

Article

Discovering the E-Government and COVID-19 Effect on Sustainable Development: Novel Findings from the China Provinces

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Abstract: This paper investigates the effect of E-government (EG) and COVID-19 on environmental sustainability (ES), considering the Load Capacity Curve (LCC) in the Chinese provinces, which employs the panel MMQR method. This study reveals that E-government initiatives positively impact environmental sustainability, with a 1% increase in E-government effectiveness leading to a rise in ES between 0.05% and 0.40%. Conversely, COVID-19 has a pronounced negative effect on sustainability, particularly at the medium quantiles. The results also report the non-LCC hypothesis in Chinese provinces. The Dumitrescu–Hurlin (DH) causality outcome indicates a bi-directional causal association between environmental sustainability and E-government practices and the unidirectional link from COVID-19 to environmental sustainability. These findings highlight the policy implication of the critical role of E-government in promoting environmental sustainability despite the challenges posed by economic and demographic factors.

Keywords: E-government; COVID-19; environmental sustainability; MMQR; China provinces



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1. Introduction

Environmental sustainability (ES) holds immense importance in China due to its significant global ecological impact, population and economic growth size, diverse ecosystems, and substantial natural resource (NR) consumption and production levels as the world's most populous country with the largest consumers. It merits acknowledgment that China is the largest world supplier of mineral resources [1]. The nation is endowed with an extensive and diverse portfolio of NR reserves, revealing that they surpassed a staggering monetary value of USD 23 trillion between 1984 and 2016 [2].

E-government has the potential to significantly enhance environmental stewardship through data use, E-technologies, and online platforms [3]. The capacity of E-governance to gather an extensive array of satellite data and sensor systems spanning vast geographical regions facilitates a thorough comprehension of environmental conditions and resource utilization patterns [4]. Studying the effect of E-government on ecological sustainability in the context of Chinese provinces is particularly compelling due to China's rapid technological advancement, which is the main feature of government governance transformation [5]. China's provinces vary widely in terms of economic development, industrialization, and environmental conditions, providing a diverse landscape for examining the effect of E-government initiatives.

In provinces where E-government systems have been effectively implemented, there are notable improvements in efficiency and resource management. By reducing the reliance on physical documents and in-person interactions, these systems help conserve resources such as paper and fuel, directly contributing to environmental sustainability [6]. Additionally, E-government enhances transparency and accountability in environmental governance by making data and decision-making processes more accessible to the public. E-government also plays a crucial role in increasing public participation in environmental

decision making. In many Chinese provinces, online platforms allow citizens to report environmental issues, participate in discussions, and contribute to policy development [7].

Moreover, the availability of comprehensive and accurate environmental data through E-government systems enables more informed and effective policy decisions. This data-driven approach allows provincial governments to address local environmental challenges better and monitor progress toward sustainability goals. Innovative technologies and practices promoted by E-government, such as smart city initiatives, enhance ecological sustainability by optimizing energy use, increasing energy efficiency, reducing emissions, and improving waste management [8]. Internationally, Chinese provinces can use E-government platforms to share best practices and collaborate on environmental issues, contributing to global sustainability efforts. Economically, promoting environmental sustainability through E-government can lead to cost savings, create green jobs, and attract investments in green technologies, fostering economic growth at the provincial level. The COVID-19 impact on the study of E-government and environmental sustainability in Chinese provinces is particularly significant. The pandemic has accelerated the adoption of digital technologies and highlighted the critical role of E-government in managing environmental sustainability during crises [9]. Firstly, the pandemic led to an increased reliance on digital platforms as lockdowns and social distancing measures made physical interactions difficult [10]. E-government systems became essential in maintaining administrative functions, allowing for continued governance without needing in-person contact. The pandemic also accelerated the adoption of innovative technologies and smart city initiatives as governments sought solutions to manage urban environments more effectively. These technologies, often facilitated by E-government platforms, contributed to optimizing energy use, reducing emissions, improving waste management, addressing environmental challenges, and contributing to a sustainable and resilient future [11].

Based on the context above, this study examines the impact of E-government on environmental sustainability across 30 Chinese provinces, with a particular focus on the effects of COVID-19. This study makes several key contributions. Firstly, it addresses the significant gap between theoretical models and the practical implementation of environmental sustainability policies, resulting from insufficient attention to evaluative aspects. Secondly, this research offers a comprehensive analysis during COVID-19, bridging gaps in prior studies within this field. While previous research has explored policies in multiple contexts relevant to environmental-based regions, such studies have been limited and sparse across Chinese provinces [12–14]. Thirdly, this study acknowledges the economic and geographical diversity of the sampled towns, which can influence digitalization, policy interventions, and environmental sustainability outcomes.

This research provides policy recommendations aimed at enhancing environmental sustainability. Integrating E-governance in environmental sustainability efforts aligns with several United Nations (UN) sustainable development goals (SDGs). Primarily, it improves transparency and promotes digital governance (SDG 16: Peace, Justice, and Strong Institutions). It also emphasizes sustainable management and responsible consumption of natural resources (SDG 12: Responsible Consumption and Production) and supports climate change action (SDG 13: Climate Action). Additionally, integrating E-government initiatives supports SDG 7 (Affordable and Clean Energy) by promoting efficient energy use and the transition to renewable energy sources through improved monitoring, data analysis, and policy enforcement. It also aligns with SDG 9 (Industry, Innovation, and Infrastructure) by fostering innovation, developing sustainable infrastructure, and supporting sustainable industrialization. It contributes to SDG 11 (Sustainable Cities and Communities) by enhancing urban planning, reducing pollution, and improving waste management systems. Furthermore, it supports SDG 14 (Life Below Water) by strengthening the management and protection of marine resources and ecosystems, reducing pollution and overfishing. Lastly, it aligns with SDG 15 (Life on Land) by supporting better land use management, deforestation control, and biodiversity protection through data-driven policies and increased public participation in environmental conservation efforts.

Recent studies have provided valuable perspectives on the significant relationship and impact of E-governance and environmental sustainability in different countries and regions. Lee [15] explores the link between E-government and ES, mainly focusing on Small Island Developing States (SIDS). The findings suggest that E-government positively influences environmental sustainability both directly and indirectly by enhancing government efficiency. It identified the importance of intermediary factors in assessing E-government effectiveness. Ziolo et al. [8] analyze the association between the digitalization of E-government and the ESG factors in European countries alongside various socioeconomic and environmental variables from 2003 to 2020. The findings reveal statistically significant relationships between E-government and the ESG, indicating that digitalized administrative processes genuinely and positively impact ES. They confirm that investments in digital infrastructure and government have substantial long-term advantages, contributing to environmental, social, and economic sustainability.

Castro and Lopes [16] examined the link between E-government and ES, indicating that digital transformation can drive government changes by enhancing transparency, accountability, and efficiency. Using a logit model of 103 countries from 2003 to 2018, the study finds that E-government development positively influences an ES, as measured by adjusted net savings, which reflects economic, social, and environmental development. The results indicate that E-government is particularly beneficial for sustainability in developing and transitioning economies. Hashim [17] investigates the impact of E-government on smart cities in Saudi Arabia, focusing on the opportunities and challenges involved. The study recognizes the recent impact of information and communication technologies (ICT) on E-government. It examines the definitions of E-government and the technologies that support it, including smart cities, IoT, big data, cloud computing, and various digital government platforms.

Regardless of the China case, Vashkevich et al. [18] examined how elderly citizens in China engage with electronic governance (E-governance) platforms. They conducted an online survey distributed via WeChat in major cities, namely Beijing, Shanghai, Tianjin, and Changsha. Using Structural Equation Modeling (SEM), They identified the primary factors affecting subjective norms, including perceived ease of use, perceived usefulness, trust, supportive conditions, and previous exposure to technology. They also contribute to developing Social Sustainability Marketing Technologies in China, highlighting the need for actionable strategies to address the digital divide among older populations.

Li and Xu [19] investigate how digital government policies influence urban economic sustainable development through enterprise digital transformation. Using data from A-share listed companies from 2012 to 2022, the study finds that digital government policies significantly drive enterprise digital transformation, particularly in central and western cities, provincial capitals, and cities with lower economic development levels. The authors of [20] emphasized the critical role of digital infrastructure in addressing the resource curse in urban environments in the 242 Chinese prefectures. Likewise, the authors of [21] highlighted the potential of numerical infrastructure in improving the allocation of alternative resources.

Focusing on COVID-19, extensive studies have highlighted the effect of COVID-19 on environmental sustainability [22–26]. Ullah et al. [10] examined the role of E-governance in combating COVID-19, focusing on China and Pakistan. They analyzed the E-Government Development Index (EGDI) reports and highlighted the use of 5G and big data technologies during the pandemic. China's EGDI ranking improved from 74 to 65, while Pakistan's ranking declined from 137 to 148. The study suggests that Pakistan can learn from China's E-governance model to enhance its sustainable development, especially in the context of the China–Pakistan Economic Corridor (CPEC). The authors conclude that CPEC collaboration can help combat COVID-19 and promote sustainable development in Pakistan.

Moreover, the study by Palos-Sánchez et al. [27] found that Digital Transformation (DT) processes significantly influenced the attitude of local governments (LGs) in Spain toward the COVID-19 pandemic. The research, based on data collected from 124 LGs

through a questionnaire, revealed that the implementation of DT, along with factors such as the IT skills of workers, budgets, regulatory compliance, and the use of trust seals, played a crucial role in how LGs responded to the pandemic. The findings underscore the importance of IT infrastructure and security in the context of public health emergencies and sustainable development initiatives.

2. Materials and Methods

2.1. Data Specification

While sustainable development encompasses economic growth, social inclusion, and environmental protection, it is a broader concept that aims to meet the needs of the present without compromising the ability of future generations to meet their own needs [28]. On the other hand, ES focuses explicitly on the health, involving responsible interaction with the environment to avoid depletion or degradation of natural resources and enhance long-term environmental quality [29]. Based on this distinguished term, this research investigates the impact of E-government on ES in Chinese provinces. To achieve this goal, we conducted a thorough data collection from 2012 to 2021, a period recognized as crucial for the maturity of the digital government in the Chinese provincial administrations [30]. This timeframe also aligns with heightened Chinese government efforts to improve environmental health, exemplified by initiatives like the China Pilot Low Carbon City Program introduced in 2010 [31–33].

This study employs the technique proposed by Ahmad et al. [34] to evaluate NR extraction as a proxy for determining environmental sustainability across various provinces. The parameter used for quantification is the fixed investment in the mining sector, normalized as units per 100 million RMB. This approach reflects how efficiently and responsibly natural resources are managed, ensuring their consumption does not lead to depletion or significant environmental harm [35]. A higher investment ratio may imply a province's economic model heavily relying on natural resource extraction. Consequently, areas with significant investment in their mining industries indicate the presence of valuable resources and indirectly reveal their policies for managing these resources [36]. The second primary variable consists of the dimension of the E-government index, drawing upon the analytical framework established by [35,37]. It utilizes a Principal Component Analysis (PCA) of indicators sourced from NIPAC to illuminate the progression of digital technology, with a particular emphasis on digital public services, representing the extent of internet access, the level of mobile technology use, and, notably, the advancements in digitizing government services.

This study considers the LCC context in which GDP2 represents the squared term of Gross Domestic Product (GDP). This term is included to capture the potential non-linear relationship between economic growth and environmental impact [38–40]. The inclusion of GDP2 allows for modeling a quadratic relationship, indicating that the impact of economic growth on the environment may vary at different levels of development. Typically, a positive coefficient for GDP and a negative coefficient for GDP2 suggest an inverted U-shaped curve. This means that at lower levels of GDP, economic growth might lead to higher environmental degradation, but further economic growth could improve ES beyond a certain point (the turning point).

The baseline methodology for this research is outlined as follows:

Environmental sustainability = (E-government, FDI, GDP, government intervention, R and D, Population, and Oil prices)

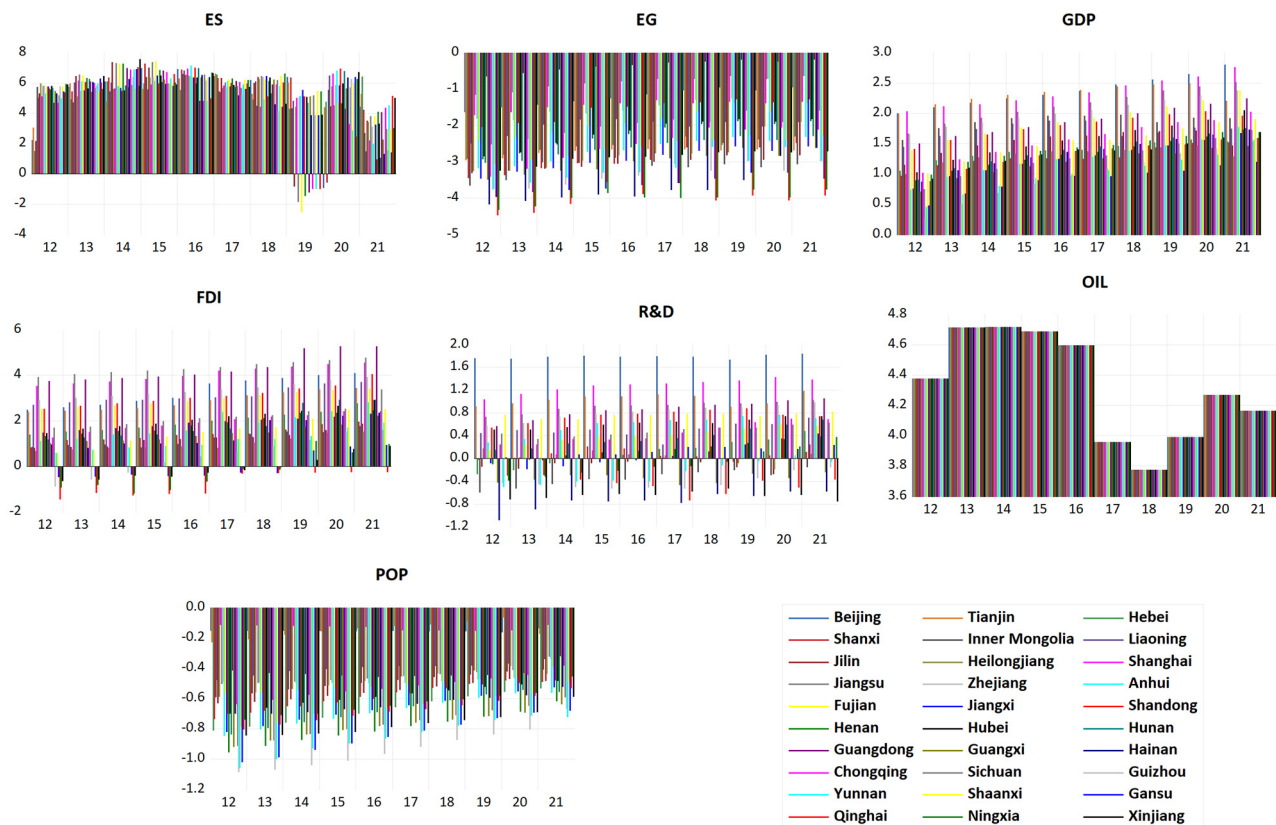
$$ES = \psi_0 + \psi_1 GDP_{it} + \psi_2 GDP2_{it} + \psi_3 ED_{it} + \psi_4 R\&D_{it} + \psi_5 OIL_{it} + \psi_6 FDI_{it} + \psi_7 POP + \vartheta_{it} \quad (1)$$

ψ_1 to ψ_7 are the coefficients. ϑ_{it} represents the error term. All data are converted to the logarithm. Table 1 shows the corresponding source and measures while Figure 1 shows the data trend.

Table 1. Data definition.

Data	Abbreviation	Unit	Source
Environmental sustainability	ES	Sustainable use of natural resources.	CCSY
GDP	GDP	Per capita	CCSY
E-government	EG	Index	NIPAC
FDI	FDI	Per cent of GDP	CCSY
Oil prices	OIL	Us dollar per barrel	EIA
Population	POP	Million	CCSY
Research and development	R and D	%	CCSY

Note: CCSY is the Chinese City Statistical Yearbook; NIPAC is the Chinese National Intellectual Property Administration.

**Figure 1.** Data trend.

2.2. The CSTD Test

The choice of appropriate tests becomes particularly relevant in settings with heterogeneous cross-sectional units (CSTD), where diverse economic conditions and behaviors may influence the data. By rigorously applying these tests, researchers can obtain more reliable insights and make informed decisions based on their panel data analyses. This test encompasses several statistical approaches, including those developed in [41–43]. Employing these tests is crucial for ensuring the accuracy. The system performs effectively over extended periods and in critical software development contexts. This assertion is supported by observing significant disparities among cities within a nation. The CSTD proposed by Pesaran [43] can be summarized in the following equation:

$$\text{CSTD} = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{\rho}_{ij} \right) \rightarrow N(0,1) \quad (2)$$

2.3. Heterogeneity Test

Accounting for slope heterogeneity in panel data studies is crucial due to varying slopes among panel units. Statistical tests developed by the authors of [44,45] are instrumental in addressing this issue. Based on a fixed-effects model, the Pesaran et al. [46] test assesses slope heterogeneity by examining the link between each individual's slope. On the other hand, the test in [44] evaluates slope heterogeneity by comparing the homogeneous slope values, and it applies to both fixed.

By thoroughly addressing slope heterogeneity, researchers can ensure that variations among individual units are accurately captured, leading to more robust and reliable conclusions. This approach enhances the validity of panel data analyses and contributes to a deeper understanding of the studied phenomena. This research delves into the implications of the homogeneity panel data:

$$\tilde{\Delta}_{ASH} = (N)^{\frac{1}{2}} \left(\frac{2k(T-k-1)}{T+1} \right)^{-\frac{1}{2}} \left(\frac{1}{N} \tilde{S} - 2k \right) \quad (3)$$

2.4. Unit Root Test (URT)

The unit root test (URT) is a crucial statistical test used to determine the presence of a unit root in the panel, indicating non-stationarity in the series. Indicating a unit root signifies that the variables do not revert to a mean or exhibit constant variance over time, assessing the stationarity's essential and dynamic effect. Several statistical methods can be employed to conduct a URT, one of which is the (CIPS) test proposed in [47]. The CIPS statistic test is a comprehensive tool that effectively addresses serial correlation through a straightforward linearity regression. By augmenting the standard IPS test with cross-sectional averages of lagged levels and first differences of the individual series, the CIPS test enhances the ability to manage cross-sectional dependence, making it more robust in practical applications.

The asymptotic properties of the CIPS test are illustrated in Equation (4). Utilizing the CIPS test allows researchers to accurately determine the stationarity of time series data, providing a solid foundation for subsequent econometric analyses.

$$\text{CIPS}(N, T) = N^{-1} \sum_{i=1}^N t_i(N2.4, T) \quad (4)$$

2.5. Co Integration Test

By utilizing the Westerlund test, researchers can effectively determine the presence of co-integration, ensuring that the analysis captures the long run dynamics among the non-stationary data. This is crucial for understanding the underlying economic or financial relationships and making reliable long-term predictions based on the co-integrated series. One prominent method is the one proposed in [48].

$$VR_P = \sum_{i=1}^N \sum_{t=1}^T \hat{E}_{it}^2 \left(\sum_{i=1}^N \hat{R}_i \right)^{-1} \quad (5)$$

2.6. Dumitrescu and Hurlin Causality

The Dumitrescu and Hurlin [49] test is widely used for examining causality in panel data. This test extends the Granger causality concept to panel data, allowing for the analysis of causal relationships between variables across different cross-sectional units while accommodating heterogeneity. This makes it a valuable tool for researchers examining causal relationships in economics, finance, and social sciences. The Dumitrescu and Hurlin test evaluates the null hypothesis that no Granger causality exists from one variable to another across all panel units. This test allows for heterogeneity in the causal relationships by permitting individual-specific effects and varying lag lengths among the panel units.

2.7. MMQR Method

The MMQR is a statistical technique used to estimate quantile regression parameters by matching sample moments of the dependent variable with those predicted by the model [50]. Unlike traditional quantile regression, which minimizes a loss function, MMQR directly estimates the quantile parameters by equating the sample moments to the theoretical moments implied by the model [13,14].

In MMQR, the moments of the dependent variable are expressed as functions of the parameters of interest, and these equations are solved to obtain estimates of the quantile parameters. This approach is advantageous when the distributional assumptions of traditional quantile regression models are not met or when the conditional quantile function is not easily specified [51]. MMQR offers a flexible and computationally efficient alternative to traditional quantile regression methods, especially in cases where the underlying distribution of the data is poorly understood or when the quantile function is complex [52]. The conditional quantiles estimate $Qy(\tau | X)$ of the location-scale variant model is written in the following equation:

$$y_{it} = a_i + X_{it}b' + (\vartheta_i + Z_{it}d')U_{it} \quad (6)$$

$P(c_i + Z_{it}'\gamma > 0) = 1$ determines the probability. (a, b', c, d') denote the coefficient to be calculated. (a_i, c_i) , $i = 1, 2, 3, \dots, n$, address the fixed effect i of each data variable. Z corresponds to a k -vector of operators in X , which signifies conversions that are differentiable by a factor of l .

3. Results

3.1. Summarize Statistics

Table 2 shows the descriptive statistics for the variables ES, EG, GDP, OIL, FDI, POP, and R and D in the dataset reveal several key insights. The ES variable has a mean of 5.29 and a median of 5.79, with a high standard deviation of 1.72, indicating considerable variability and a negatively skewed distribution with significant kurtosis, as confirmed by the JB test ($p < 0.001$).

Table 2. Descriptive statistic.

	ES	EG	GDP	OIL	FDI	POP	R_D
Mean	5.290104	−2.500279	1.552672	4.324208	1.900141	−0.580980	0.293520
Median	5.794598	−2.628372	1.511991	4.322298	1.772568	−0.585653	0.273829
Maximum	7.553078	−0.184979	2.798634	4.715190	5.274666	−0.064201	1.842136
Minimum	−2.525729	−4.465113	0.271477	3.775974	−1.448595	−1.084626	−1.078810
Std.Dev.	1.721116	0.926558	0.458974	0.330086	1.380674	0.210525	0.596327
Skewness	−2.192733	0.379931	0.225359	−0.194134	−0.028494	0.360397	0.285565
Kurtosis	8.360378	2.694702	2.858112	2.611977	2.728925	3.096445	2.734759
Jarque–Bera	599.5747	8.382469	2.790974	25.96702	0.959116	6.610562	4.956782
Probability	0.000000	0.015128	0.047712	0.000002	0.019057	0.036689	0.083878
Observations	300	300	300	300	300	300	300

For EG, the mean is −2.50, and the median is −2.63, with moderate variability ES of 0.93 and a slightly positive skew, suggesting minor deviation from normality ($JB = 0.015$).

GDP shows a mean of 1.55 and a median of 1.51, with low variability (about 0.46) and a distribution close to normal ($JB = 0.25$). The OIL variable, with a mean and median around 4.32, has low variability (ES of 0.33) but a significant distribution, indicated by a low kurtosis value and a strong rejection of normality ($JB < 0.001$).

FDI exhibits a mean of 1.90 and a median of 1.77, with moderate variability (ES of 1.38) and a symmetric, showing no significant deviation from normality ($JB = 0.62$). The POP variable has a mean of −0.58 and a median of −0.59, with low variability (ES of 0.21), slightly positive skewness, and a near-normal kurtosis. However, it shows a minor deviation from normality ($JB p = 0.037$). Lastly, the R and D variable, with a mean of 0.29

and a median of 0.27, displays a moderate variability of about 0.60. Overall, all annual data do not follow a normal distribution. The results from the JB test statistics indicate that utilizing quantile-based frameworks represents the optimal strategy for addressing non-linearity within data series. This approach enables the effective utilization of quantile models to fulfill the intended objectives.

3.2. Correlations Results

Table 3 presents the pairwise correlation coefficients of sustainability development with EG, GDP, OIL, FDI, POP, and the R_D, respectively. ES demonstrates a weak negative correlation with EG (−0.1032) and a slightly stronger negative correlation with GDP (−0.1746), indicating a tendency to decrease as economic growth and GDP increase. On the other hand, ES shows a moderate positive correlation with OIL (0.3176), suggesting a tendency to increase with higher oil production. The correlations with FDI (−0.1556), POP (−0.1367), and R_D (−0.0551) are also negative but relatively weak, indicating a slight tendency to decrease with higher levels of foreign direct investment, population, and research and development expenditures, respectively.

Table 3. Ccorrelation results.

	ES	EG	GDP	OIL	FDI	POP	R_D
ES	1						
EG	−0.1032	1					
GDP	−0.1746	0.6834	1				
OIL	0.3176	−0.1723	−0.2709	1			
FDI	−0.1556	0.8961	0.7515	−0.1977	1		
POP	−0.1367	0.5614	0.8927	−0.2014	0.6768	1	
R_D	−0.0551	0.7572	0.6954	−0.0879	0.7656	0.6996	1

3.3. CSTD Result

Before discussing the MMQR results, we conducted the CSTD test to detect any interrelationships among the chosen variables across provinces. This test evaluates whether CSTD exists among the entities under investigation, with the null hypothesis (H0) suggesting no such dependence and the alternative hypothesis (H1) indicating the presence of CSD across Chinese provinces. The results in Table 3 decisively reject the null hypothesis, indicating an absence of CSD in the residuals. This finding underscores the significance of the CSD issue, particularly considering the increasing interdependence among the Chinese provinces. Furthermore, the results in Table 4 suggest that the CSTD problem is present among the panel of 30 Chinese provinces.

Table 4. CD findings.

	Stat
BBLM	1382.884 ***
PSLM	32.13627 ***
PCD	25.85809 ***

Note: BBLM, PSLM, and PCD represent B-Pagan LM, Pesaran S-LM, and the Pesaran CD, respectively. *** indicate 1% significance levels.

Table 5 displays the results of the unit root test (URT) conducted on the selected data series. To address the potential issue of CSTD, we applied for a stationarity test. Specifically, we utilized the CIPS and Bai and Ng tests, which suggest that all panel data are integrated into order one, denoted as I(1), after taking the first difference.

Having established the stationarity of our chosen data series, we conducted a co-integration analysis as the subsequent step. We utilized the test in [48] to uncover enduring co-movements among variables over the long term. The detailed findings of the

co-integration test are presented in Table 6. Our analysis reveals a persistent long-term co-movement between ES and EG, GD, FDI, OIL, R and D, COVID-19, and oil prices.

Table 5. URT tests.

Tests	CIPS	Bai and Ng	
ES	−2.51 ***	−2.6 ***	First level
GDP	−2.17 **	−1.75	First level
EG	−2.18 **	−2.71 ***	First level
FDI	−2.1 **	−2.15 **	First level
R and D	−2.2 **	−2.67 ***	First level
OIL	−3.42 ***	−3.41 ***	First level
POP	4.51 ***	4.62 ***	First level

Note: ***, ** indicate 1%, 5%, significance levels, respectively.

Table 6. Westlnd cointegration.

S-Value	p-Value
−1.912	0.03

3.4. MMQR Results

The results of the co-integration test affirm that we can advance with our estimation across 6 quantile levels (5th, 20th, 40th, 60th, 80th, and 95th). The outcomes of the MMQR method are illustrated in Figure 2. Our result indicates that a 1% increase in the E-government effect is positive and statistically significant on sustainability development (ES), resulting in a rise of 0.05% to 0.40% in ES at the 5th to 40th percentiles, respectively. However, this impact diminishes in the median and upper quantiles. Integrating E-governmental practices, facilitated by satellite imaging and Internet of Things (IoT) devices, has significantly enhanced the monitoring and management of ES initiatives. This technological advancement has enabled prompt responses to climate and environmental changes and more effective enforcement of policy regulations. As a result, the Chinese provincial strategy for tackling environmental sustainability challenges has become more flexible while requiring fewer resources to implement effectively; incorporating digital technology into ES has fostered a more profound response. This has facilitated the implementation of more informed and strategic policies by Chinese provinces, considering regional ecological demands and sustainability objectives [53]. In these areas, human activities were the primary factor in the spread of COVID-19, making physical isolation through digital administration the most effective measure for controlling the outbreak despite existing waste management issues. These findings are consistent with previous studies in different nations [10,18,30,35]. Conversely, it can be observed that COVID-19 exhibits a more pronounced deleterious influence across quantiles. The effect is less substantial in the upper quantiles than in the median and lower quantiles. This indicates that the pandemic's negative impact is greater for regions with a median level of sustainability, in which less extreme weather events indirectly affect epidemic intensity than decreased biomedical waste [54]. In the upper quantile, lockdowns, characterized by restricted movement and workplace shutdowns, resulted in reduced transportation and lower use of natural resources like oil and coal rather than increased environmental quality. The results indicate that the impact of FDI ES diminishes. In less developed provinces, which typically fall into the lower quantiles of ES, the influx of FDI often leads to increased industrial activity and higher consumption of natural resources. This surge in economic activity, driven by foreign investments, tends to exacerbate environmental degradation due to insufficient regulatory frameworks and a lack of advanced environmental technologies. As a result, these regions experience significant declines in ES as they struggle to balance economic growth with environmental protection. For instance, in the western provinces of China, where economic development is a priority, FDI tends to focus on resource-intensive industries. These regions' lack of stringent environmental regulations means increased

industrial activity directly translates to higher pollution levels and greater environmental damage. This finding is consistent with the prior studies [27].

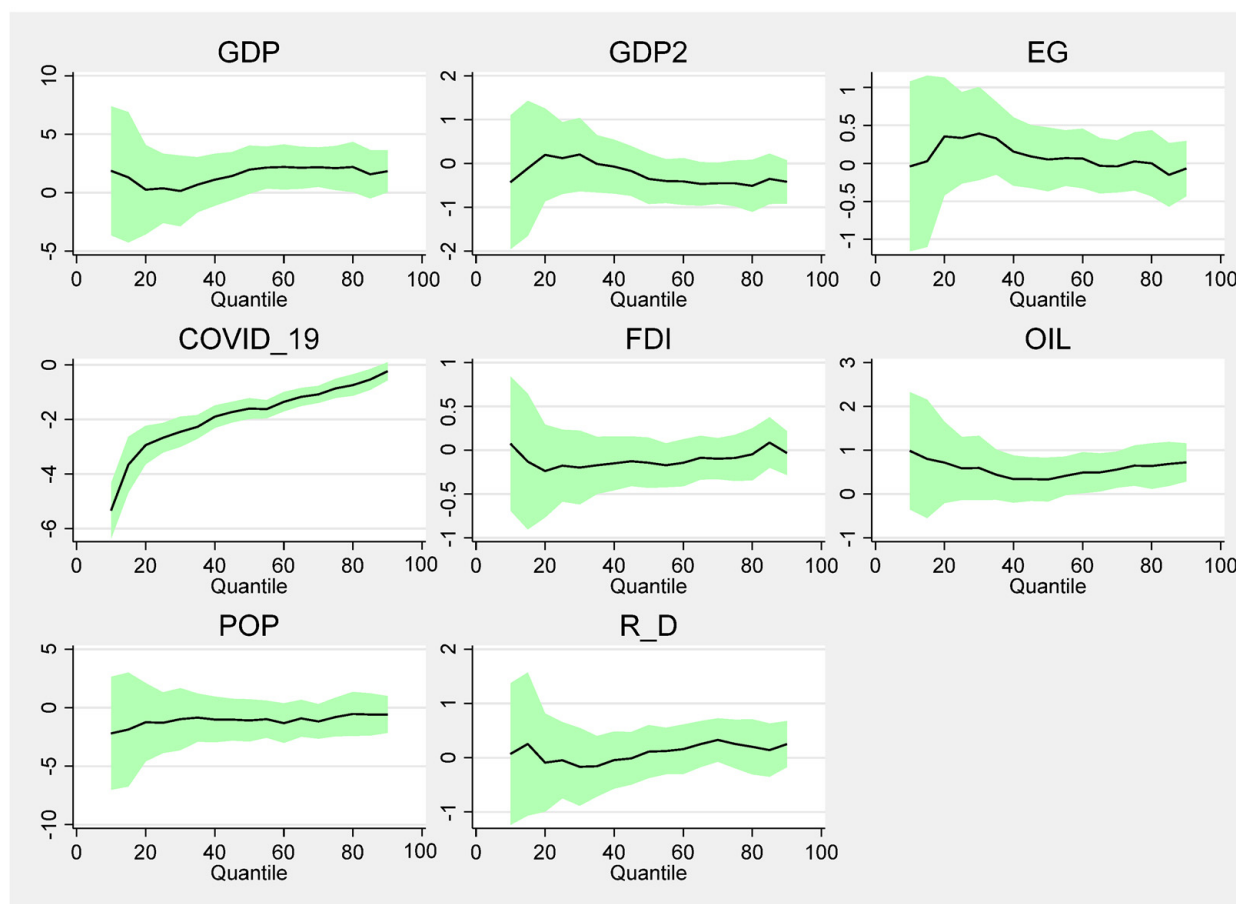


Figure 2. MMQR results.

The impact of GDP growth on ES demonstrates a correlation between a 1% increase in GDP and an augmentation in ES in the lower quantile. The upper quantiles exercise had a significant positive impact, with a rise of 0.4% compared to 0.05% in the 40th quantile. On the contrary, the GDP squared effect negatively impacts ES under all quantiles except the 30th. This study investigated the factors impacting ES and found that higher GDP has a positive effect, whereas GDP2 has a negative effect in the long term. These findings are consistent with those of [40], which report the non-LCC in China [55].

Furthermore, the results indicate that a 1% increase in R and D has a very modest effect on managing ES, ranging from 0.03% at the lower quantiles to 0.9% at the upper quantiles. This implies that although the significant advantages of increased R and D in ES might be challenging to discern reliably, there are still modest benefits [56,57]. It is also important to show statistical significance; ES maintains a positive trend (ranging between 0.5% in the medium and 1% across lower and upper quantiles), while the population variable significantly negatively affects ES across different quantiles. These results align with the previous studies [58–60].

3.5. QR Finding

To make the MMQR results presented in Figure 2 more robust, the QR outcome is illustrated in Figure 3. The results provide the empirical report for the substantial effect of GDP and the limited effect of EG, R and D, OIL, and FDI while noting the negative impact of COVID-19 and population POP. The conclusions derived from the quantile regression

(QR) proffer corroborating evidence regarding the influence of these explanatory variables, lending credence to the MMQR methods.

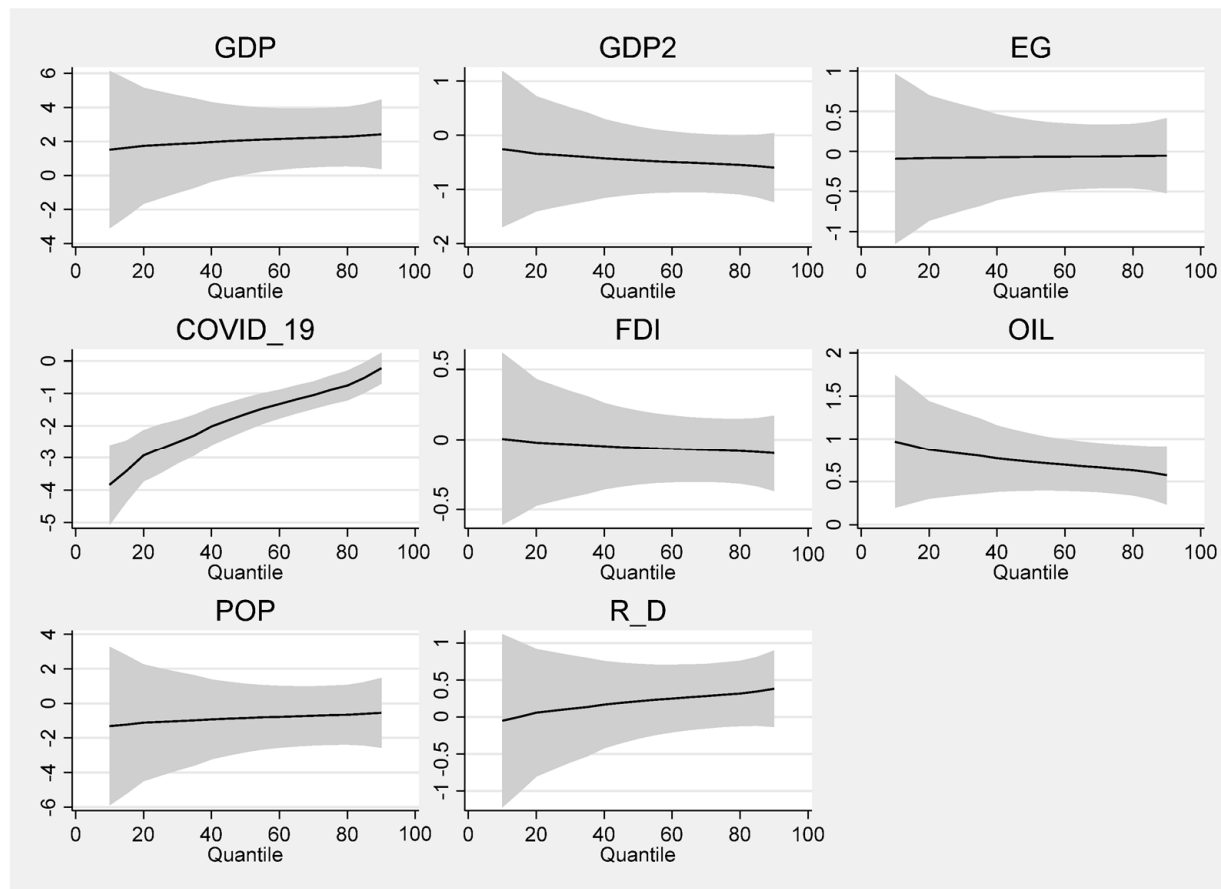


Figure 3. QR Results.

3.6. The DH Causality Results

After completing the MMQR and QR techniques, the research used the causality test proposed [49], as presented in Table 7. It was utilized to determine the direction of causality associated with environmental sustainability and explanatory variables, including E-government. The findings indicate a bi-directional causal association between environmental sustainability (ES) and E-government practices. Conversely, there is an absence of a causal link between GDP and ES. The causality results also indicate the bi-directionality link from ES concerning oil, FDI, and POP.

Table 7. Causality results.

Null Hypothesis:	W-Stat.	Zbar-Stat.	Prob.	Causality Type
GDP → ES	2.13484	1.03668	0.2999	No causality
ES → GDP	2.28155	1.27627	0.2019	
EG → ES	2.69494	1.95133	0.0510	bi-directional
ES → EG	3.71226	3.61261	0.0003	
COVID_19 → ES	3.73289	3.64629	0.0003	un-directional
ES → COVID_19	1.07969	−0.68637	0.4925	

Table 7. Cont.

Null Hypothesis:	W-Stat.	Zbar-Stat.	Prob.	Causality Type
FDI → ES	3.50200	3.26925	0.0011	bi-directional
ES → FDI	4.09012	4.22966	2×10^{-5}	
OIL → ES	6.04456	7.42123	1×10^{-13}	bi-directional
ES → OIL	3.56282	3.36857	0.0008	
POP → ES	3.95220	4.00443	6×10^{-5}	bi-directional
ES → POP	3.73758	3.65395	0.0003	
R_D → ES	3.19707	2.77131	0.0056	un-directional
ES → R_D	1.95380	0.74105	0.4587	

4. Conclusions

This research investigated how E-governance and COVID-19 affected sustainable development in 30 Chinese provinces from 2012 to 2021, considering the GDP, FDI, R and D, urbanization, and oil prices using MMQR. The findings demonstrate that a 1% increase in E-government significantly boosts environmental sustainability (ES) by 0.05% to 0.40% in the 5th to 40th percentiles, though this effect diminishes at higher quantiles.

COVID-19 negatively affects ES across all quantiles, while the impact of Foreign Direct Investment (FDI) on ES diminishes over time. GDP growth positively correlates with ES, with a more substantial effect at higher economic levels. Research and Development (R and D) has a modest positive impact on ES. Despite significant energy prices, ES continues to trend positively, supported by investments in renewable energy. However, population growth negatively impacts ES, underscoring the need for effective population management.

The findings of this research, which examined the impact of E-governance and COVID-19 on environmental sustainability in 30 Chinese provinces from 2012 to 2021 using MMQR, have several important policy implications. Firstly, there is a clear need to prioritize and promote E-governance initiatives. These initiatives have significantly boosted environmental sustainability, particularly in the lower to middle quantiles. Governments should invest in digital infrastructure and technology to enhance monitoring, data collection, and analysis, which are critical for informed decision making and effective policy implementation.

Secondly, the negative impact of COVID-19 on environmental sustainability highlights the importance of implementing policies and strategies to mitigate these effects. Governments should prioritize recovery plans that address the pandemic's immediate impacts and integrate environmental sustainability goals into long-term recovery strategies. This could include green stimulus packages, investment in sustainable infrastructure, and support for green industries.

Thirdly, the findings suggest the need for economic diversification strategies. While E-governance positively impacts environmental sustainability, its effects diminish at higher quantiles of development. Therefore, policymakers should focus on diversifying the economy beyond digital governance to ensure environmental sustainability across all levels of economic development. Fourthly, given the significant impact of energy prices on environmental sustainability, there is a need for policies that promote renewable energy investments and efficient resource management practices. This includes incentivizing renewable energy sources and promoting energy efficiency measures. Lastly, addressing the negative impact of population growth on environmental sustainability requires effective population management policies. This includes family planning initiatives, urban planning strategies that promote environmental sustainability, and policies that ensure equitable resource allocation. This study has several limitations that provide a foundation for future research. Firstly, our analysis is confined to Chinese provinces, restricting our understanding of how sustainability and global crises, such as the pandemic and armed conflicts, impact ES in other developing and emerging nations. Secondly, the study does not

capture underlying micro and macro economic variables such as green productivity, AI, and urban digitalization, which could offer deeper insights into environmental sustainability dynamics. Finally, the spatial distribution estimation techniques should be used in future studies. Subsequent research could include a comparative analysis of E-government policies across different Chinese cities, evaluating their effectiveness in enhancing renewable energy capacity and improving environmental quality. Additionally, examining the impact of green finance mechanisms, such as China's Green Credit Guidelines, could offer insights into financial instruments' crucial role in steering economies toward sustainable practices.

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