EMERGING MARKETS FINANCE AND TRADE
https://doi.org/10.1080/1540496X.2023.2258260

Nexus Among Digital Economy, Green Innovation, and Green Development: Evidence from China

Ying Lin[a], Quan-Jing Wang[b], and Mei-Qi Zheng[b]

[a]School of Economics and Finance, Xi'an Jiaotong University, Xi'an, Shaanxi, China; [b]School of Business, Zhengzhou University, Zhengzhou, Henan, China

ABSTRACT

Green development is an essential requirement for the high-quality development. In the context of the new round of technological revolution, the digital economy has injected new momentum into China's high-quality economic development. This article aims to clarify the relationships among digital economy, green innovation, and green development using Westerlund and Edgerton (2007) cointegration test as well as pooled mean group (PMG) estimation and utilizing yearly data from 274 cities in China from 2011 to 2019. Overall, the results confirm the existence of cointegration relationships between green development and green innovation, between green development and digital economy, as well as between digital economy and green innovation, and support that digital economy and green innovation can affect the green development in the long-term positively. Additionally, while digital economy positively affects the green development in the short-run, green innovation cannot affect the green development. Furthermore, while the long-run positive impact of digital economy and green innovation on green development is generally established among eastern, central, and western regions, the short-run impact of such two factors on green innovation varies among different regions, seeing as both two variables exert no significant impact on green development in western region. Empirical findings offer important policy implications for the policymakers to attach more importance on the emerging economy model such as digital economy or green innovation, which can bring about long-term green development.

KEYWORDS

Green development; digital economy; green innovation; cross-section dependence; cointegration

JEL

C01; C32; Q40

1. Introduction

For more than 40 years in China, the traditional economic development model, in which GDP growth is the core indicator of economic development, has led to problems such as environmental pollution, which has become an important constraint to sustainable development (Wang and Shao 2019; Wang et al. 2019). The contradiction between economic development and ecological environment increased (Chen et al., 2021; Fu et al., 2023; Hickel 2019; Wang et al., 2022; Wen et al., 2023; Yang et al., 2022; Yin et al., 2023a; Zheng et al., 2023a; Zheng et al., 2023b). China's sustainable development is constrained by social problems such as the widening gap between the rich and the poor and the inequality of income distribution and environmental pollution. Green development is a way of sustainable development that balances environmental friendliness and social inclusiveness, balancing environmental protection and social equity in the process of economic growth (World Bank 2012). In the context of ecological civilization and the critical period of transformation of social contradictions, economic green development is undoubtedly an effective economic growth model to achieve sustainable

CONTACT Quan-Jing Wang wqj9333@163.com School of Business, Zhengzhou University, 100 Kexue Road, Zhengzhou, Henan 450001, China

© 2023 Taylor & Francis Group, LLC

development under the new normal (Chai et al., 2022; Hao et al., 2023; Long et al., 2022; Peng et al., 2023; Ren et al., 2022; Xue et al., 2022; Yin et al., 2022a; Yin et al., 2023b; Zou et al., 2023). Green development provides an opportunity and direction for China to seek new ways of growth, making it possible to balance economic growth, social equity, and environmental protection. It can provide clear solutions to the challenges of environmental sustainability and socio-economic development (Adams 2005; Chen, 2023; El Hafdaoui, 2024; Motla et al., 2023; Pan et al., 2024; Raihan, 2023b; Shahid et al., 2024; Silva et al., 2023; Wilson et al. 1998; Yahaya and Augustine, 2023; Yi et al., 2023; Zheng and Wong, 2024). Adams (2019) argued that green growth not only promotes economic development but also ensures that the natural environment continues to provide resources for human beings. Wu, Wang, and Chen (2019) stated that the construction of green development index model and evaluation system is not only conducive to the formulation of rational green development strategy but also to the promotion of sustainable development.

At this stage, China needs to deal with the relationship between human and nature in order to achieve green development (Harlan 2021). The digital economy can play a key role in transforming and upgrading industries, optimizing resource allocation, improving production efficiency, and reducing pollution emissions (Kovacikova et al. 2021). Specifically, the development of the digital economy has encouraged corporations to use more advanced production technologies and production equipment, enabling a shift in production methods from the traditional model to an advanced and intelligent one. Litvinenko (2020) suggested that the use of advanced digital technology in the production process can contribute to significant increases in productivity. The digital economy not only improves productivity but also reduces waste of resources and pollution emissions, helping companies to achieve a greening transformation (Chen 2022).

Under the era of sustainable development, the process of green innovation has led to greater reliance on technological innovation for economic growth. The new development model replaces the traditional economic development driven by cheap labor and energy and achieves the goals of ecological improvement and sustainable development, ultimately leading to an overall green development of society (Awan and Yaqoob, 2023; Kalnbalkite et al., 2023; Li et al. 2017; Li et al., 2023; Miao et al. 2017; Mushafiq, 2023; Raihan, 2023a; Tchouto, 2023; Yang and Chen, 2023; Yin et al., 2022; Yolcan, 2023). Sun et al. (2020) believed that the inconsistency between technological change and green development level hinders China's green development. Therefore, it is necessary for China to coordinate the overall green development level from both technical and regional aspects. Furthermore, in recent years, the conclusions that digital and information technologies could promote quality economic development and green growth have been widely accepted by scholars (Bibi et al. 2022; Chakpitak et al. 2018; Jorgenson and Motohashi 2005). However, previous studies on green development have mainly focused on the measurement of green development level and improved methods (Luukkanen et al. 2019; Ma et al. 2018; Wang et al. 2019; Zhang and Liu 2021), and influencing factors (Niebel 2018; Yuan and Xiang 2018). In addition, few studies have examined whether there is a co-integration relationship between digital economy, green innovation, and green development, and few have empirically tested whether digital economy and green innovation have an impact on green development. Scientifically identifying the relationship between these three variables can help the government better promote green development based on the current development level of China's digital economy and green innovation. Hence, this article aims to reveal the relationship among digital economy, green innovation, and green development in China. Specifically, we firstly investigate that whether there exist cointegration among digital economy, green innovation, and green development. Once the cointegration is confirmed, we further query that what is the long-term and short-term relationship between the digital economy, green innovation, and green development, as well as the heterogeneity of in the eastern, central, and western regions of China. Finally, we also conduct the causality test to clarify the true relationship among such three factors.

The relationship among digital economy, green innovation, and green development in China can be interpreted as follows. On the one hand, the digital economy can boost economic openness and upgrade the industrial structure in order to improve green innovation levels (Dai et al. 2022). Savina (2018) stated that full digitalization and the introduction of information and communications technology is a natural and inevitable process. Awan et al. (2021) suggested that the digital economy is developing rapidly. Its in-depth integration with different industries in the economy and in society promote an economic model driven by innovation (Anser et al. 2020). On the other hand, with the rapid development and continuous innovation of information and communication technologies, the way people work, learn, and communicate is changing by the digital revolution (Kehal and Singh 2005). Su et al. (2021) pointed out that the digital economy promotes green innovation by building a clean and intelligent industrial chain through technological innovation. It will help shape a new pattern of dual-cycle development at home and abroad and achieve high-quality and sustainable economic development in China.

The potential contributions of our study mainly lie at following three aspects: First, this article empirically examines the relationship among the digital economy, green innovation, and green development. It also analyses the long-term impact of the digital economy and green innovation on green development at the level of comprehensive panel data, providing deeper insights into green development pathways, which is essential for building a theoretical system focusing on the digital revolution and green development from the perspective of green innovation. Second, we further construct studies in different regions to study whether there are differences in the relationship between digital economy, green innovation and green development. Third, this article can provide detailed advice on the digital economy and green innovation from the four oversight of policymakers, investors, regulators, and corporate sectors, as well as policy references for green development practices in China and other developing countries.

The remaining parts of our article are displayed as follows. The second one mainly briefly summarize the relevant studies, while the third one provides more details about methodology. The fourth part presents the empirical results and potential explanations, whereby the final one concludes and offers some useful suggestions.

2. Literature Review

2.1. The Impact of Digital Economy on Green Development

The existing literatures mainly focus on the influencing factors of green development. For instance, Gu et al. (2021) argued that environmental regulation has a multi-dimensional impact on green development, including the direct policy-economy effect, the mediating effect of the neighbor-friendly model, and the moderating effect of the good-neighborly approach through media attention. Zhu and Ye (2018) showed that the foreign direct investment (FDI) is conducive to promoting inclusive green total factor productivity in China. He and Du (2022) argued that improper allocation of land resources is not conducive to improving the efficiency of green development in China. Sun et al. (2022) argued that China's Western Region has limited local green development due to lower levels of economic output, green production and consumption, and larger income disparities. In addition, the more developed economies and higher population concentrations in the eastern and central regions posed challenges to ecological resource endowments and environmental management, thus inhibiting green development (Cheng et al. 2021). According to Miao (2021), the digital economy could bring more benefits than the traditional economy and generate stronger impetus for other development directions. Liu et al. (2022) argued that digitalization represented by the digital technologies is a central driver of green development in cities. Yuan et al. (2021) proposed that digital economy was entrusted with the mission of driving the global economy. Information technology is considered the core of the digital economy, helping to reduce energy consumption and boost economic growth (Usman et al. 2021). Digitalization brings more opportunities for sustainable development (Ghobakhloo et al. 2021). Ma and Zhu (2022) clarified the impact and mediating effect of digital economy on green development by employing Chinese data and suggesting that there exists nonlinear impact of digital economy on green development.

However, there are also some contrary views, Ren et al. (2021) believed that at different significance levels, the Internet has different impacts on the scale of energy consumption. At certain significance levels, the Internet has a negative effect on the structure or intensity of energy consumption. Nguyen et al. (2020) pointed out that information and communications technology (ICT) is a driver of environmental degradation. It increased carbon emissions and led to waste of technology and redundancy of labor.

2.2. The Impact of Digital Economy on Green Innovation

Green innovation is the output of technological innovation that integrates environmental burdens and draws on new ideas and technologies to reduce environmental pollution and the use of raw materials and energy (Albort-Morant et al. 2017). The term digital economy makes extensive use of information technology and includes two core areas: digitalization of industry and digital industrialization (Bukht and Heeks 2017). Some scholars investigated the role of digital economy in green innovation and argued that the digital economy has brought significant enabling effects for green innovation, driving changes in products, business models, and industrial patterns, and opening up new development paths and viable spaces for effective breakthroughs in innovation activities (Bressanelli et al. 2018; Luo et al. 2023).

Kohli and Melville (2019) proposed that the gradual improvement of digital infrastructure has a positive impact on the increased frequency of innovation, the diffusion of technological innovation, the nurturing of high-end production factors, and the optimization of changes in the production chain. The digital economy promoted the harmonization of economic activities with resources and the environment (Teece 2018). In the process of increasing the efficiency of resource allocation, high-quality development with green and innovation as the key stimulated the green innovation momentum of the digital economy (Zhang et al. 2021). Li and Wang (2022) pointed out that the knowledge spillover effect of the digital economy forced the optimization and reduction of manufacturing costs within the industrial system and enhanced the linkage and responsiveness to the external environment, thus achieving the goal of eco-environmental governance and resource conservation in the process of technological innovation. Thompson et al. (2013) similarly argued that with the help of digital technologies, information knowledge can be generated, shared, and exchanged in innovation networks in a cost-effective, rapid, and real-time manner. The increasingly innovative digital technologies in the digital economy are powerful in reducing inefficiencies and unnecessary loss of resources in the process of allocating resources (Ding et al. 2021). Digitalization has the effect of economies of scale and network economies, which not only helps resource-based companies to reduce the cost of information search and the consumption of resources in the industry chain but also helps to access innovation resources in the value network and achieve green innovation. Dai et al. (2022) believed that digital economy can improve regional green innovation capacity by effectively improving scientific research funding and human resource. Luo et al. (2023) examined the spatial impact of digital economy on green innovation by utilizing the city-level data of China and supported that the digital economy would promote the green innovation through economic openness, industrial upgrade, and the digital economy also exerts a spillover effect on green innovation. Ferraris et al. (2018) argued that the penetration of information technology into micro-enterprises could help alleviate agency problems and enhance the effectiveness of decision-making, potentially leading to a shift toward a greener development path.

2.3. The Impact of Green Innovation on Green Development

To achieve the common goal of sustainable development, innovation must be promoted, which will provide the basis for sustained growth and bring about new economic opportunities (Fleming et al. 2017; Halati and He 2018). Many scholars have studied green innovation from different perspectives (Kunapatarawong and Martínez-Ros 2016). The results and recommendations of previous studies have been positive (Song et al., 2019).

For instance, Aghion and Howitt (1992) argued that if a continuous flow of innovation is maintained through technological innovation so that the productivity of innovation is greater than the discount rate of time, it is possible to drive the economic equilibrium point outward in a new development phase, to obtain more economic output, and ultimately to achieve sustainable economic and social development. That is technological innovation is the core driver of green development. Wurlod and Noailly (2018) pointed out that green technology can enhance the digitalization, informatization, and automation capabilities of manufacturing enterprises by providing cleaner production technologies. The use of the Internet had increased the intelligence of equipment and supported new industries and new energy to streamline processes (Ren et al. 2021). Albort-Morant, Leal-Millán, and Cepeda-Carrión (2016) suggested that green innovation can promote the development of green technology, control, and prevent pollution. In other words, green technologies could reduce or eliminate environmental pollution and damage at the source of production and the end product. Ulucak and Khan (2020) proposed that green technologies could be used to develop efficient, clean renewable energy sources, facilitate the transformation of pollution-intensive businesses, help encourage green growth, and promote green development. Saunila (2017) argued that the green innovation not only helps companies to differentiate themselves competitively, but also has a green, low-carbon clean value. Compared with non-green technology, green technology innovation can reduce pollution, effectively manage environmental externalities, and finally realize the purpose of ecological improvement of economy and green development. Therefore, only by speeding up the breakthrough of green innovation can we provide technical guarantee for the realization of green development, so as to realize green growth (Albort-Morant, Leal-Millán, and Cepeda-Carrión 2016).

Through browsing the abovementioned literatures, we find that previous studies have provided a solid foundation for our research, but there are still some limitations and research gaps in the existing literatures. First, many studies only focus on the unidirectional causal relationship from digital economy and green innovation to green development from the static perspective, but rarely examine the cointegration among these three variables. Second, there is also no empirical evidence in the literatures to test the long-term impact of the digital economy and green innovation on green development. To offer more clearer path to achieve sustainable development, according to the yearly data of 274 cities in China from 2011 to 2019, we try to answer such issues to fill the potential gap among existing literatures.

3. Methodology

3.1. Variables and Data

3.1.1. Definitions and Source

3.1.1.1. Green economy (GEI). To construct production possibility set (PPS) is the first prerequisite for green economy efficiency analysis. When measuring the efficiency of green economy, many studies usually regard the frontier of each period as independent, which leads to the intertemporal comparability of the measured efficiency of green economy. Therefore, this article draws on Pastor and Lovell's (2005) global reference method to solve the comparability problem of green economy efficiency in different periods.

$$PPS = \left\{ \begin{array}{l} \left(\bar{x}, \bar{y}, \bar{b}\right) \mid \sum_{t=1}^{T} \sum_{j=1, j\neq o}^{n} x_j^t \lambda_j^t \leq \bar{x}^t; \sum_{t=1}^{T} \sum_{j=1, j\neq o}^{n} y_j^t \lambda_j^t \geq \bar{y}^t \\ \sum_{t=1}^{T} \sum_{j=1, j\neq o}^{n} z_j^t \lambda_j^t \leq \bar{z}^t; \sum_{t=1}^{T} \sum_{j=1, j\neq o}^{n} \lambda_j^t = 1; \lambda \geq 0 \end{array} \right\} \tag{1}$$

where, $(x_{1o}, x_{2o}, \ldots, x_{mo})$ is the optimal solution of the model. x is the input factor, y is the expected output, z is the undesired output. and λ is the weight variable, If λ=1, the constraint condition that the weight variable and if 1 is considered, it represents the technical assumption of variable return to scale (VRS). Then, it represents the technical assumption of constant return to scale (CRS). On this basis, the global super-efficiency EBM model considering undesired output can be written as follows:

$$
\begin{aligned}
&\rho^G\left(\boldsymbol{x}^t, \boldsymbol{y}^t, \boldsymbol{b}^t\right) = \min \frac{\theta + \varepsilon_x \sum_{i=1}^{m} \frac{w_i^- s_i^-}{x_{io}}}{\eta - \varepsilon_y \sum_{i=1}^{s} \frac{w_r^+ s_r^+}{y_{ro}} - \varepsilon_z \sum_{q=1}^{p} \frac{w_q^{z-} s_q^{z-}}{z_{qo}}} \\
&\text{s.t.} \sum_{t=1}^{T} \sum_{j=1, j\neq o}^{n} x_{ij}^t \lambda_j^t - s_i^- \le \theta x_{io}, i = 1, \cdots, m \\
&\sum_{t=1}^{T} \sum_{j=1, j\neq o}^{n} y_{rj}^t \lambda_j^t + s_r^+ \ge \eta y_{ro}, r = 1, \cdots, s \\
&\sum_{t=1}^{T} \sum_{j=1, j\neq o}^{n} z_{qj}^t \lambda_j^t - s_q^{z-} \le \eta z_{qo}, q = 1, \cdots, p \\
&\sum_{t=1}^{T} \sum_{j=1, j\neq o}^{n} \lambda_j^t = 1 \\
&\lambda \ge 0, s_i^- \ge 0, s_r^+ \ge 0, s_q^{z-} \ge 0
\end{aligned}
\tag{2}
$$

Among them, s_i^- represents the non-zero relaxation of input factors, namely, the input redundancy variable, s_r^+ represents the non-zero relaxation of output factors, namely, the variable of insufficient expected output, s_q^{z-} represents the non-zero relaxation of non-expected output, namely, the non-expected
output redundancy variable. w_i^-, w_r^+, w_q^{z-}, respectively, represent the weights of input factors, desired output and undesired output. ε_x, ε_y, ε_z are the key parameters in EBM model, which represent the combination degree of radial and non-radial relaxation variables, and their values range between [0, 1]. If all three values are 0, the EBM model will degenerate into a general radial model; if all three values are 1, then EBM model will degenerate into an SBM model. Based on the global super-efficiency EBM model considering undesired output, we measure the green economy efficiency of 274 prefecture-level cities in China from 2011 to 2019, denoted by *GEI*.

3.1.1.2. Green innovation (GI). In accordance with previous literatures, we chose to utilize the total number of applications of green inventions and green utility models that focusing on environmental management to capture the level of green innovation, which considers the economic and environmental dimensions simultaneously (Zhao et al. 2021; Zheng et al. 2021), which is derived from the patent search and data analysis website of the State Intellectual Property Office of China (Zhao et al. 2022).

3.1.1.3. Digital economy (DE). PCA is used to bring out significant information from a complex dataset by converting the data into a compact set of new variables while it controls the issue of multicollinearity. This method is significantly useful for examining a compound index that envelopes several dimensions. According to Hosseini and Kaneko (2011), the specified procedures followed to construct an index using PCA are: data matrix building, variables standardization, correlation matrix calculation, the eigenvectors determination, principal components selection, and results from interpretation. Thus, we follow the work of Ofori and Asongu (2021) and Alderete (2017) to construct an index for digital economy. We select the digital finance, revenue from telecommunications services, number of people employed in information transmission computer services and software, number of Internet broadband access users and number of mobile phone users to construct such indicator, denoted by *DE*.

Table 1. Summary of descriptive statistics.

	Variable	N	Mean	SD	Min	Median	Max
Full	*GEI*	2466	0.234	0.076	0.099	0.221	0.693
	GI	2466	6.275	1.676	0.000	6.089	11.086
	DE	2466	4.669	0.623	2.609	4.619	6.880
Eastern	*GEI*	882	0.249	0.087	0.134	0.231	0.693
	GI	882	7.060	1.627	0.000	6.948	11.086
	DE	882	4.977	0.602	3.444	4.937	6.880
Central	*GEI*	873	0.229	0.062	0.119	0.224	0.693
	GI	873	6.041	1.484	2.708	5.811	10.478
	DE	873	4.552	0.542	3.054	4.549	6.191
Western	*GEI*	711	0.220	0.075	0.099	0.213	0.693
	GI	711	5.590	1.570	0.000	5.472	10.787
	DE	711	4.432	0.589	2.609	4.419	6.694

We take the log of such three variables to conduct appropriate empirical test, the balanced panel covers 274 prefecture-level cities in China from 2011 to 2019, with the data sources being Digital Finance Research Centre, Peking University and the China City Statistical Yearbook.

3.1.2. Data Description

Table 1 briefly gives the basic description of such employing variables. For all sampled cities, the *GEI* owns a mean value of 0.234 and possesses a standard deviation of 0.076. Referring for the variable of green innovation, the mean value and S.D of *GI* is 6.275 and 1.676 for all sampled cities, respectively. Referring for the digital economy, we can find that that the mean value and S.D of *DE* is 4.669 and 0.623 for all sampled cities, respectively.

Considering the differences in different regions, for GEI, the mean value and S.D of *GEI* is 0.249 and 0.087, respectively in the Eastern sub-sample, whereby the mean and S.D of this variable and is 0.229 and 0.062 in the Central sub-sample, as well as 0.220 and 0.075 in the Western sub-sample. Considering *GI* among the different regions, we can find that the mean value and S.D of *GI* is 7.060 and 1.627, respectively, in Eastern sub-sample, whereby the mean and S.D of this variable and is 6.041 and 1.484 in the Central sub-sample, as well as 5.590 and 1.570 in the Western sub-sample. Considering the digital divide among the different regions, we can find that the mean value and S.D of *DE* is 4.977 and 0.602, respectively, in Eastern sub-sample, whereby the mean and S.D of this variable and is 4.552 and 0.542 in the Central sub-sample, as well as 4.432 and 0.589 in the Western sub-sample. This comparison indicates that the levels of green development, green innovation, and digital economy are on average higher in eastern regions than that in the central and western regions.

3.2. Methodology

3.2.1. Cross-Sectional Dependence

Since the question of cross-section dependence (CSD) is generally found in empirical investigation that utilizing panel data (Baltagi and Pesaran 2007; Wang et al. 2022a) and the existence of CSD would bring about biased results of traditional panel estimations that suppose that all cross-units are independent with each other. It is thus necessary to test that whether the CSD is existed. Followed by previous literatures, we also chose to employ the method provided by Pesaran (2004) and (Pesaran 2015) to do this examination, the Pesaran's (2004) test is given as follows.

$$CD = \sqrt{\frac{2T}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\rho_{ij} \tag{3}$$

where ρ_{ij} is the corresponding correlations of errors for the individual i and individual j.

In addition to the strong CSD, Pesaran (2015) also proposed a weak CSD test in 2015, which can incorporate the heterogenous slope to a small sample. In Pesaran's (2015) test, the ρ_{ij} in equation (3) is calculated as follows:

$$\hat{\rho}_{ij} = \hat{\rho}_{ji} = \frac{\sum_{t=1}^{T} \hat{u}_{it}\hat{u}_{jt}}{\left(\sum_{t=1}^{T} \hat{u}_{it}^2\right)^{1/2}\left(\sum_{t=1}^{T} \hat{u}_{jt}^2\right)^{1/2}} \tag{4}$$

In this equation, u represents the estimating residual obtained by the traditional panel estimation.

3.2.2. Panel Unit Root Test

Due to that we prefer to include the CSD question into consideration, thus the traditional panel unit root tests such as ADF and LLC unit root are invalid, we chose to utilize the second-generation unit root test. According to previous study such as Wang et al. (2022a) and Zhang et al. (2022), we chose to utilize the Pesaran's (2007) CIPS method to test that whether these variables are stationary or not, the model is given as follows:

$$\vee y_{it} = \delta_i + \vartheta_i y_{it-1} + \boldsymbol{\phi}_i \bar{y}_{it-1} + \sum_{j=1}^{\rho} \lambda_{ij} \vee y_{it-1} + \sum_{j=0}^{\rho} v_{ij} \vee \bar{y}_{t-j} + d_{it} + \varepsilon_{it} \tag{5}$$

In this equation, $\bar{y}_t = \frac{1}{N}\sum_{i=1}^{N} y_{it}$, $\vee y_{it}$ is the first difference of y_{it}, y_{it-1} is the first lag term of y_{it} and ϑ is the estimating coefficient of it; $\boldsymbol{\phi}_i$ stands for the individual effect, λ_{ij} denotes the linear trend of individual, while the v_{ij} represents the time effect; in this equation, ϑ is utilized to analyze that whether there is unit root in the variable.

3.2.3. Panel Cointegration

To gain a credible conclusion on the cointegration among such three essential variables, we chose to utilize the Westerlund and Edgerton's (2007) cointegration test to conduct empirical examination, which can incorporate the potential CSD in the panel data and avoid the bias caused by the heterogeneity (Yang et al. 2021). The structure of WE's cointegration is given as follows:

$$y_{it} = \vartheta_{0i} + \vartheta_{1it} + n_i D_{it} + \boldsymbol{\phi}_i \bar{y}_{it-1} + x_{it}{}' \beta_i + (D_{it} x_{it})' \varsigma_i + Z_{it} \tag{6}$$

where $x_{it} = x_{it,t-1} + v_{it}$ is I (1) progress; in this test, they provided four statistics such as Gt, Ga, Pt, and Pa. the first two statistics can provide the evidence on that whether the whole panel is cointegrated or not, while the latter two provide some evidence on that whether at least one unit is cointegrated.

3.2.4. Panel Long-Run Estimations

Although the cointegration test can offer some insight on the long-run relationship among digital economy, green innovation, and green development, we are more willing to understand that what impact do digital economy and green innovation exert on green development in the long-term, which is essential for the governments to gain sustainable development. To answer such issue, we utilize the pooled means group (PMG) estimation to conduct empirical investigation (Balcilar et al., 2019), which owns advantages such as allowing for CSD, as well as non-stationarity (Wang et al. 2022b). The estimating method is structured as follows:

$$\Delta GEI_{it} = \xi_0 + \xi_1 \Delta GI_{it} + \xi_1 \Delta DE_{it} + d_1(w_t) + \mu_{it} \tag{7}$$

w_t denotes for the general-purpose procedure which applies to every individual.

4. Empirical Results

4.1. CSD Test's Result

We first test that whether there exist CSD in the panel data for such three variables according to the CSD method provided by Pesaran (2004) and Pesaran (2015), which can effectively identify the strong and weak CSD, respectively, whose results are displayed in Table 2. It can be obtained that all the statistics for strong and weak CSD test are significant at 1%, offering strong evidence to reject the null that the variables are cross-section independence and supporting that there exists CSD for the panel data for these three variables. In addition, the remaining results support that there also exist CSD in the three sub-samples. It is thus necessary to utilize the estimations to conduct further empirical investigations by utilizing the methods that account for CSD (Abban et al. 2020).

4.2. Panel Unit Root Test's Result

To take the existence of CSD into account, we then employ the second-generation panel unit root test such as panel CIPS proposed by Pesaran (2007) to test the stationarity of such three variables, whose results can be found in Table 3. Taken the results for the full sample as an example, it is obvious that the corresponding statistics for the level of such three variables are all not significant at 10%, suggesting that there exists unit root of these variables. Additionally, the statistics for the first difference of such three variables are all significant at 1%, indicating

Table 2. Cross-section dependence tests.

		Pesaran (2004)				Pesaran (2015)	
	Variable	CSD-test	*p*-value	Corr	abs(corr)	CSD	P
Full	*GEI*	168.94***	0	0.291	0.534	168.939***	0
	GI	429.67***	0	0.741	0.768	429.673***	0
	DE	521.02***	0	0.898	0.899	521.019***	0
Eastern	*GEI*	55.09***	0	0.266	0.604	55.095***	0
	GI	161.97***	0	0.783	0.784	161.968***	0
	DE	181.89***	0	0.879	0.879	181.889***	0
Central	*GEI*	90.10**	0	0.440	0.600	90.099***	0
	GI	141.51***	0	0.691	0.764	141.510***	0
	DE	189.56***	0	0.926	0.926	189.559***	0
Western	*GEI*	32.52**	0	0.195	0.472	32.524***	0
	GI	127.47***	0	0.765	0.767	127.469***	0
	DE	148.80***	0	0.894	0.895	148.800***	0

Note: ***, **, and * represent that the corresponding statistic is significant at 1%, 5%, and 10%, respectively.

Table 3. Pesaran (2007) panel unit root test accounting for CSD.

Group	*GEI*	Δ*GEI*	*GI*	ΔGI	*DE*	Δ*DE*
Full						
CIPS	41.122	−6.577***	41.001	−13.263***	41.122	−9.097***
Eastern						
CIPS	25.164	−3.536***	0.205	−7.667***	25.164	−5.542***
Central						
CIPS	25.035	−2.189***	25.035	−6.543***	25.035	−5.135***
Western						
CIPS	22.593	−2.464***	22.246	−6.492***	22.593	−6.400***

Note: ***, **, and * represent that the corresponding statistic is significant at 1%, 5%, and 10%, respectively. The results in this table confirm that such three variables all follow I (1) process.

that there is no unit root for the difference of such three variables. In combination with the results for the level and difference of such three variables, we can conclude that all three variables such as *GEI*, *GI*, and *DE* follow I (1) process. Besides, the results for the three sub-samples provide similar viewpoint as well.

4.3. Panel Cointegration Test's Result

Given by that there exist CSD of the panel data for such three variables as well as all variables follow I (1) process, we further utilized the bootstrap panel cointegration test provided by Westerlund and Edgerton (2007), which incorporates potential within and between CSD to clarify the long-term relationships among variables, with the results providing in Table 4. For the model of *GEI V.S.GI* for the full sample, we can obtain that the statistics are significant at 1% except for the G_α statistic, suggesting that the null of no cointegration should be rejected. Similar conclusion can be derived for the model of *GEI V.S.DE*, as well as *GI V.S.DE*, suggesting that the long-term cointegrations among digital economy, green innovation, and green development are well established. Most results for the three sub-samples offer similar idea; however, there is no cointegration between green development and digital economy in western or central regions, neither nor between green development and green innovation in eastern or central regions.

4.4. PMG Estimation's Result

Given by the cointegration among digital economy, green innovation, and green development, we move a further step to query the role of digital economy and green innovation in green development due to that the sustainable development has been a widely accepted global issue. As provided in the methodology, we chose to utilize the PMG estimation to examine the long-run and short-run impact of *DE* and *GI* on *GEI*. The results shown are in Table 5. Taken the result for the full sample as an

Table 4. Panel cointegration test Westerlund and Edgerton (2007).

		G_τ	G_α	P_τ	P_α
Full	*GEI V.S.GI*	−3.877***	−5.754	−34.416***	−5.646***
		(−38.801)	(4.422)	(−9.878)	(−4.655)
	GEI V.S.DE	−3.691***	−4.084	−50.250***	−5.110***
		(−35.330)	(9.523)	(−25.509)	(−2.720)
	GI V.S.DE	−3.261***	−5.349	−36.489***	−5.817***
		(−27.324)	(5.659)	(−11.924)	(−5.271)
Eastern	*GEI V.S.GI*	−5.925***	−6.633	−30.998**	−6.901
		(−46.011)	(1.039)	(−16.189)	(−5.491)
	GEI V.S.DE	−4.655***	−4.501	−42.663***	−7.150***
		(−31.869)	(4.933)	(−27.705)	(−6.028)
	GI V.S.DE	−3.311***	−5.868	−21.623***	−5.352**
		(−16.906)	(2.436)	(−6.935)	(−2.150)
Central	*GEI V.S.GI*	−2.805***	−5.276	−26.181***	−3.731
		(−11.210)	(3.500)	(1.017)	(1.342)
	GEI V.S.DE	−2.841***	−3.191	−17.428***	−2.869
		(−11.607)	(7.288)	(−2.867)	(3.193)
	GI V.S.DE	−3.332***	−5.851	−20.825***	−5.933***
		(−17.051)	(2.454)	(−6.221)	(−3.385)
Western	*GEI V.S.GI*	−2.653***	−5.250	−14.729*	−5.252**
		(−8.594)	(3.201)	(−1.602)	(−1.736)
	GEI V.S.DE	−3.537***	−4.661	−16.893***	−3.362
		(−17.439)	(4.166)	(−3.738)	(1.925)
	GI V.S.DE	−3.110***	−4.088	−20.416***	−6.073***
		(−13.164)	(5.107)	(−7.216)	(−3.325)

Note: ***, **, and * represent that the corresponding statistic is significant at 1%, 5%, and 10%, respectively. Z statistics are in parentheses.

Table 5. PMG estimators.

	(1) Full	(2) Eastern	(3) Central	(4) Western
GI	0.043***	0.042***	−0.013***	−0.046***
	(26.14)	(24.16)	(−15.86)	(−11.77)
DE	0.173***	0.174***	0.102***	0.126***
	(51.67)	(49.28)	(22.07)	(12.65)
CONS	−0.155***	−0.283***	−0.091***	−0.024***
	(−8.18)	(−8.24)	(−2.58)	(−2.70)
ECM	−0.180***	−0.293***	−0.487***	−0.295***
	(−8.81)	(−8.87)	(−2.60)	(−5.42)
ΔGI	−0.020***	−0.016***	−0.031***	0.004
	(−5.86)	(−4.26)	(−3.41)	(0.94)
ΔDE	0.051***	0.032**	0.055**	−0.016
	(4.61)	(2.55)	(2.19)	(−0.84)

Note: ***, **, and * represent that the corresponding statistic is significant at 1%, 5%, and 10%, respectively. Z statistics are in parentheses.

example, we can notice that the coefficient of *GI* is 0.043, which is significant at 1% and larger than 0, indicating that green innovation is usually associated with higher green development. Our conclusion is similar with Wang et al. (2022a) who provided that the green innovation would bring about green development and Zhao et al. (2023) who suggested that green innovation is critical in green development, as well as Zhao et al. (2022) who presented that the green innovation is beneficial for the green growth. Additionally, the coefficient of *DE* is 0.173, significant at 1% with a positive symbol, supporting that digital economy would lead to the improvement of green development, which is consistent with the Chen (2022) who argued that the digital economy would do some good in reducing the carbon emissions, as well as Ding et al. (2021) who supported that the digital economy would promote the high-quality economic development.

Referring to the three sub-regions, the results for such three sub-samples in column (2)-(4) support the long-run impact of digital economy on green development, which is consistent with the result for full sample. However, referring to the role of green innovation, it only promotes green development in eastern regions in the long-run, while inhibits the green development among central and western regions in long-run.

In addition to the long-run estimating results, PMG estimations also provide the short-run impact of digital economy and green innovation on green development. Specifically, the coefficient of *ΔGI* for the full sample is −0.020, significantly negative at 1%, and that of *ΔDE* is 0.051, significantly positive at 1%, suggesting that green innovation negatively affects the green development in the short term, while the digital economy can improve the green development in the short term. The results for the east regions and central regions also support similar idea, except for that of Western sub-sample which suggests that both variables cannot affect the green development in the short-run.

4.5. Robustness Test

To test that whether the relationship among digital economy, green innovation, and green development depends on the level of digital economy and green economy, we conduct further empirical test by setting four sub-samples according to the median value of digital economy or green economy in line with Wang et al. (2022a). Specifically, if one city owns a mean level of digital economy which is higher than the median level of digital economy among all cities, then it belongs to the high-DE sub-sample; otherwise, it belongs to low-DE one. Two another sub-samples such as high- or low-GI sub-samples can be built in similar method.

We further re-do the above-mentioned estimations by employing such four samples, the Pesaran's (2004, 2015) results support the existence of CSD for such three variables among such four sub-samples, and hence panel unit root test of CIPS provides that all variables follow I (1) process among such four samples.[1] We hence carry out the cointegration test for these four sub-samples, whose

Table 6. WE (2007) panel cointegration test for sub-samples.

		G_τ	G_α	P_τ	P_α
High-GI	*GEI V.S.GI*	−4.836***	−6.111	−39.655***	−7.084***
		(−40.066)	(2.356)	(−22.108)	(−6.959)
	GEI V.S.DE	−4.707***	−4.647***	−58.159***	−7.087***
		(−38.365)	(5.517)	(−40.374)	(−6.966)
	GI V.S.DE	−2.816***	−5.045	−20.578***	−5.016***
		(−13.470)	(4.659)	(−3.276)	(−1.683)
Low-GI	*GEI V.S.GI*	−2.918***	−5.396	−17.022	−4.531
		(−14.807)	(3.898)	(0.235)	(−0.446)
	GEI V.S.DE	−2.674***	−3.520	−17.592	−2.901
		(−11.599)	(7.951)	(−0.328)	(3.711)
	GI V.S.DE	−3.705***	−5.653	−30.811***	−6.459***
		(−25.172)	(3.344)	(−13.377)	(−5.366)
High-DE	*GEI V.S.GI*	−4.822***	−6.374	−36.046***	−6.887***
		(−39.880)	(1.787)	(−18.545)	(−6.456)
	GEI V.S.DE	−4.685***	−5.246	−46.678***	−7.110***
		(−38.074)	(4.224)	(−29.040)	(−7.025)
	GI V.S.DE	−2.891***	−4.636	−21.133***	−4.730
		(−14.462)	(5.541)	(−3.824)	(−0.95)
Low- DE	*GEI V.S.GI*	−2.932***	−5.133	−17.89	−4.655
		(−14.994)	(4.467)	(−0.625)	(−0.763)
	GEI V.S.DE	−2.696***	−2.922***	−21.509***	−2.875***
		(−11.890)	(9.243)	(−4.195)	(3.778)
	GI V.S.DE	−3.630***	−6.061	−28.643***	−6.487***
		(−24.181)	(2.462)	(−11.237)	(−5.436)

Note: ***, **, and * represent that the corresponding statistic is significant at 1%, 5%, and 10%, respectively. Z statistics are in parentheses.

Table 7. PMG estimators for four sub-samples.

	GEI			
	High-GI	Low-GI	High-DF	Low-DF
GI	0.043***	0.091***	0.044***	0.009***
	(24.35)	(5.68)	(24.68)	(3.87)
DE	0.174***	0.465***	0.173***	0.184***
	(48.75)	(8.55)	(49.24)	(19.94)
CONS	−0.190***	−0.168***	−0.221***	−0.095***
	(−5.72)	(−5.80)	(−7.17)	(−4.41)
ECM	−0.194***	−0.079***	−0.227***	−0.169***
	(−5.99)	(−5.37)	(−7.64)	(−4.86)
ΔGI	−0.032***	−0.002***	−0.029***	−0.007*
	(−6.25)	(−0.54)	(−5.78)	(−1.68)
ΔDE	0.064***	0.045***	0.059***	0.040***
	(3.52)	(3.64)	(3.34)	(3.18)

Note: ***, **, and * represent that the corresponding statistic is significant at 1%, 5%, and 10%, respectively. Z statistics are in parentheses.

results can be seen in Table 6. We can find that while most models in such four samples support that there exist cointegration between green innovation and green development, between digital economy and green development, as well as between digital economy and green innovation, but there exists no cointegration between green development and green innovation in low-DE and low-GI sub-sample, neither nor between green development and digital economy in low-GI sub-sample, as well as between digital economy and green innovation in high-DE sub-sample.

Finally, we also try to clarify the heterogeneity in the long-run and short-run impact of digital economy and green innovation on green development from the perspective of different level of digital economy and green innovation, whose results can be seen in Table 7. For the long-run impact, all results are in line with our earlier finding that both green innovation and digital finance can positively affect the green development. Referring for the short-run impact, our earlier conclusion that green

Table 8. D-H causality.

MODEL	W-bar	Z-bar	*P*	Lag	Conclusion
Full					
GI GEI	7.432	75.290***	0.000	1	Two-way
GEI GI	2.684	19.718***	0.000	1	
DE GEI	4.186	37.301***	0.000	1	Two-way
GEI DE	2.687	19.756***	0.000	1	
DE GI	3.144	25.102***	0.000	1	Two-way
GI DE	3.824	33.059***	0.001	1	
Eastern					
GI GEI	15.455	101.191***	0.000	1	Two-way
GEI GI	2.155	8.087***	0.000	1	
DE GEI	7.644	46.508***	0.000	1	Two-way
GEI DE	3.542	17.799***	0.000	1	
DE GI	1.759	5.316***	0.000	1	Two-way
GI DE	4.493	24.454***	0.000	1	
Central					
GI GEI	3.615	18.213***	0.000	1	Two-way
GEI GI	3.287	15.931***	0.000	1	
DE GEI	1.566	3.945***	0.000	1	Two-way
GEI DE	1.530	3.695***	0.000	1	
DE GI	2.246	8.680***	0.000	1	Two-way
GI DE	3.817	19.619***	0.000	1	
Western					
GI GEI	2.166	7.329***	0.000	1	Two-way
GEI GI	2.601	10.061***	0.000	1	
DE GEI	3.115	13.296***	0.000	1	Two-way
GEI DE	3.048	12.874***	0.000	1	
DE GI	5.965	31.210***	0.000	1	Two-way
GI DE	3.003	12.592***	0.000	1	

Note: ***, **, and * represent that the corresponding statistic is significant at 1%, 5%, and 10%, respectively.

innovation negatively affects the green development while digital economy exerts a positive impact on green development in the short-run is still confirmed in such four sub-samples.

4.6. Causality Test's Results

We further uncover the direction of long-term causality via Dumitrescu and Hurlin (2012) (D-H) causality test, which can be seen in Table 8. D-H causality results support that there exists bi-directional process between *GEI* and *GI*, between *GI* and *DF* as well as between *GEI* and *DF*. When analyzing the result for whole sample, we can find that there exists bi-directional causal link between green development and green innovation, between green development and digital economy, as well as between green innovation and digital economy, similar conclusions can be found in the three sub-samples.

5. Conclusions

Taking China as the sample, this study mainly empirically queries the long-run relationships among digital economy, green innovation, and green development and examines that what impact do digital economy and green innovation exert on green development in the short term or long term. We carry out empirical investigation by employing several panel estimations that allow for cross-section dependence such as CIPS unit root test provided by Pesaran (2007), and Westerlund and Edgerton's (2007) cointegration, as well as the Pooled Mean Group estimation based on the panel data covers for 274 cities during the period ranges from 2011 to 2019.

Once the CSD test of Pesaran (2004, 2015) supports the existence of CSD for digital economy, green innovation, and green development and the panel CIPS unit root test which allows for CSD confirms that all variables follow I (1) progress, we conduct the panel cointegration in the method similar to Westerlund and Edgerton (2007) and conclude that there exist cointegrations among digital economy, green innovation, and green development. Additionally, the results of PMG estimation suggest that both digital economy and green innovation can positively affect the green development in the long-run. Furthermore, green innovation negatively affects the green development while digital economy positively affects the green development in the short-run in the whole sample, eastern region, and central region, however, green innovation and digital economy cannot affect short-run green development in western region. While we consider the heterogeneity in different level of digital economy and green innovation, we find that both green innovation and digital economy exert a long-run positively impact on green development in four sub-samples such as high-DE, low-DE, high-GI, and low- GI sub-samples, and the green innovation negatively affects the green development while digital economy positively affects the green development in the short-run in these samples.

As an application research is focusing on the sustainable development, this study can offer some insight to policymakers, investors, regulators, and corporate sector on how two pursue green development from the view of green innovation and digital transformation.

(1) Referring for policymakers in China and other developing countries who prefer to achieve the sustainable development goals, governments should explore new pathways for the coordinated development of the green economy and digital economies and develop long-term financial investments on digital transformation or green projects over a longer horizon. In order to make the digital economy become a sustainable driver for green innovation in cities, a strong digital infrastructure should be built to improve the regions' digital presence and increase the integration of digitalization and green innovation. Developing countries should encourage free trade to enhance the dynamism of international markets and the openness of the country's economy. It is worth noting that due to more green innovation would lead to the long-run green development, the governments in developing countries should evaluate the role of green innovation in a long-term perspective and be patient to it despite that it cannot promote green development immediately. Additionally, local governments should use networking, informative technology, intelligence, and other means to catch the opportunities led by the revolution of information technology and engage into the development of digital economy, which is critical to achieve the green development and bring about more green innovation.
(2) For investors: Investors should deepen the concept of green and sustainable investment and fully integrate with major data platforms to translate the advantages of massive amounts of data into more accurate behavioral decisions and more efficient investments, and investors should evaluate the project on digital economy or green innovation from a long-term perspective. Therefore, there is a case for institutional investors to invest more in research and development of green technologies that promote green development. In addition, investors should seize the opportunity to place more emphasis on the process of digital transformation by investing into the infrastructure of information and communication technology or investing on the firms which carried out digital transformation and green innovation.
(3) For regulators: China and other developing countries should move Intellectual Property into the digital age by updating its concepts and ensuring that traditional areas of Intellectual Property are modernized to meet the needs and address the problems of our global knowledge economy. Therefore, regulators should clearly define data property rights, prevent information leakage and other security risks, and lead the healthy development of the digital economy with security at the technical level and regulation at the institutional level. Regulators should further enhance the control of technology innovation and digital economy industries, prevent and resolve possible systemic risks during the development of the digital economy, and provide a good market environment for green development.

(4) For corporate sector: due to that there exist cointegration among digital economy, green innovation and green development, corporates should spur the process of digitalization to take advantage of the digital platform and digital network, which can do some good to improving the level of green innovation and green governance, which can eventually improve their own competitiveness facing the background of low-carbon development. Corporations in developing countries should attract more foreign capital to participate in their own green bond markets and continue to promote innovation in green financial services such as green bonds in their own countries with the aim of attracting more specific capital and promoting the advancement of green technologies. Additionally, more talents and green industries should be introduced. Corporations should enhance staffs' ability to use digital technology and actively make use of digital technology to promote the level of technological innovation in the production and consumption process, continuously enrich the types of green products and green services, and guide the green consumption trend in the market with quality products and services. Corporations should effectively apply the advantages of data elements to the core process of manufacturing in order to achieve real-time monitoring and intelligent control of all aspects of production, reduce energy consumption.

While this article has examined the relationship between the digital economy, green innovation, and green development, it still has limitations. As for the measurement of the digital economy, the development of new digital industries such as the communications industry and the aviation and satellite industry has become the mainstream of the digital economy, so future research can include them in the measurement of the digital economy to improve the comprehensiveness and accuracy of the measurement indicators. This study is purely empirical and has not yet explored the theoretical mechanisms between the digital economy and green development. Therefore, subsequent studies can attempt to develop relevant theoretical models to further explore the intrinsic link between them. In addition, this study uses city-level data from China. The relationship between the digital economy, green innovation, and green development in emerging markets or developed markets deserves more detailed study and our analysis can be used as a starting point.

Note

1. Due to the results for such 4 sub-samples are similar to that of full sample, these results are not reported to save the space, but are available upon request.

Acknowledgement

We would like to thank Professor Chun-Ping Chang, co-editor in chief of *Emerging Markets Finance and Trade*, as well as all anonymous reviewers for their comments and support in our revision.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

Funding

Ying Lin thanks financial support from the National Social Science Fund of China (No. 20CGL030) and the Humanities and Social Science Fund of Ministry of Education of China (No. 19YJC790075). The work was also supported by the Humanities and Social Science Fund of Ministry of Education of China [22YJC790130] and the National Natural Science Foundation of China [72204227].

References

Abban, O. J., J. Wu, and I. A. Mensah. 2020. Analysis on the nexus amid CO 2 emissions, energy intensity, economic growth, and foreign direct investment in belt and road economies: Does the level of income matter? *Environmental Science and Pollution Research* 27 (10):11387–402. doi:10.1007/s11356-020-07685-9.

Adams, B. 2019. *Green development: Environment and sustainability in a developing world*. Routledge. doi:10.4324/9780203386033.

Adams, W. M. 2005. Green development theory?: Environmentalism and sustainable development. In *Power of development*, ed. J. Crush, 85–96. UK: Routledge.

Aghion, P., and P. Howitt. 1992. Amodel of growth through creative destruction. *Econometrica* 60 (2):323–351.

Albort-Morant, G., J. Henseler, A. Leal-Millán, and G. Cepeda-Carrión. 2017. Mapping the field: A bibliometric analysis of green innovation. *Sustainability* 9 (6):1011. doi:10.3390/su9061011.

Albort-Morant, G., A. Leal-Millán, and G. Cepeda-Carrión. 2016. The antecedents of green innovation performance: A model of learning and capabilities. *Journal of Business Research* 69 (11):4912–17. doi:10.1016/j.jbusres.2016.04.052.

Alderete, M. V. 2017. Examining the ICT access effect on socioeconomic development: The moderating role of ICT use and skills. *Information Technology for Development* 23 (1):42–58. doi:10.1080/02681102.2016.1238807.

Anser, M. K., M. A. Khan, U. Awan, R. Batool, K. Zaman, M. Imran, and Z. A. Bakar. 2020. The role of technological innovation in a dynamic model of the environmental supply chain curve: Evidence from a panel of 102 countries. *Processes* 8 (9):1033. doi:10.3390/pr8091033.

Awan, U., R. Sroufe, and M. Shahbaz. 2021. Industry 4.0 and the circular economy: A literature review and recommendations for future research. *Business Strategy and the Environment* 30 (4):2038–60. doi:10.1002/bse.2731.

Awan, A. G., and R. Yaqoob. 2023. Economic value of introducing technology to improve productivity: An ARDL approach. *Innovation and Green Development* 2 (3):100069. doi:10.1016/j.igd.2023.100069.

Balcilar, M., H. Gungor, and G. Olasehinde-Williams. 2019. On the impact of globalization on financial development: A multi-country panel study. *European Journal of Sustainable Development* 8 (1):350–350. doi:10.14207/ejsd.2019.v8n1p350.

Bibi, M., M. K. Khan, M. M. B. Tufail, D. I. Godil, R. Usman, and M. Faizan. 2022. How ICT and globalization interact with the environment: A case of the Chinese economy. *Environmental Science and Pollution Research* 30 (3):1–19. doi:10.1007/s11356-022-22677-7.

Bressanelli, G., F. Adrodegari, M. Perona, and N. Saccani. 2018. Exploring how usage-focused business models enable circular economy through digital technologies. *Sustainability* 10 (3):639. doi:10.3390/su10030639.

Bukht, R., and R. Heeks. 2017. Defining, conceptualising and measuring the digital economy. *Development Informatics working paper*, 68.

Chai, J., H. Wu, and Y. Hao. 2022. Planned economic growth and controlled energy demand: How do regional growth targets affect energy consumption in China? *Technological Forecasting & Social Change* 185:122068. doi:10.1016/j.techfore.2022.122068.

Chakpitak, N., P. Maneejuk, S. Chanaim, and S. Sriboonchitta (2018). Thailand in the era of digital economy: How does digital technology promote economic growth? In *International Conference of the Thailand Econometrics Society* (pp. 350–62). Cham: Springer, January.

Chen, P. 2022. Relationship between the digital economy, resource allocation and corporate carbon emission intensity: New evidence from listed Chinese companies. *Environmental Research Communications* 4 (7):075005. doi:10.1088/2515-7620/ac7ea3.

Chen, X., Q. Fu, and C. P. Chang. 2021. What are the shocks of climate change on clean energy investment: A diversified exploration. *Energy Economics* 95:105136. doi:10.1016/j.eneco.2021.105136.

Chen, Z. 2023. Enhancing the engineering supervision process in China: A solution enabled by integrating hybrid blockchain system. *Innovation and Green Development* 2 (4):100091. doi:10.1016/j.igd.2023.100091.

Cheng, Y., U. Awan, S. Ahmad, and Z. Tan. 2021. How do technological innovation and fiscal decentralization affect the environment? A story of the fourth industrial revolution and sustainable growth. *Technological Forecasting and Social Change* 162:120398. doi:10.1016/j.techfore.2020.120398.

Dai, D., Y. Fan, G. Wang, and J. Xie. 2022. Digital economy, R&D investment, and regional green innovation—analysis based on provincial panel data in China. *Sustainability* 14 (11):6508. doi:10.3390/su14116508.

Ding, C., C. Liu, C. Zheng, and F. Li. 2021. Digital economy, technological innovation and high-quality economic development: Based on spatial effect and mediation effect. *Sustainability* 14 (1):216. doi:10.3390/su14010216.

Dumitrescu, E. I., and C. Hurlin. 2012. Testing for Granger non-causality in heterogeneous panels. *Economic Modelling* 29 (4):1450–60. doi:10.1016/j.econmod.2012.02.014.

El Hafdaoui, H., F. Jelti, A. Khallaayoun, A. Jamil, and K. Ouazzani. 2024. Energy and environmental evaluation of alternative fuel vehicles in Maghreb countries. *Innovation and Green Development* 3 (1):100092. doi:10.1016/j.igd.2023.100092.

Ferraris, A., A. Mazzoleni, A. Devalle, and J. Couturier. 2018. Big data analytics capabilities and knowledge management: Impact on firm performance. *Management Decision*, 57 (8):1923–1936.

Fleming, A., R. M. Wise, H. Hansen, and L. Sams. 2017. The sustainable development goals: A case study. *Marine Policy* 86:94–103. doi:10.1016/j.marpol.2017.09.019.

Fu, Q., Q. Gong, X. X. Zhao, and C. P. Chang. 2023. The effects of international sanctions on green innovations. *Technological and Economic Development of Economy* 29 (1):141–64. doi:10.3846/tede.2022.17782.

Ghobakhloo, M., M. Iranmanesh, A. Grybauskas, M. Vilkas, and M. Petraitė. 2021. Industry 4.0, innovation, and sustainable development: A systematic review and a roadmap to sustainable innovation. *Business Strategy and the Environment* 30 (8):4237–57. doi:10.1002/bse.2867.

Gu, K., F. Dong, H. Sun, and Y. Zhou. 2021. How economic policy uncertainty processes impact on inclusive green growth in emerging industrialized countries: A case study of China. *Journal of Cleaner Production* 322:128963. doi:10.1016/j.jclepro.2021.128963.

Halati, A., and Y. He. 2018. Intersection of economic and environmental goals of sustainable development initiatives. *Journal of Cleaner Production* 189:813–29. doi:10.1016/j.jclepro.2018.03.322.

Hao, X., Y. Li, S. Ren, H. Wu, and Y. Hao. 2023. The role of digitalization on green economic growth: Does industrial structure optimization and green innovation matter? *Journal of Environmental Management* 325:116504. doi:10.1016/j.jenvman.2022.116504.

Harlan, T. 2021. Green development or greenwashing? A political ecology perspective on China's green belt and road. *Eurasian Geography and Economics* 62 (2):202–26. doi:10.1080/15387216.2020.1795700.

He, Q., and J. Du. 2022. The impact of urban land misallocation on inclusive green growth efficiency: Evidence from China. *Environmental Science and Pollution Research* 29 (3):3575–86. doi:10.1007/s11356-021-15930-y.

Hickel, J. 2019. The contradiction of the sustainable development goals: Growth versus ecology on a finite planet. *Sustainable Development* 27 (5):873–84. doi:10.1002/sd.1947.

Hosseini, H. M., and S. Kaneko. 2011. Dynamic sustainability assessment of countries at the macro level: A principal component analysis. *Ecological Indicators* 11 (3):811–23. doi:10.1016/j.ecolind.2010.10.007.

Jorgenson, D. W., and K. Motohashi. 2005. Information technology and the Japanese economy. *Journal of the Japanese and International Economies* 19 (4):460–81. doi:10.1016/j.jjie.2005.05.001.

Kalnbalkite, A., V. Brakovska, V. Terjanika, J. Pubule, and D. Blumberga. 2023. The tango between the academic and business sectors: Use of co-management approach for the development of green innovation. *Innovation and Green Development* 2 (4):100073. doi:10.1016/j.igd.2023.100073.

Kehal, H. S., and V. P. Singh, (Eds.) 2005. *Digital economy: Impacts, influences, and challenges*. IGI Global.

Kohli, R., and N. P. Melville. 2019. Digital innovation: A review and synthesis. *Information Systems Journal* 29 (1):200–23. doi:10.1111/isj.12193.

Kovacikova, M., P. Janoskova, and K. Kovacikova. 2021. The impact of emissions on the environment within the digital economy. *Transportation Research Procedia* 55:1090–97. doi:10.1016/j.trpro.2021.07.080.

Kunapatarawong, R., and E. Martínez-Ros. 2016. Towards green growth: How does green innovation affect employment? *Research Policy* 45 (6):1218–32. doi:10.1016/j.respol.2016.03.013.

Li, D., M. Zheng, C. Cao, X. Chen, S. Ren, and M. Huang. 2017. The impact of legitimacy pressure and corporate profitability on green innovation: Evidence from China top 100. *Journal of Cleaner Production* 141:41–49. doi:10.1016/j.jclepro.2016.08.123.

Li, G., Y. Wang, S. Zhou, Z. Lu, and T. Yin. 2023. Effectiveness and challenge of environmental impact assessment in industrial park, a case study in northeast rust belt China. *Innovation and Green Development* 2 (4):100072. doi:10.1016/j.igd.2023.100072.

Li, Z., and J. Wang. 2022. The dynamic impact of digital economy on carbon emission reduction: Evidence city-level empirical data in China. *Journal of Cleaner Production* 351:131570. doi:10.1016/j.jclepro.2022.131570.

Litvinenko, V. S. 2020. Digital economy as a factor in the technological development of the mineral sector. *Natural Resources Research* 29 (3):1521–41. doi:10.1007/s11053-019-09568-4.

Liu, X., S. Fan, F. Cao, S. Peng, H. Huang, and G. Chen. 2022. Study on the drivers of inclusive green growth in China based on the digital economy represented by the Internet of Things (IoT). *Computational Intelligence and Neuroscience* 2022:1–15. doi:10.1155/2022/8340371.

Long, H., C. P. Chang, S. Jegajeevan, and K. Tang. 2022. Can Central Bank mitigate the effects of the COVID-19 pandemic on the macroeconomy? *Emerging Markets Finance & Trade* 58 (9):2652–69. doi:10.1080/1540496X.2021.2007880.

Luo, S., N. Yimamu, Y. Li, H. Wu, M. Irfan, and Y. Hao. 2023. Digitalization and sustainable development: How could digital economy development improve green innovation in China? *Business Strategy and the Environment* 32 (4):1847–71. doi:10.1002/bse.3223.

Luukkanen, J., J. Kaivo-Oja, N. Vähäkari, T. O'Mahony, M. Korkeakoski, J. Panula-Ontto, and N. Hogarth. 2019. Green economic development in Lao PDR: A sustainability window analysis of green growth productivity and the efficiency gap. *Journal of Cleaner Production* 211:818–29. doi:10.1016/j.jclepro.2018.11.149.

Ma, D., and Q. Zhu. 2022. Innovation in emerging economies: Research on the digital economy driving high-quality green development. *Journal of Business Research* 145:801–13.

Ma, X., C. Wang, Y. Yu, Y. Li, B. Dong, X. Zhang, and Y. Gu. 2018. Ecological efficiency in China and its influencing factors—a super-efficient SBM metafrontier-malmquist-tobit model study. *Environmental Science and Pollution Research* 25 (21):20880–98. doi:10.1007/s11356-018-1949-7.

Miao, C., D. Fang, L. Sun, and Q. Luo. 2017. Natural resources utilization efficiency under the influence of green technological innovation. *Resources, Conservation and Recycling* 126:153–61. doi:10.1016/j.resconrec.2017.07.019.

Miao, Z. 2021. Digital economy value chain concept, model structure, and mechanism. *Applied Economics* 53 (37):4342–57. doi:10.1080/00036846.2021.1899121.

Motla, R., A. Kumar, N. Saxena, and S. S. Sana. 2023. Inventory optimization in a green environment with two warehouses. *Innovation and Green Development* 2 (4):100087. doi:10.1016/j.igd.2023.100087.

Mushafiq, M. 2023. Towards green development: Role of researchers. *Innovation and Green Development* 2 (4):100075. doi:10.1016/j.igd.2023.100075.

Nguyen, T. T., T. A. T. Pham, and H. T. X. Tram. 2020. Role of information and communication technologies and innovation in driving carbon emissions and economic growth in selected G-20 countries. *Journal of Environmental Management* 261:110162. doi:10.1016/j.jenvman.2020.110162.

Niebel, T. 2018. ICT and economic growth–comparing developing, emerging and developed countries. *World Development* 104:197–211. doi:10.1016/j.worlddev.2017.11.024.

Ofori, I. K., and S. A. Asongu. 2021. ICT diffusion, foreign direct investment and inclusive growth in Sub-Saharan Africa. *Telematics and Informatics* 65:101718. doi:10.1016/j.tele.2021.101718.

Pan, Y., S. Zhang, and M. Zhang. 2024. The impact of entrepreneurship of farmers on agriculture and rural economic growth: Innovation-driven perspective. *Innovation and Green Development* 3 (1):100093. doi:10.1016/j.igd.2023.100093.

Pastor, J. T., and C. K. Lovell. 2005. A global malmquist productivity index. *Economics Letters* 88 (2):266–71. doi:10.1016/j.econlet.2005.02.013.

Peng, X. Y., X. Y. Zou, X. X. Zhao, and C. P. Chang. 2023. How does economic policy uncertainty affect green innovation? *Technological and Economic Development of Economy* 29 (1):114–40. doi:10.3846/tede.2022.17760.

Pesaran, M. H. 2004. General diagnostic tests for cross section dependence in panels. *Available at SSRN 572504*. doi:10.2139/ssrn.572504.

Pesaran, M. H. 2007. A simple panel unit root test in the presence of cross-section dependence. *Journal of Applied Econometrics* 22 (2):265–312. doi:10.1002/jae.951.

Pesaran, M. H. 2015. Testing weak cross-sectional dependence in large panels. *Econometric Reviews* 34 (6–10):1089–117. doi:10.1080/07474938.2014.956623.

Raihan, A. 2023a. The influences of renewable energy, globalization, technological innovations, and forests on emission reduction in Colombia. *Innovation and Green Development* 2 (4):100071. doi:10.1016/j.igd.2023.100071.

Raihan, A. 2023b. Economy-energyenvironment nexus: The role of information and communication technology towards green development in Malaysia. *Innovation and Green Development* 2 (4):100085. doi:10.1016/j.igd.2023.100085.

Ren, S., Y. Hao, and H. Wu. 2022. Digitalization and environment governance: does internet development reduce environmental pollution? *Journal of Environmental Planning and Management* 66 (7):1–30. doi:10.1080/09640568.2022.2033959.

Ren, S., Y. Hao, L. Xu, H. Wu, and N. Ba. 2021. Digitalization and energy: How does internet development affect China's energy consumption? *Energy Economics* 98:105220. doi:10.1016/j.eneco.2021.105220.

Saunila, M. 2017. Understanding innovation performance measurement in SMEs. *Measuring Business Excellence* 21 (1):1–16. doi:10.1108/MBE-01-2016-0005.

Savina, T. N. 2018. Digital economy as a new paradigm of development: Challenges, opportunities and prospects. *Finance and Credit* 24 (3):579–90. doi:10.24891/fc.24.3.579.

Shahid, R., H. Shahid, L. Shijie, and G. Jian. 2024. Developing nexus between economic opening-up, environmental regulations, rent of natural resources, green innovation, and environmental upgrading of China-empirical analysis using ARDL bound-testing approach. *Innovation and Green Development* 3 (1):100088. doi:10.1016/j.igd.2023.100088.

Silva, L. C. S., C. S. Ten Caten, and S. Gaia. 2023. Conceptual framework of green technology transfer at public university scope Brazilian. *Innovation and Green Development* 2 (4):100076. doi:10.1016/j.igd.2023.100076.

Song, M., R. Fisher, and Y. Kwoh. 2019. Technological challenges of green innovation and sustainable resource management with large scale data. *Technological Forecasting and Social Change* 144:361–68. doi:10.1016/j.techfore.2018.07.055.

Su, J., K. Su, and S. Wang. 2021. Does the digital economy promote industrial structural upgrading?—A test of mediating effects based on heterogeneous technological innovation. *Sustainability* 13 (18):10105. doi:10.3390/su131810105.

Sun, H., W. Mao, Y. Dang, and D. Luo. 2022. What inhibits regional inclusive green growth? Empirical evidence from China. *Environmental Science and Pollution Research* 29 (26):39790–806. doi:10.1007/s11356-021-17250-7.

Sun, Y., W. Ding, Z. Yang, G. Yang, and J. Du. 2020. Measuring China's regional inclusive green growth. *Science of the Total Environment* 713:136367. doi:10.1016/j.scitotenv.2019.136367.

Tchouto, T. T. 2023. An empirical assessment on the leveraging evidence of economic complexity under environmental kuznets curve hypothesis: A comparative analysis between Nordic and Non-Nordic European countries. *Innovation and Green Development* 2 (4):100074. doi:10.1016/j.igd.2023.100074.

Teece, D. J. 2018. Profiting from innovation in the digital economy: Enabling technologies, standards, and licensing models in the wireless world. *Research Policy* 47 (8):1367–87. doi:10.1016/j.respol.2017.01.015.

Thompson, P., R. Williams, and B. Thomas. 2013. Are UK SMEs with active web sites more likely to achieve both innovation and growth? *Journal of Small Business and Enterprise Development* 20 (4):934–65. doi:10.1108/JSBED-05-2012-0067.

Ulucak, R., and S. U. D. Khan. 2020. Determinants of the ecological footprint: Role of renewable energy, natural resources, and urbanization. *Sustainable Cities and Society* 54:101996. doi:10.1016/j.scs.2019.101996.

Usman, A., I. Ozturk, A. Hassan, S. M. Zafar, and S. Ullah. 2021. The effect of ICT on energy consumption and economic growth in South Asian economies: An empirical analysis. *Telematics and Informatics* 58:101537. doi:10.1016/j.tele.2020.101537.

Wang, D., K. Wan, and J. Yang. 2019. Ecological efficiency of coal cities in China: Evaluation and influence factors. *Natural Hazards* 95 (1–2):363–79. doi:10.1007/s11069-018-3441-6.

Wang, Q. J., G. F. Feng, H. J. Wang, and C. P. Chang. 2022. The influence of political ideology on greenhouse gas emissions. *Global Environmental Change* 74:102496. doi:10.1016/j.gloenvcha.2022.102496.

Wang, Q. J., H. J. Wang, and C. P. Chang. 2022a. Environmental performance, green finance and green innovation: What's the long-run relationships among variables? *Energy Economics* 110:106004.

Wang, Q. J., and Y. H. Sun. 2022b. The impact of governmental ideology on forest preservation: Evidence from cross-country data. *Land Use Policy* 119:106208.

Wang, X., and Q. Shao. 2019. Non-linear effects of heterogeneous environmental regulations on green growth in G20 countries: Evidence from panel threshold regression. *Science of the Total Environment* 660:1346–54. doi:10.1016/j.scitotenv.2019.01.094.

Westerlund, J., and D. L. Edgerton. 2007. A panel bootstrap cointegration test. *Economics Letters* 97 (3):185–90. doi:10.1016/j.econlet.2007.03.003.

Wen, J., H. T. Yin, C. L. Jang, H. Uchida, and C. P. Chang. 2023. Does corruption hurt green innovation? yes–global evidence from cross validation. *Technological Forecasting & Social Change* 188:122313. doi:10.1016/j.techfore.2022.122313.

Wilson, A., J. L. Uncapher, L. McManigal, W. D. Browning, L. H. Lovins, and M. Cureton. 1998. *Green development: Integrating ecology and real estate*, vol. 9. Hoboken, NJ: John Wiley & Sons.

World Bank. 2012. *Inclusive green growth: The pathway to sustainable development*. Herndon, USA: The World Bank.

Wu, Y., Y. Wang, and H. Chen. (2019, February). "Three-circle model" under the green development. In *IOP Conference Series: Earth and Environmental Science*, vol. 237, No. 5, 052041. Bristol, England: IOP Publishing.

Wurlod, J. D., and J. Noailly. 2018. The impact of green innovation on energy intensity: An empirical analysis for 14 industrial sectors in OECD countries. *Energy Economics* 71:47–61. doi:10.1016/j.eneco.2017.12.012.

Xue, Y., C. Jiang, Y. Guo, J. Liu, H. Wu, and Y. Hao. 2022. Corporate social responsibility and high-quality development: Do green innovation, Environmental Investment and corporate governance matter? *Emerging Markets Finance & Trade* 58 (11):3191–214. doi:10.1080/1540496X.2022.2034616.

Yahaya, A. K., and L. Augustine. 2023. Livelihood activities in the lawra municipality of Ghana: A blessing or a curse to the riparian vegetation of the Black Volta Basin. *Innovation and Green Development* 2 (4):100090. doi:10.1016/j.igd.2023.100090.

Yang, J., and S. Chen. 2023. Corporate financialization, digitalization and green innovation: A panel investigation on Chinese listed firms. *Innovation and Green Development* 2 (3):100068. doi:10.1016/j.igd.2023.100068.

Yang, H. C., G. F. Feng, X. X. Zhao, and C. P. Chang. 2022. The impacts of energy insecurity on green innovation: A multi-country study. *Economic Analysis & Policy* 74:139–54. doi:10.1016/j.eap.2022.01.017.

Yang, Q. C., G. F. Feng, C. P. Chang, and Q. J. Wang. 2021. Environmental protection and performance: A bi-directional assessment. *Science of the Total Environment* 774:145747. doi:10.1016/j.scitotenv.2021.145747.

Yi, J., Y. Hou, and Z. Z. Zhang. 2023. The impact of foreign direct investment (FDI) on China's manufacturing carbon emissions. *Innovation and Green Development* 2 (4):100086. doi:10.1016/j.igd.2023.100086.

Yin, H.-T., C.-P. Chang, and H. Wang. 2022a. The impact of monetary policy on green innovation: Global evidence. *Technological and Economic Development of Economy* 28 (6):1933–53. doi:10.3846/tede.2022.17020.

Yin, H. T., J. Wen, and C. P. Chang. 2022. Science-technology intermediary and innovation in China: Evidence from State Administration for market regulation, 2000–2019. *Technology in Society* 68:101864. doi:10.1016/j.techsoc.2022.101864.

Yin, H. T., J. Wen, and C. P. Chang. 2023a. How do earthquakes shock energy innovation? A holistic cross-country investigation. Working Paper.

Yin, H. T., C. P. Chang, D. F. Anugrah, and I. Gunadi. 2023b. Gender equality and central bank independence. *Economic Analysis & Policy* 78:661–72. doi:10.1016/j.eap.2023.04.006.

Yolcan, O. O. 2023. World energy outlook and state of renewable energy: 10-year evaluation. *Innovation and Green Development* 2 (3):100070. doi:10.1016/j.igd.2023.100070.

Yuan, B., and Q. Xiang. 2018. Environmental regulation, industrial innovation and green development of Chinese manufacturing: Based on an extended CDM model. *Journal of Cleaner Production* 176:895–908. doi:10.1016/j.jclepro.2017.12.034.

Yuan, S., H. O. Musibau, S. Y. Genç, R. Shaheen, A. Ameen, and Z. Tan. 2021. Digitalization of economy is the key factor behind fourth industrial revolution: How G7 countries are overcoming with the financing issues? *Technological Forecasting and Social Change* 165:120533. doi:10.1016/j.techfore.2020.120533.

Zhang, R. L., and X. H. Liu. 2021. Evaluating ecological efficiency of Chinese industrial enterprise. *Renewable Energy* 178:679–91. doi:10.1016/j.renene.2021.06.119.

Zhang, W., S. Zhao, X. Wan, Y. Yao, and L. Vasa. 2021. Study on the effect of digital economy on high-quality economic development in China. *PloS One* 16 (9):e0257365. doi:10.1371/journal.pone.0257365.

Zhang, X., W. Guo, and M. B. Bashir. 2022. Inclusive green growth and development of the high-quality tourism industry in China: The dependence on imports. *Sustainable Production and Consumption* 29:57–78. doi:10.1016/j.spc.2021.09.023.

Zhao, N., X. Liu, C. Pan, and C. Wang. 2021. The performance of green innovation: From an efficiency perspective. *Socio-Economic Planning Sciences* 78:101062. doi:10.1016/j.seps.2021.101062.

Zhao, X., J. Nakonieczny, F. Jabeen, U. Shahzad, and W. Jia. 2022. Does green innovation induce green total factor productivity? Novel findings from Chinese city level data. *Technological Forecasting and Social Change* 185:122021. doi:10.1016/j.techfore.2022.122021.

Zhao, X. X., J. Wen, X. Y. Zou, Q. J. Wang, and C. P. Chang. 2023. Strategies for the sustainable development of China in the post-epidemic era. *Sustainable Development* 31 (1):426–38.

Zheng, M., G. F. Feng, C. L. Jang, and C. P. Chang. 2021. Terrorism and green innovation in renewable energy. *Energy Economics* 104:105695. doi:10.1016/j.eneco.2021.105695.

Zheng, M., G.-F. Feng, R.-A. Jiang, and C.-P. Chang. 2023. Does environmental, social, and governance performance move together with corporate green innovation in China? *Business Strategy and the Environment* 32 (4):1670–79. doi:10.1002/bse.3211.

Zheng, M., G. F. Feng, X. Zhao, and C. P. Chang. 2023. The transaction behavior of cryptocurrency and electricity consumption. *Financial Innovation* 9 (1):44. doi:10.1186/s40854-023-00449-7.

Zheng, M., and C. Y. Wong. 2024. The impact of digital economy on renewable energy development in China. *Innovation and Green Development* 3 (1):8 of 8 100094. doi:10.1016/j.igd.2023.100094.

Zhu, S., and A. Ye. 2018. Does foreign direct investment improve inclusive green growth? Empirical evidence from China. *Economies* 6 (3):44. doi:10.3390/economies6030044.

Zou, X. Y., X. Y. Peng, X. X. Zhao, and C. P. Chang. 2023. The impact of extreme weather events on water quality: International page 6 of 8 evidence. *Natural Hazards* 115 (1):1–21. doi:10.1007/s11069-022-05548-9.

Copyright of Emerging Markets Finance & Trade is the property of Taylor & Francis Ltd and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.