ICT and education as determinants of environmental quality: The role of financial development in selected Asian countries. *Technological Forecasting and Social Change, 177*, 121547.
28. Asongu, S. A., Le Roux, S., & Biekpe, N. (2018). Enhancing ICT for environmental sustainability in sub-Saharan Africa. *Technological Forecasting and Social Change, 127*, 209-216.
29. Zhang, C., & Liu, C. (2015). The impact of ICT industry on CO_2 emissions: a regional analysis in China. *Renewable and Sustainable Energy Reviews, 44*, 12-19.
30. Salahuddin, M., Alam, K., & Ozturk, I. (2016). The effects of Internet usage and economic growth on CO_2 emissions in OECD countries: A panel investigation. *Renewable and Sustainable Energy Reviews, 62*, 1226-1235.
31. Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2022). Dynamic impacts of energy use, agricultural land expansion, and deforestation on CO_2 emissions in Malaysia. *Environmental and Ecological Statistics*, *29*(3), 477-507.
32. Begum, R. A., Raihan, A., & Said, M. N. M. (2020). Dynamic impacts of economic growth and forested area on carbon dioxide emissions in Malaysia. *Sustainability*, *12*(22), 9375.
33. Raihan, A., & Tuspekova, A. (2022). The nexus between economic growth, renewable energy use, agricultural land expansion, and carbon emissions: New insights from Peru. *Energy Nexus*, *6*, 100067.
34. Dickey, D. A., & Fuller, W. A. (1979). Distribution of the estimators for autoregressive time series with a unit root. *Journal of the American Statistical Association, 74*(366a), 427-431.
35. Elliott, G., Rothenberg, T. J., & Stock, J. H. (1992). Efficient tests for an autoregressive unit root. National Bureau of Economic Research.
36. Phillips, P. C., & Perron, P. (1988). Testing for a unit root in time series regression. *Biometrika, 75*(2), 335-346.
37. Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics, 16*(3), 289-326.
38. Usman, A., Ozturk, I., Ullah, S., & Hassan, A. (2021). Does ICT have symmetric or asymmetric effects on CO_2 emissions? Evidence from selected Asian economies. *Technology in Society, 67*, 101692.
39. Chatti, W. (2021). Moving towards environmental sustainability: information and communication technology (ICT), freight transport, and CO_2 emissions. *Heliyon*, *7*(10).
40. Usman, A., Ozturk, I., Ullah, S., & Hassan, A. (2021). Does ICT have symmetric or asymmetric effects on CO_2 emissions? Evidence from selected Asian economies. *Technology in Society*, *67*, 101692.
41. Wilson, C., Kerr, L., Sprei, F., Vrain, E., & Wilson, M. (2020). Potential climate benefits of digital consumer innovations. *Annual Review of Environment and Resources*, *45*, 113-144.
42. Dong, Y., Jin, G., & Deng, X. (2020). Dynamic interactive effects of urban land-use efficiency, industrial transformation, and carbon emissions. *Journal of cleaner production*, *270*, 122547.
43. Thacker, S., Adshead, D., Fay, M., Hallegatte, S., Harvey, M., Meller, H., ... & Hall, J. W. (2019). Infrastructure for sustainable development. *Nature Sustainability*, *2*(4), 324-331.
44. Chen, Y., Wang, Z., & Zhong, Z. (2019). CO_2 emissions, economic growth, renewable and non-renewable energy production and foreign trade in China. *Renewable energy*, *131*, 208-216.
45. Jian, J., Fan, X., He, P., Xiong, H., & Shen, H. (2019). The effects of energy consumption, economic growth and financial development on CO_2 emissions in China: A VECM approach. *Sustainability*, *11*(18), 4850.
46. Wang, Q., & Jiang, R. (2019). Is China's economic growth decoupled from carbon emissions?. *Journal of Cleaner Production*, *225*, 1194-1208.
47. Li, B., & Haneklaus, N. (2021). The role of renewable energy, fossil fuel consumption, urbanization and economic growth on CO_2 emissions in China. *Energy Reports*, *7*, 783-791.
48. Raihan, A., Begum, R. A., & Said, M. N. M. (2021). A meta-analysis of the economic value of forest carbon stock. *Geografia–Malaysian Journal of Society and Space*, *17*(4), 321-338.
49. Raihan, A., Begum, R. A., Mohd Said, M. N., & Pereira, J. J. (2021). Assessment of carbon stock in forest biomass and emission reduction potential in Malaysia. *Forests*, *12*(10), 1294.

50. Raihan, A., Begum, R. A., Mohd Said, M. N., & Abdullah, S. M. S. (2019). A review of emission reduction potential and cost savings through forest carbon sequestration. *Asian Journal of Water, Environment and Pollution*, *16*(3), 1-7.
51. Raihan, A., Begum, R. A., Said, M. N. M., & Abdullah, S. M. S. (2018). Climate change mitigation options in the forestry sector of Malaysia. *J. Kejuruter*, *1*(6), 89-98.
52. Raihan, A., & Said, M. N. M. (2022). Cost–benefit analysis of climate change mitigation measures in the forestry sector of Peninsular Malaysia. *Earth Systems and Environment*, *6*(2), 405-419.
53. Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2022). Relationship between economic growth, renewable energy use, technological innovation, and carbon emission toward achieving Malaysia's Paris agreement. *Environment Systems and Decisions*, *42*(4), 586-607.
54. Chen, Y., Wang, Z., & Zhong, Z. (2019). CO_2 emissions, economic growth, renewable and non-renewable energy production and foreign trade in China. *Renewable energy*, *131*, 208-216.
55. Lin, B., & Zhu, J. (2019). The role of renewable energy technological innovation on climate change: Empirical evidence from China. *Science of the Total Environment*, *659*, 1505-1512.
56. Godil, D. I., Yu, Z., Sharif, A., Usman, R., & Khan, S. A. R. (2021). Investigate the role of technology innovation and renewable energy in reducing transport sector CO_2 emission in China: a path toward sustainable development. *Sustainable Development*, *29*(4), 694-707.
57. Sarkodie, S. A., Adams, S., Owusu, P. A., Leirvik, T., & Ozturk, I. (2020). Mitigating degradation and emissions in China: the role of environmental sustainability, human capital and renewable energy. *Science of the Total Environment*, *719*, 137530.
58. Bai, Y., Deng, X., Gibson, J., Zhao, Z., & Xu, H. (2019). How does urbanization affect residential CO_2 emissions? An analysis on urban agglomerations of China. *Journal of cleaner production*, *209*, 876-885.
59. Yu, B. (2021). Ecological effects of new-type urbanization in China. *Renewable and Sustainable Energy Reviews*, *135*, 110239.
60. Ahmed, Z., Asghar, M. M., Malik, M. N., & Nawaz, K. (2020). Moving towards a sustainable environment: the dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China. *Resources Policy*, *67*, 101677.
61. Wang, Z., Sun, Y., & Wang, B. (2019). How does the new-type urbanisation affect CO_2 emissions in China? An empirical analysis from the perspective of technological progress. *Energy Economics*, *80*, 917-927.
62. Adebayo, T. S., Agboola, M. O., Rjoub, H., Adeshola, I., Agyekum, E. B., & Kumar, N. M. (2021). Linking economic growth, urbanization, and environmental degradation in China: what is the role of hydroelectricity consumption?. *International journal of environmental research and public health*, *18*(13), 6975.
63. Wang, Q., & Su, M. (2019). The effects of urbanization and industrialization on decoupling economic growth from carbon emission–a case study of China. *Sustainable Cities and Society*, *51*, 101758.
64. Liu, W., Zhan, J., Zhao, F., Wei, X., & Zhang, F. (2021). Exploring the coupling relationship between urbanization and energy eco-efficiency: a case study of 281 prefecture-level cities in China. *Sustainable Cities and Society*, *64*, 102563.