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China's Pathway to a Low Carbon Economy: Exploring the Influence of Urbanization on Environmental Sustainability in the Digital Era

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Abstract: To protect the environment from any further damage, the implementation of the "smart cities" strategy supported by information and communication technologies (ICTs) is the need of the hour. Hence, this study estimates the impact of ICT and urbanization on environmental sustainability in China using the novel quantile autoregressive distributed lag (QARDL) method. The results of the QARDL model state the negative and significant impact of ICT on CO_2 emissions in China for all quantiles, implying that an increase in ICT proved to be an important factor in improving environmental quality. In contrast, the estimated coefficients of urbanization are positively significant for all quantiles. This finding sustains the idea that large-scale urbanization is detrimental to the environment because the process of urbanization is among the leading sources of carbon emissions. In the short run, the negative impact of ICT on CO_2 emissions can only be seen in higher quantiles, while the positive impact of urbanization on CO_2 emissions is confirmed for all quantiles. Lastly, the asymmetric impact of ICT and urbanization is confirmed in the short and long run with the help of Wald tests. The ICT diffusion and smart urbanization approach can help in attaining environmental sustainability targets.

Keywords: ICT; urbanization; environmental sustainability; digital economy

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Citation: Lv, Y.; Li, W.; Xu, Y.; Sohail, M.T. China's Pathway to a Low Carbon Economy: Exploring the Influence of Urbanization on Environmental Sustainability in the Digital Era. *Sustainability* **2023**, *15*, 7000. https://doi.org/10.3390/su15087000

Academic Editors: Antonio Boggia, Ilhan Ozturk and Usama Al-Mulali

Received: 19 February 2023
Revised: 16 March 2023
Accepted: 13 April 2023
Published: 21 April 2023

1. Introduction

Urbanization is beneficial for long-term economic development and industrialization, irrespective of country or location [1]. Additionally, urbanization helps enterprises and people acquire data and information, lower operating costs, and benefit from indigenous technology spillovers such as from industrial zones [2]. Additionally, clustering around certain areas occurs in tandem with expanding urbanization and thrives in metropolitan environments because of greater government services, a huge labor pool, and diversified commodities [3]. Improved public infrastructure availability makes areas more desirable for productive enterprises [4].

The urbanization process sans corresponding infrastructure and public strategic planning has a wide range of adverse repercussions on the economy in addition to high urban expenses and detrimental ecological consequences [5]. Urban expenses make up a significant portion of family income in the majority of nations, which has a detrimental effect on the standard of living in cities. Additionally, the increase in carbon footprints within major cities negatively influences business success [6]. Proper public policy may direct the movement of activity from rural to urban areas, including advanced and emerging countries, to prevent and lessen the harmful environmental effects of urbanization [7].

In this context, it is thought necessary to implement the "smart cities" strategy, which is dependent on ICTs and smart transportation networks, in order to reduce carbon footprints, which are seen as the primary ecological disadvantage of urbanization [8,9]. Chatti and Majeed [2] asserted that ICT essentially allows for required "smart technologies, automation, and the Internet of Things (IoT), making human activities in life and work more efficient (and reducing their environmental effect)." As a result, smart cities need significant levels of ICT penetration [10]. As a result, smart cities need a significant amount of ICT adoption [11]. ICTs and advanced devices do not serve as a magic bullet for sustaining traditional economic development without unfavorable effects on the ecosystem. For example, the manufacture and use of ICT infrastructure and gadgets and the accompanying reuse of materials have significant negative effects on the environment due to the use of resources and the associated energy expenditures [12]. An empirical inquiry is required to better comprehend the various environmental effects of ICT in metropolitan settings.

To our knowledge, no studies have looked at the quantitative links between ICT, urbanization, and ecological sustainability. Existing research has mostly concentrated on the environmental impacts of urbanization [13,14] or the relationships between ICT, urbanization, and economic development [15] without specifically addressing the environmental impact of ICT adoption in urban settings. In the same vein, additional studies have shown a favorable impact of ICT use on environmental conservation in the urban transportation sector [2]. Even though inherent urban features of various nations were not expressly taken into account in these earlier works, urban expenses were still implicitly incorporated in terms of urban transportation services.

This study aims to explore the impacts of ICT and urbanization on the environment, considering China. However, the "high pollution, high emissions, and low efficiency" strategy for economic development makes it difficult for the environment to assimilate contaminants and affects China in monetary terms [16]. About 600 million people have relocated from rural to urban regions over the last three decades. As a result, China is the top country on the list in terms of most cities with populations over 1 million. Furthermore, it is estimated that approximately 300 million individuals will relocate from rural to urban regions over the coming three decades. A number of dangerous urban illnesses are brought on by the fast growth of urbanization, both in terms of size and population, and these diseases pose a significant barrier to safe and sustainable urbanization process. China has led the globe in developing smart cities, having started planning to build them in the last ten years to address these issues and obstacles [17]. Therefore, selecting China for trying to answer the following questions is an interesting choice: (i) Does the ecosystem benefit from new innovations? (ii) Does additional measures of new technologies and pollutants cause the environmental impact of ICTs to alter? (iii) Does the integration of ICTs in the urbanization process positively impact the atmosphere?

We were motivated by several reasons to explore this topic. Firstly, the increasing urbanization and digitization of societies are having a significant impact on the environment. Investigating the influence of urbanization and the digital era on green sustainability can help identify the specific environmental impacts of these trends and develop strategies to reduce negative impacts. Secondly, sustainable development is a key issue in today's world. Investigating the influence of urbanization and the digital era on green sustainability can provide insights into how we can promote sustainable development and ensure that economic growth is environmentally sustainable. Thirdly, urbanization and the digital era are driving economic growth in many parts of the world. Investigating the influence of these trends on green sustainability can help policymakers ensure that economic growth is sustainable and does not have a negative impact on the environment. Finally, investigating the influence of urbanization and the digital era on green sustainability can help raise public awareness regarding this critical issue. This can lead to increased support for policies and initiatives that promote sustainable development and reduce negative environmental impacts.

In addition to these, this study makes significant contributions to the existing literature. First, China has made great strides in recent years by investing in new technologies and ICT-based solutions to reduce its environmental footprint. Considering this fact, our study contributes to the literature by determining the influence of ICT on environmental quality in China over the period 1995 to 2020. Second, China has made significant progress in urbanization by leveraging various technologies. Thus, the present study looks at how urbanization affects the environment while considering various CO_2 emission types. Third, this study focuses on both the short- and long-run analysis, while most past studies have only focused on the long-run analysis. Fourth, this research uses Cho et al. [18]'s innovative quantile ARDL econometric approach, which offers the convenience of evaluating the short- and long-run results over distinct quantiles. Empirical analysis data were collected from 1995 to 2020, which constitutes 26 years of data. Cointegration is a long-term phenomenon that requires extensive data coverage rather than a high number of observations. Therefore, 26 yearly observations are equivalent to 106 quarterly ones. Several studies have relied on this principle and used less than 30 annual observations (Usman et al., 2021 [9]). The QARDL approach has been shown to have higher accuracy in predicting short- and long-run relationships than traditional methods such as the ARDL model. Lastly, on the basis of this study's findings, important policy suggestions are also provided in the context of urbanization that can open the door for other emerging economies to work along the same lines to preserve their environment.

The rest of the study is organized as follows. The second section provides a review of the relevant literature on urbanization, digitalization, and environmental sustainability. The third section presents the methodology and research design used in this study, including data collection and analysis techniques. The fourth section presents the findings and results of the study. The final section concludes the study and provides implications for policy and practice, as well as highlighting the limitations of the study and areas for future research.

2. Literature Review

Urbanization can be seen as improving the sustainability of the environment by promoting green technologies, energy efficiency, inventiveness, and environmental consciousness [19]. According to the ecological modernization theory of urbanization, a high degree of modernization results in increased energy efficiency, ecofriendly innovation, environmental consciousness, and fundamental transformations in the economy that benefit the ecosystem [20]. A similar sort of idea is smart urbanization, which refers to using technology in a smarter way to develop cities that would enhance the ecofriendly role of cities. The literature on the impact of smart urbanization and environmental sustainability is very rare; however, the relationship between traditional urbanization and environmental performance has been investigated in many studies.

According to Prastiyo and Hardyastuti's [21], urbanization, manufacturing, and agriculture significantly impact the amount of carbon pollution in Indonesia. Using cross-country research, Sufyanullah et al. [22] looked at how urbanization affected CO_2 emissions. The results of the research demonstrate an inverse U-shaped relationship between urbanization and carbon pollution. According to Wang and Wang [23], the growth in population and the increase in carbon emissions are two of the biggest obstacles to society's capability to grow sustainably. They employed a panel threshold estimation technique by gathering data over 2002–2012 for 137 nations and investigated the impact of population aging on carbon footprints. Their results confirm that, with an aging population, industrial infrastructure and carbon emissions go hand in hand [24].

Urbanization's effect on China's carbon footprint was studied by Zhou et al. [25]. Their main contribution was to look at how urbanization's substructure processes affect carbon emission patterns. Research results show that CO_2 emissions levels vary over time and among urbanization subsystems. Using the generalized method of moments (GMM) technique, Hanif [26] examined the impact of urbanization on carbon output in Sub-Saharan African nations from 1995 to 2015. According to the study's conclusions, urbanization has a major role in the source countries' carbon emissions. Dong et al. [27] examined the effects of urbanization and industrialization on ecological security and economic expansion. From 2002 to 2017, data were gathered and analyzed using panel estimates. This analysis shows that carbon emissions are negatively associated with urban health. Mahmood et al. [28] conducted a study to examine how the fast expansion of cities affects CO_2 emissions as a result of industrialization. Urbanization and industrialization in Saudi Arabia were analyzed using yearly data from 1968 to 2014 to draw conclusions regarding the relationship between urbanization and carbon footprints. This research confirms previous findings that urbanization boosted CO_2 emissions in an industrialized setting. According to the report, increasing urbanization promotes manufacturing deeds, including using nonrenewable energy supplies (burning carbon fuels), which results in significant carbon output.

With regards to the relationship between ICT and CO_2 emissions, Chen et al. [29] examine the relationship between ICT and CO_2 emissions and present ICT as a tool to promote environmental quality in the context of social change. Khan et al. [30] contended that ICT first causes the environment to deteriorate before improving it over time by reducing CO_2 output. In addition, Lei et al. [31] highlighted how an advanced financial sector spurs economic expansion, which in turn amplifies industrial waste. According to Lahouel et al. [32], using certain ICT contributes to reducing emissions.

Awan et al. [33] observed that internet shopping has a heterogeneous impact on CO_2 emissions for industrialized and emerging nations. Although internet usage lowers CO_2 emissions in affluent nations, internet shopping has little effect on CO_2 emissions in poor nations. The sluggish internet speed in underdeveloped nations might be the cause of the heterogeneous impact. In addition, economic development, the use of energy, urbanization, and trade liberalization are the key causes of environmental degradation in both emerging and industrialized nations. Lee and Brahmasrene [34] provided evidence on the group of ASEAN nations for which ICT has a favorable and substantial effect on economic development and CO_2 emissions. According to Zafar et al. [35], ICT reduces emissions via energy-efficient production and consumption behaviors. Additionally, Asongu et al. [36] used a GMM model to analyze the effect of ICT on carbon footprints in 44 Sub-Saharan African nations. According to empirical research, ICT significantly affects CO_2 emissions, but pollution levels are reduced as ICT (square of ICT) increases. Zhang and Liu [37] investigated the effect of the ICT sector on CO_2 emissions utilizing province data from the STRIPAT framework in relation to regional disparities in China. The study concludes that China's ICT sector reduces CO_2 emissions. Environmental performance is decreased by both economic expansion and energy use but is improved by urbanization in certain parts of China. Additionally, Salahuddin et al. [38] employed the pooled mean group (PMG) approach to calculate the impact of internet usage on CO_2 emissions in organization for economic cooperation and development (OECD) nations. According to the study's findings, internet use and CO_2 emissions have a considerable long-term connection. While there are several conceptual and theoretical studies on this topic, there is still a lack of empirical studies that provide concrete evidence of the impact of urbanization and ICT on environmental sustainability. This literature review highlights the complex relationship between urbanization, ICT, and environmental sustainability in the case of China. Addressing these research gaps can contribute significantly to the existing literature on the nexus between urbanization, digitalization, and green sustainability.

3. Materials, Methods, Data

To explore the long-run and short-run asymmetries among concerning variables, we employed the QARDL technique proposed by Cho et al. [18]. The QARDL approach is superior to linear models for various reasons. The first advantage of adopting this technique is that it takes into account the locational asymmetries in which factors and findings may be conditional on the dependent variable. Due to this, QARDL is considered more appropriate, as the linear ARDL technique cannot capture the asymmetric association among variables. Another advantage is that the QARDL approach considers long-run as well as short-run dynamics over different quantile ranges. Overall, QARDL is a powerful regression model that offers several advantages over traditional linear regression models, particularly in the presence of nonlinearities, nonnormality, or small sample sizes [39]. Moreover, using this approach, the Wald test is used to detect the time-varying reliability of variables across quantiles. If the goal is to estimate the parameters of a wide range of models, including nonlinear models, the generalized method of moments (GMM) may be a better choice. If the goal is to analyze the short- and long-run relationship between variables using a distributed lag model and the dependent variable is not normally distributed, QARDL may be a better choice [40]. Thus, our study employed the QARDL approach for short- and long-run results, which is useful in a variety of research areas, such as economics, finance, and environmental studies. In the study carried out by Chatti and Majeed [2], a model signifying the link between ICT, urbanization, and environmental sustainability is presented as follows:

$$\begin{aligned} CO_{2,t} = \mu + \sum_{i=1}^{n1} \sigma_{CO_{2,i}} CO_{2,t-i} + \sum_{i=0}^{n2} \sigma_{ICT_i} ICT_{t-i} + \sum_{i=0}^{n3} \sigma_{URB_i} URB_{t-i} \\ + \sum_{i=0}^{n4} \sigma_{GDP_i} GDP_{t-i} + \sum_{i=0}^{n5} \sigma_{REC_i} REC_{t-i} + \varepsilon_t \end{aligned} \tag{1}$$

where ε_t is explained as $CO_{2,t}$-E[$CO_{2,t}/Ft-1$] with $Ft-1$ being the smallest σ field made by (ICT_t, URB_t, GDP_t, REC_t, URB_{t-1}, ICT_{t-1}, GDP_{t-1}, REC_{t-1}), and n1 … n5 denotes the lag orders for model variables indicated by the Schwarz information criterion (SIC). Equation (1) infers that ICT, urbanization, GDP growth, and renewable energy consumption are represented by ICT_t, URB_t, GDP_t, REC_t, respectively, while $CO_{2,t}$ represents CO_2 emissions. Following Cho et al. [18]'s approach, basic Equation (1) must be reformatted in the quantile ARDL format:

$$\begin{aligned} Q_{CO_{2,t}} = \mu(\tau) + & \sum_{i=1}^{n1} \sigma_{CO_{2,i}}(\tau) CO_{2,t-i} + \sum_{i=0}^{n2} \sigma_{ICT_i}(\tau) ICT_{t-i} \\ & + \sum_{i=0}^{n3} \sigma_{URB_i}(\tau) URB_{t-i} + \sum_{i=0}^{n4} \sigma_{GDP_i}(\tau) GDP_{t-i} \\ & + \sum_{i=0}^{n5} \sigma_{REC_i}(\tau) REC_{t-i} + \varepsilon_t(\tau) \end{aligned} \tag{2}$$

where $\varepsilon_t(\tau) = CO_{2,t} - QCO_{2,t}(\tau/Ft-1)$ and $QCO_{2,t}(\tau/Ft-1)$ and $0 > \tau < 1$ represent level of quantile. As Equation (2) presents a possibility of serial correlation, we can express the QARDL model as:

$$\begin{aligned} Q_{\Delta CO_{2,t}} = \mu + \; & \rho CO_{2,t-1} + \delta_{ICT} ICT_{t-1} + \delta_{URB} URB_{t-1} + \delta_{GDP} GDP_{t-1} \\ & + \delta_{REC} REC_{t-1} + \sum_{i=1}^{n1} \phi_{CO_{2,i}} \Delta CO_{2,t-i} + \sum_{i=0}^{n2} \phi_{ICT_i} \Delta ICT_{t-i} \\ & + \sum_{i=0}^{n3} \phi_{URB_i} \Delta URB_{t-i} + \sum_{i=0}^{n4} \phi_{GDP_i} \Delta GDP_{t-i} \\ & + \sum_{i=0}^{n5} \phi_{REC_i} \Delta REC_{t-i} + \varepsilon_t(\tau) \end{aligned} \tag{3}$$

As per the QARDL context, Equation (3) can be extended according to the QARDL-ECM format. This can be used avoid previous correlations with the projection of ε_t on ΔICT_t, ΔURB_t, ΔGDP_t, and ΔREC_t with the form ε_t = δ_{ICT} ΔICT_t + δ_{URB} ΔURB_t + δ_{GDP}

ΔGDP_t + δ_{REC} ΔREC_t + υ_t. As a result, the ε_t is no longer correlated with ΔICT_t, ΔURB_t, ΔGDP_t, and ΔREC_t. The QARDL-ECM version of the model is:

$$\begin{aligned} Q_{\Delta CO_{2,t}} = \mu(\tau) \quad & +\rho(\tau)(CO_{2,t-1} - \delta_{ICT}(\tau)ICT_{t-1} - \delta_{URB}(\tau)URB_{t-1} \\ & -\delta_{GDP}(\tau)GDP_{t-1} - \delta_{REC}(\tau)REC_{t-1}) + \sum_{i=1}^{n1} \phi_{CO_{2,i}}(\tau)\Delta CO_{2,t-i} \\ & + \sum_{i=0}^{n2} \phi_{ICT_i}(\tau)\Delta ICT_{t-i} + \sum_{i=0}^{n3} \phi_{URB_i}(\tau)\Delta URB_{t-i} \\ & + \sum_{i=0}^{n4} \phi_{GDP_i}(\tau)\Delta GDP_{t-i} + \sum_{i=0}^{n5} \phi_{REC_i}(\tau)\Delta REC_{t-i} + \varepsilon_t(\tau) \end{aligned} \tag{4}$$

The cumulative short-run effect of the lag of CO_2 emissions (CO_2) on current emanation is measured using $\phi^* \sum_{j=1}^{n} \phi_j$. Similarly, the cointegration among the long-run variables of ICT, urbanization, GDP growth, and REC are described with the help of $\delta_{ICT}* = -\frac{\delta ICT}{p}, \delta_{URB}* = -\frac{\delta URB}{p}, \delta_{GDP}* = -\frac{\delta GDP}{p}, \delta_{REC}* = -\frac{\delta REC}{p}$ correspondingly. In order to establish significant negative correlation for the CO_2 parameter (ρ), as estimated by Equation (4), we conducted a Wald test to evaluate the short- and long-term nonlinear effects of ICT, URB, GDP, and REC on CO_2.

This study explores the impact of ICT and urbanization on environmental sustainability in China. We assembled annual data for the period 1995–2020. The period 1995–2020 was chosen for data collection in this study for two reasons. Firstly, this period encompasses a significant time frame for the development of urbanization, digitalization, and sustainable development in China. Therefore, the period 1995–2020 provides a sufficient timeframe to observe and analyze the development of these phenomena and their impacts on sustainable development in China. Secondly, the data for digitalization is not available before 1995, which is a major data limitation of this study. The trends of digitalization, urbanization, and carbon emissions are reported in Figures 1–3. Afterward, following Deshuai, et al. [41], annual data series were transformed by using the match sum method. Environmental sustainability is a dependent variable that measures CO_2 emissions in kilotons. Following the study of Ozturk and Ullah [42], we used CO_2 emissions as a measure of environmental sustainability. ICT is determined using internet users as % of population. Urbanization (URB) is taken as the urban population as % of total population. This study incorporated GDP growth in annual % and renewable energy consumption (REC) as control variables in the model framework. The data source for REC is the OECD, whereas the data sources for CO_2, ICT, URB, and GDP are world development indicators (WDI). The descriptive statistics for these data series are provided in Table 1. Summarizing the estimates of mean, S.D., skewness, kurtosis, and the JB test for CO_2, ICT, URB, GDP, and REC data series. The mean values are reported as: 15.73 for CO_2, 2.674 for ICT, 3.848 for URB, 8.610 for GDP, and 8.859 for REC. The S.D. values are reported as: 0.441 for CO_2, 1.590 for ICT, 0.185 for URB, 2.437 for GDP, and 6.273 for REC. According to skewness results, it was confirmed that data series are not normally distributed, as the REC series shows positive skewness while CO_2, ICT, URB, and GDP series negative skewness. Additionally, the null hypothesis for normality was also rejected in the JB test as shown by the statistically insignificant estimates for all variables. This confirms that CO_2, ICT, URB, GDP, and REC series are not normally distributed.

Table 1. Results of descriptive statistics.

	Mean	Median	Max	Min	S.D	Skewness	Kurtosis	Jarque–Bera (JB)	Prob.
CO_2	15.73	15.85	16.34	14.95	0.441	−0.581	1.845	10.29	0.006
ICT	2.674	3.366	4.292	−2.432	1.590	−1.255	3.973	27.79	0.000
URB	3.848	3.869	4.125	3.511	0.185	−0.237	1.810	6.288	0.043
GDP	8.610	8.299	14.61	0.211	2.437	−0.156	4.690	11.32	0.003
REC	8.859	7.017	21.48	1.811	6.273	0.584	1.961	9.361	0.009

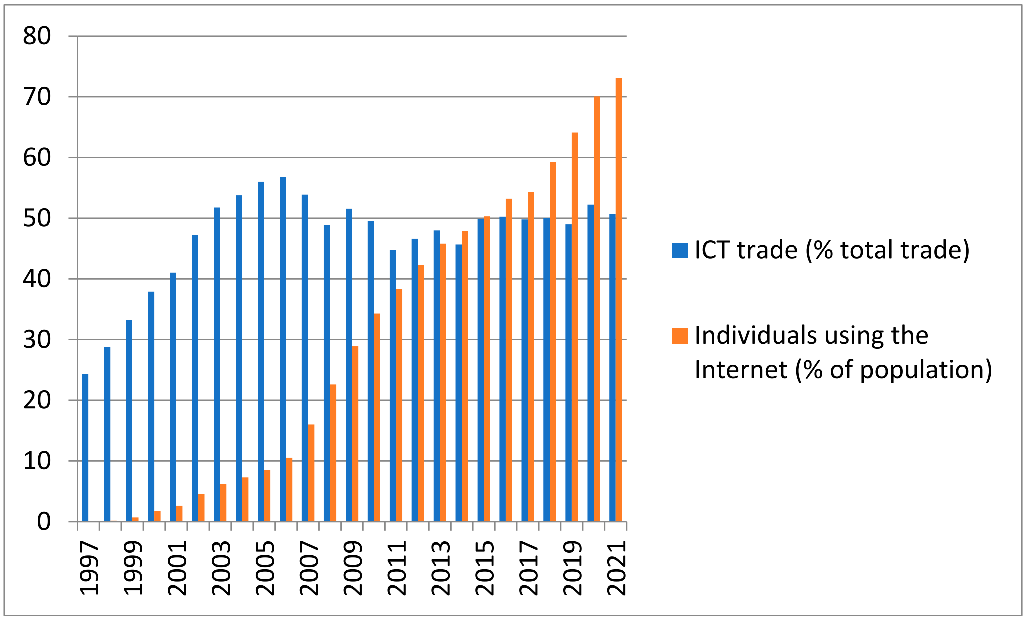

Figure 1. Trend of digitalization.

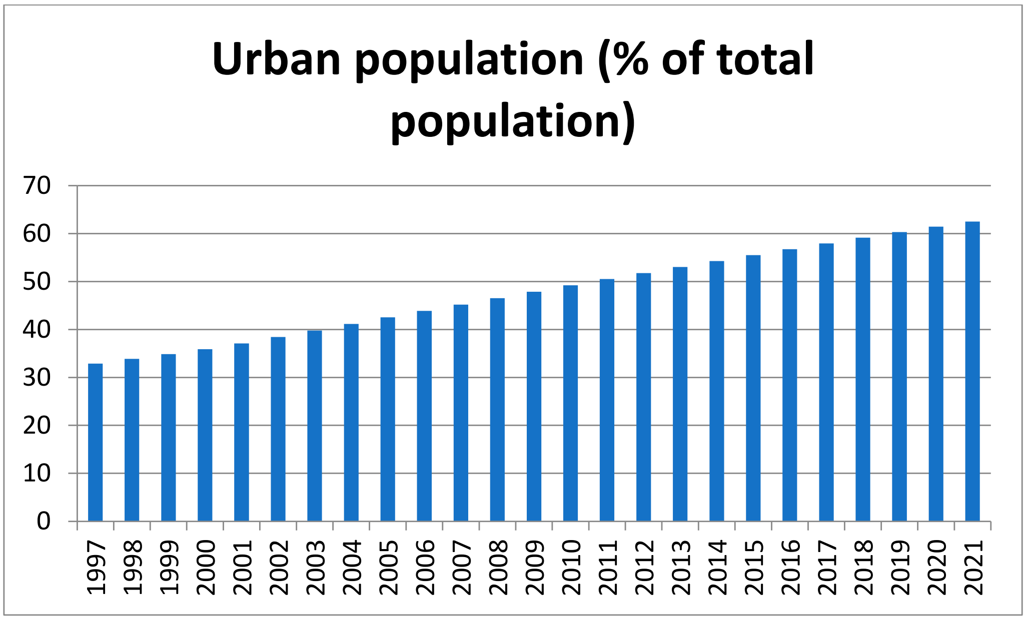

Figure 2. Urbanization trend.

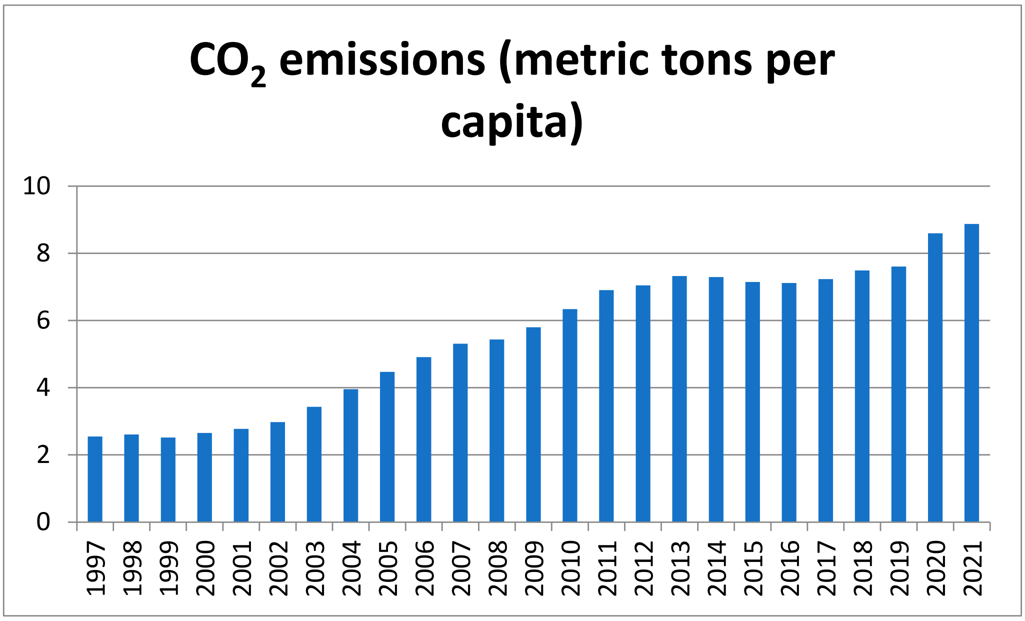

Figure 3. Carbon emissions trend.

4. Results

The results for the ADF and ZA tests are displayed in Table 2. The ADF test confirmed that the URB and REC data series are I(0) stationary, whereas other series are I(1) stationary. Moreover, the results for the ZA test confirm that the ICT and URB data series are I(0) stationary, whereas rest of the series are I(1) stationary. The ZA test also identifies break periods in each data series. It can be seen that 2011 Q1 is the break period in the CO_2 series, 2001 Q2 in the ICT series, 2000 Q4 in the URB series, 2007 Q1 in the GDP series, and 2019 Q4 in the REC series. The ADF and ZA test results justify that the concerned variables are a mixture of I(0) and I(1) integration order; thus, it is possible to apply a quantile ARDL approach for performing regression analysis.

Table 2. Results of unit root tests.

	ADF			ZA				
	I(0)	**I(1)**	**Decision**	**I(0)**	**Break Date**	**I(1)**	**Break Date**	**Decision**
CO_2	−1.452	−2.854 *	I(1)	−1.203	2001 Q2	−5.987 ***	2011 Q1	I(1)
ICT	−2.354	−4.687 ***	I(1)	−14.65 ***	2001 Q2			I(0)
URB	−3.542 ***		I(0)	−9.689 ***	2000 Q4			I(0)
GDP	−0.542	−2.987 **	I(1)	−1.658	2019 Q2	−6.256 ***	2007 Q1	I(1)
REC	−2.621*		I(0)	−3.658	2011 Q1	−4.875 **	2019 Q4	I(1)

Table footer: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 3 reports the results of the quantile ARDL model, providing both long-run and short-run estimates of the relationship in different quantiles ranging from 0.05 to 0.95, respectively. The results for the speed of adjustment parameter display that coefficient estimates are significant at all quantiles associated with a negative symbol. This confirms that variables such as CO_2, ICT, URB, GDP, and REC approach equilibrium in the long run. The findings display that ICT and CO_2 are negatively and significantly associated in all quantiles. This reveals that improvement in ICT tends to reduce CO_2 emissions in China, which demonstrates the positive role of ICT on green sustainability in the long run. Table 3 reports the association between URB and CO_2 for all quantile ranges. It was found that URB is positively linked with CO_2 in China for all quantiles. This means that an increase in urbanization positively contributes to enhancing CO_2 in China in the long run.

Table 3. Results of QARDL.

	ECM	Constant	Long-Run Estimates				Short-Run Estimates					
	$\rho(\tau)$	$\mu(\tau)$	$\delta_{ICT}(\tau)$	$\delta_{URB}(\tau)$	$\delta_{GDP}(\tau)$	$\delta_{REC}(\tau)$	$\phi_{ICT}(\tau)$	$\phi_{URB}(\tau)$	$\phi0_{GDP}(\tau)$	$\phi1_{GDP}(\tau)$	$\phi0_{REC}(\tau)$	$\phi1_{REC}(\tau)$
0.05	−0.472 **	−1.733 ***	−0.122 ***	4.668 ***	0.017	−0.041 ***	−0.065	1.798 **	0.005 ***	−0.002 **	−0.041 ***	−0.022 **
	(0.186)	(0.507)	(0.006)	(0.145)	(0.012)	(0.004)	(0.046)	(0.791)	(0.001)	(0.001)	(0.006)	(0.010)
0.10	−0.264 ***	−1.708 ***	−0.121 ***	4.663 ***	0.016	−0.041 ***	−0.039	1.174	0.005 ***	−0.003 ***	−0.037 ***	−0.024 ***
	(0.099)	(0.573)	(0.007)	(0.163)	(0.012)	(0.004)	(0.031)	(0.776)	(0.001)	(0.001)	(0.007)	(0.005)
0.20	−0.205 ***	−2.261 *	−0.122 ***	4.830 ***	0.013	−0.046 ***	−0.026	0.839 ***	0.005 ***	−0.004 ***	−0.034 ***	−0.025 ***
	(0.038)	(1.368)	(0.012)	(0.399)	(0.015)	(0.011)	(0.017)	(0.164)	(0.001)	(0.001)	(0.002)	(0.003)
0.30	−0.191 ***	−3.061 *	−0.123 ***	5.078 ***	0.006	−0.055 ***	−0.025	0.802 ***	0.006 ***	−0.004 ***	−0.035 ***	−0.026 ***
	(0.036)	(1.538)	(0.016)	(0.449)	(0.007)	(0.011)	(0.018)	(0.158)	(0.001)	(0.001)	(0.002)	(0.003)
0.40	−0.192 ***	−3.187 **	−0.121 ***	5.122 ***	0.003	−0.056 ***	−0.042	0.864 ***	0.006 ***	−0.004 ***	−0.034 ***	−0.024 ***
	(0.046)	(1.242)	(0.015)	(0.362)	(0.005)	(0.008)	(0.031)	(0.206)	(0.001)	(0.001)	(0.002)	(0.002)
0.50	−0.194 ***	−3.046 ***	−0.118 ***	5.086 ***	0.002	−0.056 ***	−0.082 **	0.855 ***	0.006 ***	−0.004 ***	−0.033 ***	−0.023 ***
	(0.051)	(1.153)	(0.015)	(0.336)	(0.006)	(0.007)	(0.040)	(0.221)	(0.001)	(0.001)	(0.002)	(0.002)
0.60	−0.265 ***	−3.496 ***	−0.120 ***	5.221 ***	0.007	−0.059 ***	−0.088 ***	1.157 ***	0.005 ***	−0.004 ***	−0.033 ***	−0.021 ***
	(0.070)	(0.930)	(0.013)	(0.269)	(0.004)	(0.006)	(0.030)	(0.267)	(0.001)	(0.001)	(0.003)	(0.002)
0.70	−0.233 ***	−3.089 ***	−0.114 ***	5.106 ***	0.011 ***	−0.056 ***	−0.088 ***	1.087 ***	0.006 ***	−0.005 ***	−0.032 ***	−0.020 ***
	(0.056)	(0.746)	(0.011)	(0.215)	(0.003)	(0.004)	(0.031)	(0.240)	(0.001)	(0.001)	(0.003)	(0.002)
0.80	−0.190 ***	−2.914 ***	−0.110 ***	5.065 ***	0.013 ***	−0.055 ***	−0.101 ***	0.958 ***	0.006 ***	−0.005 ***	−0.031 ***	−0.020 ***
	(0.049)	(0.722)	(0.011)	(0.207)	(0.003)	(0.004)	(0.030)	(0.202)	(0.001)	(0.001)	(0.002)	(0.002)
0.90	−0.155 ***	−2.879 ***	−0.109 ***	5.053 ***	0.014 ***	−0.055 ***	−0.098 ***	0.909 ***	0.007 ***	−0.006 ***	−0.029 ***	−0.019 ***
	(0.053)	(0.540)	(0.009)	(0.155)	(0.003)	(0.003)	(0.034)	(0.204)	(0.001)	(0.001)	(0.002)	(0.002)
0.95	−0.126 *	−2.931 ***	−0.109 ***	5.070 ***	0.017 ***	−0.056 ***	−0.079 **	0.974 ***	0.009 ***	−0.007 ***	−0.028 ***	−0.017 ***
	(0.066)	(0.512)	(0.008)	(0.147)	(0.002)	(0.003)	(0.035)	(0.202)	(0.002)	(0.001)	(0.003)	(0.002)

Table footer: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

The long-run estimates of QARDL also provide results for the association between GDP and CO_2. It was found that GDP has a significant and positive impact on CO_2 emissions at quantiles 0.70 to 0.95 in the long run. This means that at these intensities of CO_2, an upsurge in GDP tends to increase CO emissions, indicating the negative role of GDP growth on environmental sustainability in the long run in China. However, the nexus between GDP growth and CO_2 is observed statistically insignificant at intensities from 0.05 to 0.60 in the long run in China. This shows that, at intensities from 0.05 to 0.60, GDP growth produces no impact on sustainability in China. Table 3 reports the association between REC and CO_2 at all quantile ranges. It was found that REC is negative and tends to reduce CO_2 emissions in China in the long run, confirming the positive role of REC in the enhancement of environmental sustainability in the region.

The output of the short-run estimation is also presented in Table 3. The findings of the short-run estimation display that ICT and CO_2 are negatively and significantly associated at quantiles from 0.50 to 0.95. This reveals that an upsurge in ICT reduces CO_2 emissions in China for these quantiles. Conversely, ICT produces no change in environmental sustainability in the short run in quantiles from 0.05 to 0.40. Table 3 reports that URB is positively and significantly associated with CO_2 in China for all quantiles except quantile 0.10. This describes that urbanization enhances CO_2 emissions in China at all intensities except 0.10 in the short run. The short-run estimates reveal that GDP has a positive impact on CO_2 emissions at all intensities in the short run. This indicates that an upsurge in GDP tends to increase CO_2 emissions at all quantiles in China. Table 3 reports that REC is negatively linked with CO_2 in the short run. This shows that an upsurge in REC positively improves environmental sustainability in China in the short run.

Table 4 reports the results of the Wald test, confirming the consistency of the parameter. The speed of adjustment parameter is statistically significant, which demonstrates that the null hypothesis is rejected. It confirms the constancy of parameters. The findings of the Wald test also confirm that long-run parameters such as ICT, URB, GDP, and REC are nonlinear in nature in the Chinese economy. The Wald test also confirms that ICT and URB are nonlinear in nature in the Chinese economy in the short run.

Table 4. Results of Wald test.

Variable	Wald Statistics	Prob.
ρ	8.031 ***	0.000
δ_{ICT}	14.05 ***	0.000
δ_{URB}	8.022 ***	0.000
δ_{GDP}	8.002 ***	0.000
δ_{REC}	9.002 ***	0.000
ϕ_{ICT}	7.039 ***	0.000
ϕ_{URB}	5.117 **	0.012
$\phi0_{GDP}$	1.014	0.848
$\phi1_{GDP}$	0.044	0.997
$\phi0_{REC}$	1.244	0.888
$\phi1_{REC}$	1.401	0.790

Table footer: *** $p < 0.01$, ** $p < 0.05$.

5. Discussion

Our findings show that ICT and CO_2 are negatively and significantly associated for all quantiles. This reveals that improvement in ICT tends to reduce CO_2 emissions in China, which demonstrates the positive influence of ICT on green sustainability in the long run. Our outcomes are supported by various studies. The utilization of information resources to assist economic growth was one potential technique for increasing efficiency while reducing energy use. ICT may improve industrial productivity and cut down on material item use, which would necessitate less energy and result in reduced pollutant emissions. Additionally, ICT helps to reduce paperwork, which enhances environmental performance. Teleconferences and integrated point-of-sale platforms are two examples of ICT-focused business practices that might ease the environmental strain. However, the increased use of online learning has led to a decline in traveling, which negatively affects carbon footprints. The previous literature highlights that ICT use improves environmental sustainability [36,43]. Ulucak and Khan [44] denoted that the use of ICT promotes online shopping, reducing the burden on the transportation sector and thus reducing CO_2 emissions. Khan et al. [45] reported that ICT use has a positive effect on environmental quality using remote sensing and pollution emission control mechanisms. However, some other studies contradict our findings. These studies report that ICT infrastructure produces waste and toxins, which are harmful for environmental sustainability [36].

This study also states that an increase in urbanization positively enhances CO_2 in China. In support of our findings, Liu and Bae [46] claimed that urbanization is necessary for social and economic transformation but it increases CO_2 emissions due to intensified energy demand. Some other studies argue that urbanization enhances energy consumption, promotes CO_2 emissions, and destroys environmental sustainability [47]. As per Ma [48], the most important route of impact for urbanization's long-term possible impact on energy and power intensity is infrastructure development. Additionally, urbanization's effect on carbon production is driven by shifts in urban home energy usage as well as the transportation and business industries, with regional variations in these effects. The most energy-intensive industries concerning the rise in CO_2 pollution from urbanization are electricity, heat, and transportation [49]. Urban families' rising utilization of high-energy consumer gadgets, which is a result of rising wealth and spending among urban people, is blamed for the growth in CO_2 emissions. In contrast, some studies reveal that urbanization reduces environmental degradation by provisioning R&D opportunities and innovation toward resource efficiencies and green technologies [50]. Moreover, urbanization enables people to use ecofriendly technologies that help in improving environmental sustainability [51].

6. Conclusions and Policy Implications

6.1. Conclusions

On one side, rapid urbanization around the globe has allowed people to enjoy better quality of life. On the other side, urbanization is widely acknowledged as a vital source of deteriorating environmental quality. In order to protect the environment from any further damage, the implementation of the "smart cities" strategy supported by ICTs and green transportation networks is the need of the hour. The role of ICTs is crucial in making a normal city into a smart city because a large-scale penetration of ICT into an urban setup will allow people to enjoy urban facilities without exerting too much burden on the environment. Therefore, this study estimated the impact of ICT and urbanization on environmental sustainability in China using the novel QARDL method.

The results of the QARDL model state the negative and significant impact of ICT on CO_2 emissions in China at all quantiles, implying that an increase in the use of ICT proved to be an important factor in improving environmental quality. The higher the use of ICT, the better the environment is. In contrast, the estimated coefficients of urbanization were positively significant for all quantiles. This finding sustains the idea that large-scale urbanization is detrimental to the environment because the process of urbanization is among the leading sources of carbon emissions. In the short run, the negative impact of ICT on CO_2 emissions could only be seen in higher quantiles, while the positive impact of urbanization on CO_2 emissions was confirmed for all quantiles. Moreover, the asymmetric impact of ICT and urbanization was confirmed in the short and long run with the help of Wald tests.

6.2. Policy Implications

Our analysis provides important results that can be crucial in providing important policy proposals. The analysis confirmed the positive role of ICT in improving environmental quality. Hence, the focus of policymakers in China should be on increasing the penetration of ICT in each and every sector of the economy. This would be an important step toward the dematerialization and digitalization of the economy, converting the economy into a weightless economy. Moreover, the increased use of information in every sector of the economy can help reduce environmental burden. Our findings confirm that urbanization deteriorates environmental quality; hence, the integration of ICT in the process of urbanization can help to convert cities into smart cities, which is essential for the sustainable future of the world.

It is important to encourage the process of urbanization in China by improving the structure of energy consumption, which will help in combating carbon intensity. There is a need for industrial upgrade and technological progress in the process of urbanization that will contribute to achieving a low-carbon environment while achieving social and economic development. It is time for the Chinese government to accelerate towards the convergence of green sustainability and a low-carbon economy. There is a need for such reforms that accelerate the urban management system and improve the construction procedure without harming the environment. It is suggested that enterprises should prefer advanced technology for constructing infrastructure. The Chinese government should encourage the implementation of low carbon intensity standards and reinforce supervision. Lastly, tax relief or financial subsidies should be afforded to construction firms and incentive policies that support construction industries should be formulated.

The Chinese government should encourage the development and deployment of green ICT solutions, such as cloud computing, virtualization, and energy-efficient data centers. This will help reduce the energy consumption of the ICT sector, which is a significant contributor to greenhouse gas emissions. China should adopt a circular economy model that emphasizes the efficient use of resources and the reduction of waste. This will help to reduce the environmental impact of smart city technologies and the associated urbanization. The Chinese government should increase public awareness of the environmental impact of smart city technologies and the importance of sustainable urban development. This could be achieved through public education campaigns, community engagement initiatives, and other outreach efforts. The Chinese government should foster partnerships between the public and private sectors to develop and implement sustainable smart city technologies. These partnerships can help to bring together the resources and expertise needed to develop and implement sustainable solutions. The Chinese government should develop and enforce environmental regulations that apply to smart city technologies and urban development projects. This will help to ensure that these technologies are developed and implemented in an environmentally responsible manner. The Chinese government should promote the use of renewable energy sources, such as solar, wind, and geothermal power, to power smart city technologies and urban development projects. This will help to reduce reliance on fossil fuels and reduce greenhouse gas emissions. The Chinese government should prioritize public transportation and nonmotorized modes of transportation, such as walking and cycling, in smart city development plans. This will help to reduce the reliance on private vehicles and the associated environmental impacts.

6.3. Limitations and New Directions

The limitations of this study include the relatively narrow scope of the research, which focuses exclusively on the impact of urbanization and the digital era on green sustainability in China. Future studies could broaden the scope of the research to include other countries or regions and investigate the impact of other factors on sustainable urban development, such as social and cultural factors. Additionally, this study relies on secondary data sources, which may have limitations in terms of data quality and representativeness. Future research could use primary data collection methods, such as surveys or interviews, to provide a more in-depth and comprehensive analysis of the topic. There are some data-based limitations of our study related to green sustainability and smart urbanization in the case of China. Future studies should collect good measures of green sustainability and smart urbanization for analysis. Future research could explore these issues further to provide a more holistic understanding of the impact of smart urbanization and the digital era on sustainable development.

Author Contributions: Methodology, Y.L. and W.L.; Formal analysis, Data curation, Writing—original draft, Writing—review and editing, Y.X. and M.T.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available on reasonable demand from corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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