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Original Research

An Analysis of Ecological Environmental Changes Driven by the Digital Economy in Sichuan Province

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Abstract

This study investigates the relationship between digital economy development and the ecological environment in Sichuan Province from 2011 to 2021, utilizing methods such as the entropy weight method, the Tapio decoupling model, the coupling coordination model, and the LMDI model for data analysis. The results show that Sichuan Province's digital economy has experienced sustained growth over the past decade, driven particularly by advances in cloud computing, big data, and artificial intelligence, which have significantly transformed the economic structure. The development of the digital economy has achieved notable success in enhancing resource utilization efficiency and reducing emissions from traditional pollutants, with outstanding performance in smart city construction and green technology applications. However, the study also finds that the rapid expansion of the digital economy has been accompanied by increased environmental pressures, especially in terms of energy consumption and electronic waste management challenges. From 2017 to 2020, the coordination between the digital economy and ecological environment quality improved significantly, but 2021 data indicates a decline in ecological environment quality, possibly related to increased economic activities. The findings underscore the need for targeted policies that balance economic growth with ecological sustainability, particularly in high-impact sectors such as energy and e-waste management. Future research should focus on developing innovative strategies to mitigate environmental risks while leveraging the benefits of digital transformation.

Keywords: digital economy, ecological environment, Tapio model, coupling coordination model, LMDI model

Introduction

The emergence and development of the digital economy and other new economic forms result from the rapid growth of modern information technology integrated with global economic development and human production and lifestyle changes [1, 2]. In recent years, developing the digital economy has become a strategic focus for countries worldwide to enhance economic development quality and gain a competitive edge in the international economic arena [3, 4]. The European Union (EU), the Organization for Economic Co-operation and Development (OECD), and countries such as China, the United States, Germany, France, Canada, and India have successively prioritized the development of the digital

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economy as a key component of their national economic strategies [5, 6]. In 2016, China released the "National Informatization Development Strategy", and President Xi Jinping has emphasized the importance of digital economy development at significant events, including the 2017 World Economic Forum Annual Meeting, the Belt and Road Forum for International Cooperation, the BRICS Leaders Meeting, and the Central Economic Work Conference. The digital economy has become a "new engine" driving global economic growth in the information age and holds a critical position in the global economic agenda. The development level of the digital economy also reflects a country's comprehensive national strength in the context of the new economy. It has transformed production, consumption, and distribution methods, offering a more efficient economic operation model [7-9].

Currently, China's economic development model is transitioning from high-speed growth to high-quality development [10, 11]. From the perspective of the "Digital China" strategic layout, the digital economy development strategy has become a crucial component of China's modernization efforts [8, 12]. The emergence and development of the digital economy have driven the transformation of traditional industries and the emergence of new industries, leading China's high-quality economic development as a "new engine" for growth [1, 13, 14].

Sichuan Province was chosen as the research sample for this study due to its pivotal role as an economic and technological hub in western China. As a leading force in digital economy development, Sichuan has actively implemented the "Digital Economy Innovation and Development Pilot Zone" initiative, making it a representative region for studying the interaction between digital economy growth and ecological environmental changes. Additionally, Sichuan's unique geographical conditions and diverse ecosystem make it an ideal case for exploring how regional characteristics influence the relationship between the digital economy and ecological environment quality. The province is undergoing significant economic restructuring, with an emphasis on digital transformation and green development, which are crucial for achieving sustainable development. Studying Sichuan provides valuable insights into the challenges and opportunities faced by other regions in China and similar developing economies undergoing digital transformation [15, 16]. Promoting high-quality digital economic development is a new challenge for future digital growth [7, 17]. However, while accelerating the transformation of traditional economic models, the advancement of the digital economy also significantly impacts energy development patterns and environmental governance systems [18, 19]. This has led to issues such as an overemphasis on the speed of digital economy development at the expense of resource allocation matching, widening the digital divide, and exacerbating regional development imbalances and industrial coordination problems. To balance the regional development of the digital economy, explore new digital development paths, and improve digital production efficiency, particularly for Sichuan Province, which is in a critical period of industrial structure adjustment and upgrading, it is necessary to systematically advance the high-quality transformation of industrial digitalization in stages. This involves exploring the coordination between ecological environment and digital economy development at multiple levels to support the "sustainable development" and "Eastern Data, Western Calculation" strategies [20].

From a theoretical research perspective, the relationship between the digital economy and the ecological environment has been a growing area of interest among scholars. Existing studies have predominantly focused on the economic benefits and technological advancements associated with digital economy growth, such as increased productivity, improved efficiency, and innovation [21, 22]. However, fewer studies have delved into the environmental implications of digital economy expansion. The digital economy, while enhancing economic performance, may also pose environmental challenges, including increased electronic waste, higher energy consumption, and potential ecological degradation [23, 24]. This paper addresses this research gap by systematically reviewing the existing literature on the relationship between the digital economy and the ecological environment, particularly in the context of regional disparities and influencing factors. By focusing on the case of Sichuan Province, this study provides a comprehensive analysis of how the digital economy can simultaneously drive economic growth and contribute to environmental stress, thus highlighting the dual impacts of digitalization on sustainable development.

The contributions of this paper are threefold. First, it provides a detailed spatiotemporal analysis of the coupling relationship between digital economy development and ecological environment quality in Sichuan Province over the past decade, using a combination of quantitative models, including the entropy weight method, the Tapio decoupling model, the coupling coordination model, and the LMDI model. Second, this study identifies key influencing factors and regional disparities that affect the coordination between digital economy growth and environmental sustainability, offering a nuanced understanding of the complex dynamics at play. Third, the findings of this research offer policy implications for other regions in China and globally, aiming to balance economic growth with environmental protection by leveraging digital technologies for green development. These contributions not only fill the existing research gap but also provide actionable insights for policymakers and stakeholders in the digital and environmental sectors.

Given the complexity and multi-dimensionality of the relationship between the digital economy and the ecological environment, this study employs a combination of multiple methods, each serving a specific analytical purpose.

First, the entropy weight method is utilized to objectively assign weights to various indicators related to the digital economy and ecological environment quality, ensuring that the evaluation is not biased by subjective factors. This method helps establish a comprehensive index system that accurately reflects the development level of both systems [21, 22].

Second, the Tapio decoupling model is used to assess the degree of decoupling between digital economy growth and environmental impact. This model allows for a dynamic evaluation of the relationship over time, revealing whether economic growth is occurring alongside increasing or decreasing environmental pressure [23, 24].

Third, the coupling coordination model measures the interaction and coordination between the digital economy and ecological environment quality. It helps identify the extent to which the two systems are synchronized and whether they are developing in harmony or conflict. This is crucial for understanding the overall balance and sustainability of the region's development [25].

Lastly, the LMDI (Logarithmic Mean Divisia Index) model is applied to decompose the factors contributing to changes in the coupling coordination degree, offering insights into the specific drivers of positive or negative changes in the relationship between digital economy and ecological environment quality [26, 27].

The integration of these methods provides a robust analytical framework that captures different aspects of the relationship between the digital economy and the ecological environment. This multi-method approach is necessary to address the complexity of the research questions and to provide a comprehensive analysis that single methods cannot achieve alone. By using a combination of quantitative techniques, this study aims to offer a holistic understanding of the dynamic interactions between digital economic development and ecological sustainability, providing a solid foundation for policy recommendations and future research directions.

From a theoretical research perspective, scholars believe that the digital economy can address information asymmetry, making environmental governance more efficient [21, 22]. Digital technologies can enhance resource allocation efficiency and reduce the resource consumption of traditional production methods, thereby conserving resources and protecting the environment [23, 24]. However, the digital economy may also lead to increased energy consumption and potential pollution, threatening the resilience of ecosystems. Conversely, a healthy ecological environment and a green lifestyle can provide the material and human resources necessary for the development of the digital economy, promoting both digital industrialization and industrial digitization. Scholars have conducted extensive research on the relationship between the digital economy and the ecological environment but have yet to identify the primary influencing factors, particularly the regional differences in these factors. This study explores the spatiotemporal characteristics and influencing factors of the coordinated development of the digital economy and ecological environment in Sichuan Province from 2011 to 2021, using panel data and employing the entropy weight method, Tapio decoupling model, coupling coordination model, and LMDI model.

Materials and Methods

Data Sources

The data used in this study comprises panel data from Sichuan Province for the years 2011 to 2021. The primary sources of all variable data are the Sichuan Statistical Yearbook and the China Regional Economic Statistical Yearbook. Additional data are obtained from the China Environmental Statistical Yearbook and the Annual Water Resources Statistics Bulletin of Sichuan Province. Missing data were supplemented using interpolation methods.

Research Methods

Construction of the Digital Economy Evaluation Index System

In existing literature, methods for evaluating the development level of the digital economy can be categorized into four types: national economic accounting methodologies [25], value-added measurement methods [26], index compilation methods [27], and satellite account methods [28]. Among these, the index compilation method is the most popular and mature approach. It involves categorizing the digital economy from various perspectives and constructing a quantifiable evaluation index system using different measurement indicators to calculate the digital economy development index and analyze its development characteristics.

In this study, we adopt this conceptual framework and incorporate the "Four Needs" theory proposed by relevant scholars to design an evaluation index system across four dimensions: digital economy carriers, digital application services, digital industry development, and digital innovation capability. Given the externalities of the digital economy and the fact that most provinces in China are still in the growth phase of the digital economic scale, it is essential to consider the total resources available in each province and their resource aggregation capabilities when selecting indicators to assess digital economy development. Using an evaluation model with more absolute indicators can provide a more objective reflection of the digital economy development status in each province.

Regarding ecological environment quality, the influencing factors are numerous and diverse, with

Table 1. Evaluation Index System of Digital Economy and Ecological Environment Quality.

Primary Indicators	Secondary Indicators	Attribute
Digital Economy Carrier	Number of Domain Names (10,000s)	+
	Length of Long-distance Optical Cable Lines (10,000 km)	+
	Number of Broadband Access Ports (10,000s)	+
Digital Application Services	Digital Inclusive Finance Index	+
	Mobile Phone Penetration Rate (units per 100 people)	+
	Revenue from Express Services Above Designated Size (10,000 yuan)	+
Digital Industry Development	Fixed Asset Investment in the Information Industry (billion yuan)	+
	Number of Employees in the Information Industry (10,000s)	+
	Added Value of the Tertiary Industry (billion yuan)	+
Digital Innovation Capability	Research and Development Expenditure (10,000 yuan)	+
	Number of Domestic Invention Patent Applications Accepted	+
Ecological Environment Level	Proportion of Grain Planting Area to Total Land Area	+
	Greening Coverage Rate in Built-up Areas	+
Ecological Environment Pressure	Industrial "Three Wastes" Per Capita	-
	Population Density	-
Ecological Environment Response	Comprehensive Utilization Rate of General Industrial Solid Waste	+
	Centralized Sewage Treatment Rate	+
	Harmless Treatment Rate of Household Waste	+

some factors directly or indirectly impacting ecological environment quality over time. Therefore, the selection of evaluation factors must comprehensively reflect the evaluation objectives, covering ecological environment quality issues at multiple levels and from multiple angles. This study constructs an ecological environment evaluation system from the perspectives of the ecological environment level, ecological environment pressure, and ecological environment response while adhering to the principles of data availability, comprehensiveness, and scientific rigor. The digital economy evaluation index system includes relative indicators, such as digital finance and mobile phone penetration rate, and absolute indicators, such as express business revenue and the added value of the tertiary industry (Table 1).

Measurement of Digital Economy Development Level

When calculating the weight of indicators, the digital economy is less affected by subjective human factors. To ensure that the evaluation results for each year are more reasonable, this study adopts an improved entropy method [29, 30] to objectively assign weights to the selected indicators, thereby calculating the comprehensive index of the digital economy and the ecological environment quality index. Let *t* represent the year and i represent the indicator, with X_{it} denoting the *i*-th indicator for year *t*. The specific calculation steps are as follows:

The following formula is used to standardize the 11 indicators shown in Table 1:

$$X_{it}^{'} = \frac{X_{it} - X_{imin}}{X_{imax} - X_{imin}}$$

where $X_{it}^{'}$ represents the normalized data, and X_{imin} and X_{imax} are the minimum and maximum values of the *i*-th indicator, respectively.

Calculate the proportion of the *i*-th indicator for year *t*:

$$P_{it} = \frac{X_{it}^{'}}{\sum X_{it}^{'}}$$

Calculate the entropy value of the *i*-th indicator:

$$e_i = -\frac{1}{\ln 11} \sum P_{it} \ln P_{it}$$

Calculate the weights of each indicator:

$$W_i = \frac{1 - e_i}{\sum 1 - e_i}$$

Use the normalized data and indicator weights to calculate the weighted digital economy index and ecological environment quality index:

Table 2. Classification of Coupling Coordination Types between Digital Economy Development Index and Ecological Environment Quality Index.

Category	Range of D
Low Coordination	[0.0,0.5]
Moderate Coordination	[0.5,0.7]
High Coordination	[0.7,0.9]
Excellent Coordination	[0.9,1.0]

$$Z_t = \sum W_i X_{it}^{'}$$

Tapio Model

The "decoupling" theory originates from the concept of "decoupling" in the field of physics and was first proposed by the OECD [31, 32]. It aims to break the link between "environmental pollution" and "economic goods". The Tapio decoupling model uses an elasticity analysis method based on time span to derive the decoupling elasticity coefficient, which dynamically reflects the decoupling relationship between variables [33]. This makes the analysis results more accurate and objective. Based on Tapio's method for studying the relationship between economic development, transportation capacity, and carbon emissions in Europe, this study constructs a corresponding decoupling index model according to the variation relationship between the digital economy index and ecological environment quality index:

$$\varepsilon_{D,E} = \frac{\Delta D/D}{\Delta E/E}$$

In the formula, $\varepsilon_{D,E}$ represents the decoupling index between the digital economy index and ecological environment quality index, D denotes the digital economy index, ΔD represents the difference in the digital economy index between the current period and the base period, and ΔE denotes the difference in the ecological environment quality index between the current period and the base period.

Coupling Coordination Model

The coupling coordination degree model is primarily used to reflect the state of interaction and coordination between two or more systems under the influence of both internal and external factors [34, 35]. This model indicates not only the strength of coupling between systems but also the degree of coordination between them. When both the coupling degree and coordination degree between systems are high, the systems are considered to achieve a benign coupling. The coupling coordination degree model can quantify the coupling coordination degree between the digital economy development level and ecological environment quality in China. The formulas are as follows:

$$C = \left[(N \times E)/\left(\frac{N+E}{2}\right)^2\right]^{\frac{1}{2}}$$

$$D = C \times T$$

$$T = \alpha N \times \beta E$$

Where N represents the digital economy development index; E represents the ecological environment quality index; C denotes the coupling degree, indicating the extent of interaction and influence between the systems; T is the comprehensive coordination index, representing the overall development level of the two systems; D is the coupling coordination degree, providing a more comprehensive evaluation of the development status of the two systems; Α and β denote the relative importance of the digital economy development index and ecological environment quality index, respectively.

The entropy weight method is utilized to determine the specific values of α and β. Additionally, the coupling coordination degree is classified into four categories (Table 2). Since the numerical ranges of the digital economy development level and ecological environment quality data are inconsistent, this study first normalizes the data before constructing the coupling coordination degree model.

LMDI Model

Index Decomposition Analysis (IDA) is a method for quantitatively analyzing the impact of various influencing factors on dependent variables. It has been widely used in past studies, particularly in the fields of energy consumption, carbon emissions, and environmental changes [36]. Among the many IDA models, the Logarithmic Mean Divisia Index (LMDI) model overcomes the issues of "zero" values and residuals in the decomposition process, making it one of the most ideal decomposition methods [37]. The LMDI model is also simple in structure, highly applicable, and easily combined with other models. This research effectively combines the coupling coordination degree model and the LMDI model. The calculation formula is as follows:

$$D = C \times T$$

$$\Delta D = D^t - D^0 = \Delta D_c + \Delta D_t$$

$$\Delta D_c = \left(\frac{D^t - D^0}{lnD^t - lnD^0}\right) ln\frac{C^t}{C^0}$$

$$\Delta D_t = \left(\frac{D^t - D^0}{lnD^t - lnD^0}\right) ln\frac{T^t}{T^0}$$

where 0 represents the starting year (2003), t represents the ending year (2022), and ΔD represents the change in the coupling coordination degree from the start year to the end year. ΔD_c and ΔD_t represent the contributions of the coupling degree and the comprehensive coordination index to the change in the coupling coordination degree, respectively.

Data Processing

In this study, Excel 2019 software was used for basic statistical analysis and processing of the collected data. The images and charts were created using Origin 2021 Pro software.

Results and Discussion

Development Level of the Digital Economy

From 2011 to 2021, the digital economy development index in Sichuan Province showed an overall upward trend (Fig. 1). The development of the digital economy went through several significant stages. During the initial growth phase from 2011 to 2013, the digital economy development index increased from 0.14 to 0.17. This phase marked the beginning of the digital economy in Sichuan Province, with the initial achievements in digital infrastructure construction. With the promotion of policies and the popularization of internet technology, the digital economy began to receive increasing attention and laid the foundation for subsequent development [38, 39].

The period from 2014 to 2016 was a stable growth phase for the digital economy. During this time, the digital economy development index continued to rise to 0.19, indicating that the digital economy in Sichuan Province had entered a relatively stable development stage. The digital industrial chain began to take shape, and technological innovation capabilities gradually increased. The years from 2017 to 2020 marked a period of rapid growth for the digital economy, with the index rising from 0.21 to 0.24. The widespread application of new technologies such as cloud computing, big data, and artificial intelligence significantly propelled the leapfrog development of the digital economy [40, 41]. This was closely related to Sichuan Province's strategic position in the development of the digital economy in western China. However, in 2021, the index slightly decreased to 0.23, possibly due to global economic uncertainties, the impact of the COVID-19 pandemic [42, 43], and various factors related to structural adjustments within Sichuan Province.

The rapid development of the digital economy has become an important driver of economic growth in Sichuan Province. The processes of industrial digitalization and digital industrialization have accelerated, reshaping the economic structure of Sichuan Province and promoting the transformation and upgrading of traditional industries. In this context, Sichuan Province's technological innovation capabilities have significantly improved [44], forming new economic growth points by introducing and cultivating high-tech enterprises. Furthermore, the development of the digital economy has created numerous job opportunities [45], fostered the prosperity of related industries, and enhanced the overall economic vitality and social benefits of the province.

However, the impact of the digital economy on the ecological environment quality in Sichuan Province is complex. On one hand, the development of the digital economy has promoted technological innovation, particularly in the application of green technologies. The implementation of projects such as smart cities and smart transportation [46] in Sichuan Province has improved resource utilization efficiency and reduced carbon emissions, contributing to the improvement of ecological environment quality. On the other hand, the rapid development of the digital economy has also brought environmental challenges, such as the increase in electronic waste and the consumption of natural resources due to the construction of digital infrastructure. In particular, some energy-intensive digital industries may lead to increased energy consumption and carbon emissions [47, 48].

As an important economic center in western China, the development status of Sichuan Province's digital economy has a significant impact on the entire region. The support of national policies and the active promotion by local governments have provided a favorable environment for the development of the digital economy. In terms of industrial layout, Sichuan Province has actively developed digital industries by establishing industrial parks and innovation centers, attracting high-tech enterprises to settle in, and promoting the optimization of the province's industrial structure. In terms of environmental governance, Sichuan Province is also continuously strengthening its efforts, actively responding to the ecological challenges brought by the development of the digital economy through policy guidance and technological innovation.

Ecological Environment Quality

From 2011 to 2021, the ecological environment quality index in Sichuan Province exhibited a significant

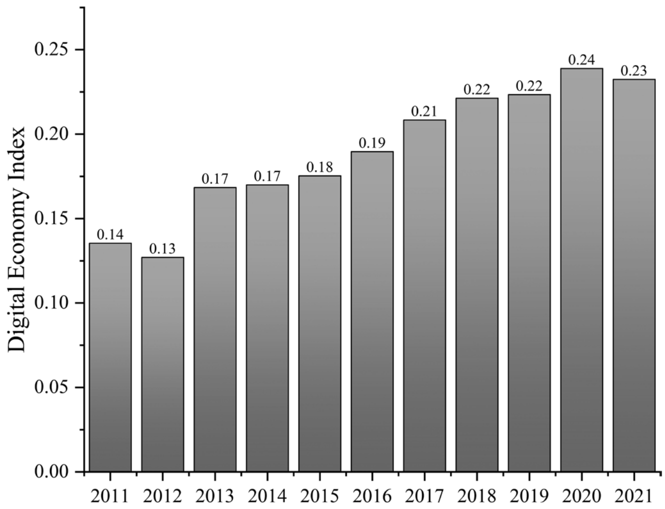

Fig. 1. Changes in the Digital Economy Index of Sichuan Province from 2011 to 2021.

fluctuation trend (Fig. 2). Between 2011 and 2013, the index dropped from 0.42 to 0.27. This marked decline may be associated with accelerated urbanization and increased industrial activities, leading to greater environmental pressure and a deterioration of ecological quality. However, from 2013 to 2016, the ecological environment quality index rebounded and stabilized at around 0.33, indicating that Sichuan Province may have implemented a series of measures during this period to curb the decline in ecological quality, such as strengthening environmental protection policies and advancing pollution control projects. Between 2017 and 2020, the index gradually increased from 0.35 to 0.40, reflecting significant achievements in environmental protection. This improvement might have resulted from stricter environmental regulations, increased use of renewable energy, and investments in ecological restoration projects. However, in 2021, the ecological environment quality index fell again to 0.23, signaling new challenges for environmental quality, possibly due to a rebound in economic activities or a weakening of environmental protection efforts.

The rapid development of the digital economy has had a complex impact on the ecological environment quality in Sichuan Province. During the period from 2011 to 2021, although the digital economy development index showed an upward trend, the ecological environment quality did not improve concurrently. This phenomenon reflects the dual effect of the digital economy on the ecological environment: on the one hand, the application of digital technologies can enhance resource utilization efficiency and reduce pollutant emissions from traditional industries, thereby contributing to environmental quality improvement. On the other hand, the development of the digital economy may also create new environmental pressures, such as increased electronic waste and the consumption of natural resources by digital infrastructure. Particularly

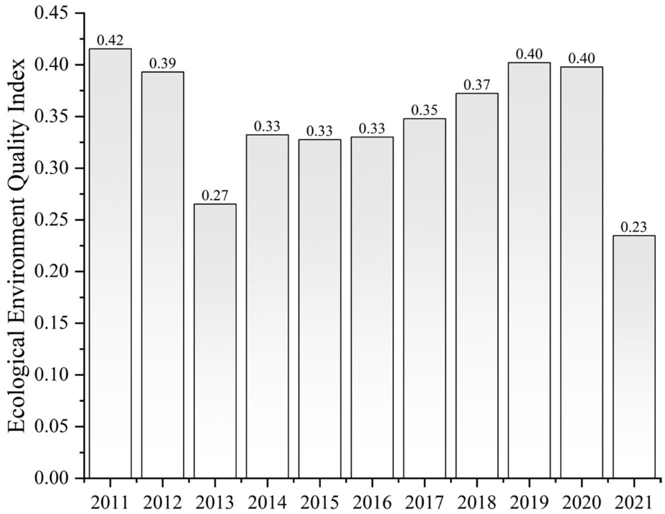

Fig. 2. Changes in the Ecological Environment Quality Index of Sichuan Province from 2011 to 2021.

between 2017 and 2020, the improvement in ecological environment quality paralleled the development of the digital economy, suggesting that Sichuan Province may have leveraged digital technology to promote green economic development, enhance resource efficiency, and reduce pollution emissions. However, the decline in ecological environment quality in 2021 serves as a reminder to be vigilant about the potential environmental impacts of digital economy development. Strengthening the environmental regulation of the digital industry is essential to ensure sustainable development.

As a major economic province in western China, Sichuan faces dual pressures in economic development and environmental protection. The scale and diversity of its economic activities have a substantial impact on the ecological environment. Despite significant progress in environmental protection in recent years, further efforts are required to address new challenges posed by the development of the digital economy. Sichuan Province needs to continue advancing the transition to a green economy at the policy level and achieve coordinated and unified economic development and environmental protection through innovation and technology.

Tapio Model

According to the analysis of the decoupling index, the relationship between the development of the digital economy and ecological environment quality in Sichuan Province from 2011 to 2021 exhibited complex interactions (Table 3). This period can be divided into several stages to reveal the dynamic impact of economic activities on the ecological environment.

During the initial period from 2011 to 2013, although the digital economy index increased, the ecological environment quality index significantly declined, particularly showing a strong negative decoupling in 2013. This stage reflects that, during the initial growth of the digital economy, Sichuan Province was possibly unable to effectively improve ecological conditions due to the environmental pressures brought by accelerated urbanization and industrialization. As time progressed, the years 2014 to 2016 presented characteristics of a transitional stage. Despite some improvement in the ecological environment quality index in 2014, a strong negative decoupling occurred again in 2015, indicating that the environmental benefits of economic growth were not fully realized. The expanded negative decoupling observed in 2016 suggests that, although economic growth accelerated, the impact on the environment was not promptly alleviated.

During the coordinated development stage from 2017 to 2019, the relationship between the digital economy and the ecological environment in Sichuan Province tended toward coordination. This period showed a trend of expansionary coupling and weak decoupling, indicating that the growth of the digital economy and ecological environment protection achieved some degree of synchronization. This progress may have resulted from policy adjustments, strengthened environmental protection measures, and the active promotion of green economic models. Nevertheless, strong negative decoupling reemerged in 2020, possibly due to the impact of the global pandemic, which altered economic activities and placed short-term pressure on the environment due to a focus on economic recovery. By 2021, although weak negative decoupling was observed, the declining trend in ecological environment quality remained a concern. The ongoing negative decoupling relationship from 2012 to 2021 overall reflects the ecological challenges faced by Sichuan Province amid rapid economic development. This indicates that despite significant growth in the digital economy, ecological environment quality has not improved correspondingly.

Table 3. Analysis of the Decoupling Relationship between the Digital Economy Index and Ecological Environment Quality Index of Sichuan Province from 2011 to 2021.

Year	ΔD	ΔE	Decoupling Index	Decoupling Type
2011-2012	-0.008	-0.022	0.376	Weak Negative Decoupling
2012-2013	0.041	-0.128	-0.324	Strong Negative Decoupling
2013-2014	0.002	0.067	0.024	Weak Decoupling
2014-2015	0.005	-0.005	-1.151	Strong Negative Decoupling
2015-2016	0.014	0.003	5.719	Expansive Negative Decoupling
2016-2017	0.019	0.018	1.058	Expansive Coupling
2017-2018	0.013	0.024	0.526	Weak Decoupling
2018-2019	0.002	0.030	0.071	Weak Decoupling
2019-2020	0.015	-0.004	-3.706	Strong Negative Decoupling
2020-2021	-0.006	-0.163	0.040	Strong Negative Decoupling
2011-2021	0.097	-0.181	-0.536	Strong Negative Decoupling

Therefore, this long-term negative decoupling relationship underscores the complex impact of economic activities on the ecological environment during digital economy development, necessitating in-depth research and strategic responses. By deeply understanding these dynamic relationships, future policy formulation and development directions can be better guided to achieve a more balanced and sustainable development of the economy and ecology in Sichuan Province. This analysis provides profound insights and highlights areas for further attention in order to enhance ecological environment quality while maintaining economic growth and achieving sustainable development goals.

Coupling Coordination Model

Based on the analysis of the coupling coordination model and the classification of coordination degrees, we can conduct a more comprehensive and detailed analysis of the interaction between digital economy development and ecological environment quality in Sichuan Province from 2011 to 2021 (Fig. 3). Overall, during this period, Sichuan Province experienced fluctuating development from low coordination to medium coordination and then back to low coordination, reflecting the complex relationship between the digital economy and ecological environment quality.

From 2011 to 2013, although the coupling degree in Sichuan Province remained at a high level, the comprehensive evaluation index and coordination degree were low, falling within the range of low coordination. This indicates that in the early stages of rapid digital economy development, vigorous economic activities exerted significant pressure on the ecological environment, and the ecological environment quality did not improve in tandem. The low degree of coordination during this stage reflects an imbalance between economic and environmental development, likely due to insufficient emphasis on environmental protection and inadequate implementation of related measures. The rapid expansion of the digital economy failed to fully integrate the concept of sustainable development, leading to apparent contradictions between the economy and the environment.

From 2014 to 2016, Sichuan Province gradually recognized the importance of environmental protection and began to implement a series of policies and measures to improve environmental quality. Although the coupling degree remained high during this phase, the coordination degree improved but still stayed within the low coordination range. Economic growth during this period started to pay attention to environmental impacts, yet the effects of policies and measures had not fully manifested. Nonetheless, these efforts laid the foundation for future coordinated development of the economy and the environment.

Starting in 2017, the degree of coordination between the digital economy and ecological environment quality in Sichuan Province improved significantly, entering the medium coordination range. This stage marked substantial progress in promoting synchronized economic and environmental development. The effects of policy implementation gradually became apparent, with strict pollution control and environmental protection regulations strengthening ecological protection. The development of the digital economy spurred technological innovation, improved resource utilization efficiency, and reduced environmental pollution. Additionally, as the economic structure adjusted, the proportion of the tertiary industry and high-tech industries in GDP increased, which are relatively low in resource consumption and environmental impact, contributing to improved ecological environment quality. Meanwhile, with the deepening of environmental protection education and awareness campaigns, public awareness of environmental protection increased, leading to higher participation in environmental protection activities, thus enhancing overall environmental quality.

However, in 2021, despite the coupling degree reaching its theoretical maximum, the coordination degree declined to a low coordination range. This change may reflect short-term environmental pressure from Sichuan Province's rapid economic recovery following the pandemic. During economic recovery, resources may have been more heavily allocated towards economic growth, potentially weakening support for environmental protection to some extent. Moreover, although the overall policy framework is relatively comprehensive, there remain challenges in specific implementation areas, resulting in inadequate environmental protection measures in certain sectors. This decline in coordination degree serves as a reminder that the coordinated development of the economy and environment requires ongoing attention and effort, especially in responding to emergencies and short-term economic pressures, to maintain a strong commitment to ecological environment protection.

Overall, from 2011 to 2020, Sichuan Province made significant progress in the coordinated development of the digital economy and ecological environment quality, especially through the comprehensive effects of policies, technology, industrial structure optimization, and heightened public awareness. However, the data from 2021 also warns that the balance between the economy and the environment needs to be consistently maintained. This analysis reveals the complexity and diversity of the interaction between the digital economy and the ecological environment in Sichuan Province, providing crucial guidance and reference for future development planning.

LMDI Model

The Logarithmic Mean Divisia Index (LMDI) model's decomposition analysis of the coupling relationship between the digital economy and ecological environment quality in Sichuan Province from 2011

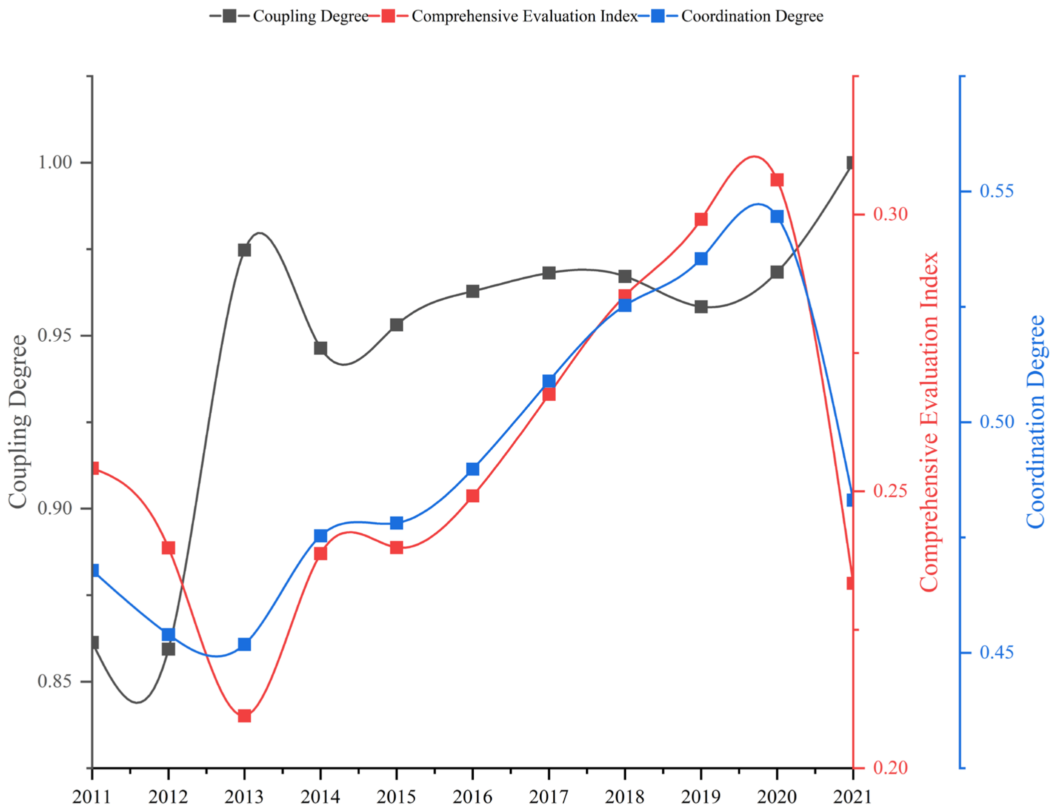

Fig. 3. Coupling Coordination between the Digital Economy and Ecological Environment in Sichuan Province from 2011 to 2021.

to 2021 reveals the complex impacts of the digital economy on ecological environment quality (Fig. 4). Over this decade, Sichuan Province transitioned from the initial development to the rapid growth of the digital economy, which had multi-layered effects on the ecological environment. Overall, from 2011 to 2021, the impact of digital economy development on ecological environment quality exhibited complex dynamic changes. The total contribution of the coupling degree was 0.0355, indicating a certain positive impact of the digital economy in its interaction with the ecological environment, while the contribution of the comprehensive evaluation index was -0.0203, suggesting that the improvement in environmental quality could not fully keep pace with the development of the digital economy. Despite achieving a good balance at certain stages, the overall ecological environment still faced considerable pressure.

Between 2011 and 2012, the digital economy was just beginning, and its positive effects on the environment were not yet apparent. The contribution of the coupling degree was -0.0005, while the contribution of the comprehensive evaluation index was -0.0134. Rapid economic growth may have led to increased resource consumption and pollution, affecting ecological environment quality. From 2012 to 2013, although the contribution of the coupling degree significantly increased to 0.0285, indicating a strengthened positive impetus from economic growth, the contribution of the comprehensive evaluation index was -0.0307, reflecting increased ecological environmental pressure. The increase in economic activities may have resulted in over-exploitation of resources and insufficient policy enforcement, thus failing to alleviate environmental issues effectively.

From 2013 to 2014, the contribution of the coupling degree was -0.0068, while the contribution of the comprehensive evaluation index was 0.0303. This showed the positive impact of policy adjustments on ecological quality, although the coupling relationship between the digital economy and the environment was somewhat weakened. This could be attributed to stricter environmental protection policies adopted by Sichuan Province, which imposed more stringent environmental regulations on economic activities, thereby improving ecological quality. From 2014 to 2017, the contribution of the coupling degree began to show positive values, and the comprehensive evaluation index also showed a positive contribution. During this period, the coordination relationship between the digital economy and the ecological environment in Sichuan Province improved, likely due to the government's strengthened implementation of green economic policies, increased use of renewable energy, and enhanced pollution control measures.

Between 2017 and 2018, although the contribution of the coupling degree slightly decreased to -0.0003, the positive contribution of the comprehensive evaluation index remained significant. At this time, Sichuan Province may have recognized the need to strengthen

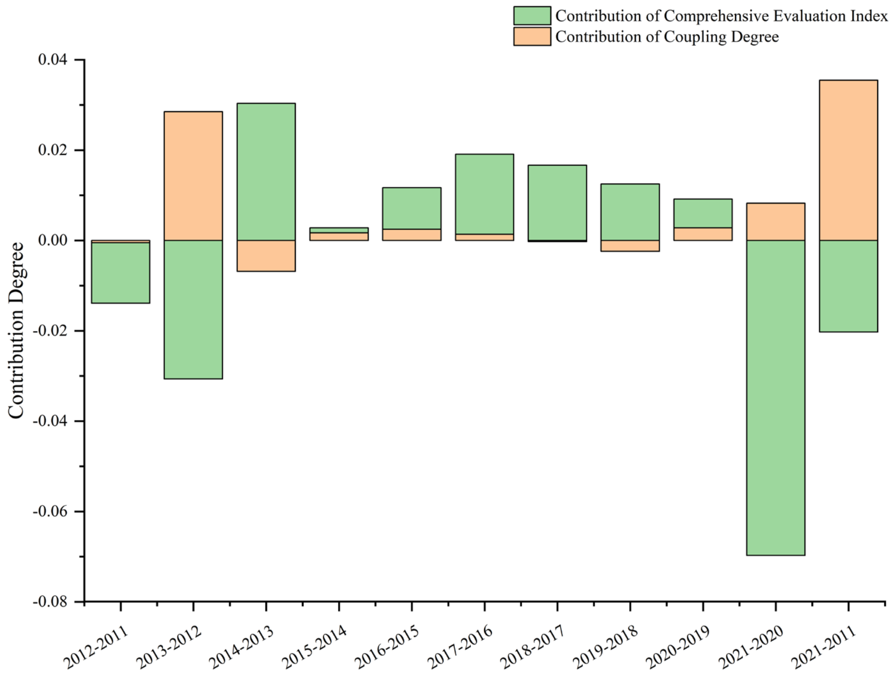

Fig. 4. Decomposition of the Coupling Relationship between the Digital Economy and Ecological Environment Quality in Sichuan Province Based on the LMDI Model.

environmental protection while rapidly developing, ensuring that economic growth and ecological environment improvement occurred in tandem through promoting technological innovation and implementing environmental protection measures. From 2018 to 2020, the contribution of the coupling degree was generally negative, particularly showing a slight rebound to 0.0028 between 2019 and 2020. This may have resulted from Sichuan Province's intensified efforts in environmental protection. Despite fluctuations in the direct coupling relationship between the digital economy and the ecological environment, the comprehensive evaluation index remained positive, indicating an improvement in overall environmental quality. During this stage, Sichuan Province made significant progress in technological innovation, industrial structure optimization, and environmental governance, promoting the enhancement of ecological environment quality.

However, between 2020 and 2021, the contribution of the coupling degree increased to 0.0082, but the contribution of the comprehensive evaluation index sharply declined to -0.0697. Despite the coupling degree indicating a strengthened interaction between the economy and the environment, the negative change in ecological environment quality showed increased environmental pressure during economic recovery. This change might have been caused by the rapid post-pandemic economic recovery, leading to renewed resource consumption and temporarily weakened environmental protection efforts, subsequently affecting environmental quality.

Overall, the relationship between digital economy development and ecological environment quality in Sichuan Province over the past decade presented complex dynamic changes. Although the digital economy has had a generally positive impact on the ecological environment in most years, the pace of environmental improvement cannot consistently keep up with the development of the digital economy. In the early stages, the ecological environment quality faced significant pressure due to insufficient attention to environmental protection. Over time, Sichuan Province gradually increased its focus on environmental protection, promoting green economic development through a series of policies, which to some extent improved the coordination relationship between the digital economy and the ecological environment. However, the changes from 2020 to 2021 also remind us of the need to continually focus on ecological environment protection alongside economic development, especially when addressing emergencies and short-term economic fluctuations, to maintain a long-term commitment to environmental protection. Future development needs to achieve a better balance between economic growth and ecological protection to realize sustainable development goals. This analysis reveals the complexity and diversity of the interaction between the digital economy and the ecological environment in Sichuan Province, providing important guidance and reference for future development planning.

Policy Recommendations

To promote the coordinated development of the digital economy and ecological environment in Sichuan Province, detailed policy recommendations can be formulated based on previous analysis results to ensure a win-win situation for economic growth and environmental protection. In terms of the deep integration of the digital economy and ecological environment, building green digital infrastructure is key [49]. Sichuan Province should accelerate the green upgrade of data centers and communication networks, adopt more efficient cooling technologies and energy management systems, and encourage the use of renewable energy sources to reduce carbon emissions [50, 51]. Furthermore, developing smart environmental protection systems is essential. By leveraging IoT and big data technologies [52], an intelligent environmental monitoring system can be constructed to enable real-time monitoring and early warning of air quality, water quality, and soil conditions. This system will optimize environmental management decisions through data analysis, enhancing the efficiency and effectiveness of environmental governance. Promoting the application of digital technology in environmental protection, such as energy conservation, emission reduction, and pollution control, as well as supporting green technology innovation in areas like smart manufacturing, green logistics, and smart agriculture, is also of utmost importance [53].

To achieve synergy between economic and environmental policies, Sichuan Province should consider ecological benefits in economic activities and promote the development of green GDP. This can be accomplished by incorporating environmental performance into the economic policy assessment system, incentivizing enterprises to adopt green production technologies, and providing tax benefits and subsidies [54]. Additionally, establishing an ecological compensation system to address ecological damage caused by economic activities is crucial. Promoting green finance, expanding green financial products and services, and encouraging banks and investment institutions to support environmental projects and the development of green enterprises with preferential loans and financing support are also essential for fostering coordinated economic and environmental development [55].

Optimizing and upgrading industrial structures is an important means of reducing environmental pressure and promoting the coordinated development of the economy and environment [56]. Sichuan Province should expedite the digital transformation of traditional industries, supporting traditional manufacturing industries in introducing digital technologies to optimize production processes, improve resource utilization efficiency, and reduce waste emissions, ultimately advancing towards low-carbon and environmentally friendly development. Concurrently, the province should actively support the development of green industries such as environmental protection technology, renewable energy, and energy-saving services, increasing their share in the economic structure and enhancing the overall green competitiveness of the economy. Building a green supply chain management system, promoting green standards and management practices across all supply chain links, and encouraging enterprises to achieve green transformation in production, procurement, logistics, and recycling processes to reduce the carbon footprint of supply chains will also positively impact industrial structure optimization [57].

High-quality talent and technological innovation are core drivers for the coordinated development of the digital economy and ecological environment [58]. Sichuan Province needs to strengthen the cultivation of green technology talent by collaborating with universities and research institutions to establish interdisciplinary fields and programs, enhancing the training of talent in green technology and digital technology, and providing scholarships and research funding. Supporting green technology innovation, encouraging enterprises and research institutions to conduct research and development in areas like energy conservation, emission reduction, and efficient resource utilization, and promoting the industrial application of green technology achievements are crucial. Building technology innovation cooperation platforms to facilitate technology exchange and cooperation and accelerate the conversion and application of technological achievements will enhance Sichuan Province's technological innovation capabilities.

Public environmental awareness and participation are vital for achieving environmental protection goals. Sichuan Province should strengthen environmental education and promotion through schools, communities, and media to increase public awareness of environmental protection and enhance social responsibility for environmental conservation. Encouraging public participation in environmental protection actions, organizing environmental volunteer activities, and community environment improvement projects can motivate public engagement and create a favorable atmosphere for society-wide environmental protection efforts. Advocating for green consumption and lifestyles, guiding the public to choose environmentally friendly products and services, and promoting the formation of a green consumption culture are also important pathways for advancing environmental protection.

International cooperation can bring in advanced experiences and technologies, elevating the local digital economy and ecological environment protection levels. Sichuan Province should actively participate in international green development cooperation, strengthen partnerships with other countries and regions in areas like green technology and environmental protection policies, and actively participate in international environmental organizations and conferences to learn from successful global experiences. Introducing advanced international green technologies and applying globally leading green technology and management experiences will enhance local technological levels and management capabilities, boosting the green competitiveness of local enterprises in international markets. Additionally, establishing international exchange platforms to facilitate the sharing and cooperation of global environmental protection technologies, policies, and experiences will enhance Sichuan Province's influence in international green development.

Lastly, efficient environmental monitoring and management are essential guarantees for improving environmental quality. Sichuan Province needs to refine its environmental monitoring network, expanding and optimizing it to enhance the accuracy and timeliness of monitoring data, providing scientific evidence for environmental governance. Implementing dynamic environmental management by introducing adaptive management mechanisms to adjust strategies and measures based on environmental changes will ensure the effectiveness and adaptability of environmental policies. Moreover, strengthening the management of ecological protection areas, improving the management of nature reserves and ecologically sensitive areas, and reinforcing ecological protection and biodiversity conservation to prevent ecological degradation and resource over-exploitation are vital. Through these comprehensive measures, Sichuan Province can effectively promote the coordinated development of the digital economy and ecological environment, achieving a win-win situation for economic growth and environmental protection. These policy recommendations not only help enhance Sichuan Province's green competitiveness but also provide residents with a more livable environment, laying a solid foundation for Sichuan Province's sustainable development.

Limitations and Future Directions

This study provides a systematic and in-depth analysis of the relationship between digital economy development and ecological environment quality in Sichuan Province. However, it is not without limitations. The research is confined to Sichuan Province, which, although representative in some aspects, does not encompass the diverse conditions and development stages of other regions in China or globally. Future research could expand the geographical scope to include comparative studies across multiple regions to uncover broader patterns and regional differences in the relationship between the digital economy and ecological sustainability. Additionally, the study primarily relies on statistical data from 2011 to 2021, which, while reliable for analyzing overall trends, may lack the granularity needed to capture more subtle changes. Incorporating high-resolution data sources, such as satellite imagery and real-time digital economic activity data, could provide more detailed insights into future studies.

From a methodological perspective, although this study employs a multi-method approach, including the entropy weight method, Tapio decoupling model, coupling coordination model, and LMDI model, each method has its limitations. For instance, the Tapio decoupling model may not fully capture the non-linear relationships between variables, and the LMDI model is sensitive to the choice of the base year, which could affect the robustness of the results. Future research could explore the use of more advanced econometric and machine learning techniques, such as structural equation modeling or deep learning, to better capture complex interactions and causal relationships. Moreover, this study does not adequately account for the impact of external factors such as policy changes, global economic fluctuations, or natural disasters (e.g., the COVID-19 pandemic) on the relationship between the digital economy and the ecological environment. Future research could incorporate these external variables through scenario analysis or sensitivity testing to better understand their potential influence on the study's outcomes.

Furthermore, this study treats the digital economy as a homogeneous entity without differentiating between various sectors such as e-commerce, digital finance, and smart cities, each of which may have distinct environmental impacts. Future research could conduct a more granular analysis of different digital economy sectors to identify the specific mechanisms through which they affect the ecological environment, thereby providing more targeted policy recommendations. Lastly, although this study analyzes the coupling relationship between the digital economy and the ecological environment from 2011 to 2021, it does not explore the long-term sustainability of these observed trends. Future research could use predictive modeling and scenario analysis to evaluate the sustainable development paths of digital economy growth and ecological quality over a longer time horizon, such as the next 20 or 30 years, considering potential technological advancements and policy changes.

By addressing these limitations in future research, scholars and policymakers can gain a more comprehensive understanding of how digital economy development can be harmonized with ecological sustainability, not only in Sichuan Province but also in other regions facing similar challenges and opportunities.

Conclusions

Over the past decade, Sichuan Province has made significant progress in the coordinated development of the digital economy and ecological environment, yet it has also faced challenges. Analyzing the coupling relationship from 2011 to 2021, we found that the digital economy has positively driven economic growth in Sichuan Province while exerting some pressure on the ecological environment. The rapid development of the digital economy, particularly in its early stages, was accompanied by increased resource consumption and environmental pollution risks. However, through effective policy guidance and technological innovation, Sichuan Province has achieved important breakthroughs in promoting the coordinated development of the digital economy and the ecological environment. Especially in the later stages, the implementation of green economic policies, adjustments in industrial structure, and increased public environmental awareness have provided strong support for achieving a win-win situation between the economy and the environment.

The analysis of the coupling coordination model and the LMDI model reveals dynamic changes in Sichuan Province's digital economy development and ecological environment protection. The initial low coordination degree reminds us of the importance of environmental protection amidst rapid economic development, while the improvements in later stages demonstrate the effectiveness of policy implementation and technological advancement in driving synchronized economic and environmental development. Nonetheless, the changes observed between 2020 and 2021 remind us once again that ecological environment protection requires continuous attention and strengthening, especially when responding to emergencies and short-term economic pressures.

In summary, the experience of Sichuan Province shows that the coordinated development of the digital economy and ecological environment is not achieved overnight but requires long-term strategic planning and meticulous policy execution. To achieve sustainable, coordinated development of the digital economy and ecological environment, Sichuan Province needs to continue to deepen green technology innovation, optimize the industrial structure, strengthen policy coordination, and enhance public participation. This not only helps to elevate Sichuan Province's influence in green development nationally and globally but also provides valuable insights for other regions. Looking ahead, Sichuan Province should build on past experiences to continuously explore new paths, promote comprehensive coordination and sustainable development of the economy and environment, ensure economic growth while achieving sustained improvements in ecological environment quality, and provide residents with a healthier and more livable living environment.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. GE L., ZHAO H., LIU J., HE T., ZHANG X., LIU Y. Towards Green Production: How Big a Role Does Digital Economic Contribution Play in China? Polish Journal of Environmental Studies. **33** (5), 5677, **2024**.
2. KUBÍKOVÁ U., RUD S. Identification of Slovak Tourists' Attitudes Towards Digitalization for Circular Economy and Waste Management. Proceedings of the International Conference on Business Excellence. **18** (1), 856, **2024**.
3. LI X., WANG L., WANG L. The Coupling Coordination Evaluation and Influencing Factors Analysis of the Development of China's Digital Economy and the Construction of an Ecological Civilization. Polish Journal of Environmental Studies. **33** (4), 3747, **2024**.
4. LIANG S., TAN Q. Can the digital economy accelerates China's export technology upgrading? Based on the perspective of export technology complexity. Technological Forecasting and Social Change. **199**, 123052, **2024**.
5. HOAGLAND I. At G20, leaders focus on WTO reform, digital economy issues. Inside U.S. Trade. (27), 37, **2019**.
6. Chinese Academy of Cyberspace Studies. Development of the World's Digital Economy. In: Chinese Academy of Cyberspace Studies (eds) World Internet Development Report 2017. Springer, Berlin, Heidelberg. **2018**.
7. YASMEEN R., TIAN T., YAN H., SHAH W.U.H. A simultaneous impact of digital economy, environment technology, business activity on environment and economic growth in G7: Moderating role of institutions. Heliyon. **10** (12), e32932, **2024**.
8. ZHANG D., BAI D., WANG C., HE Y. Distribution dynamics and quantile dynamic convergence of the digital economy: Prefecture-level evidence in China. International Review of Financial Analysis. **95**, 103345, **2024**.
9. ZHAO Y., SONG Z., CHEN J., DAI W. The mediating effect of urbanisation on digital technology policy and economic development: Evidence from China. Journal of Innovation & Knowledge. **8** (1), 100318, **2023**.
10. BRANDT L., LIM K. Opening up in the 21st century: A quantitative accounting of Chinese export growth. Journal of International Economics. **150**, 103895, **2024**.
11. CHEN Y., ZHU X., ZENG A. Decoupling analysis between economic growth and aluminum cycle: From the perspective of aluminum use and carbon emissions. Journal of Environmental Management. **344**, 118461, **2023**.
12. XIE Y., LIU H. Coupling Coordinated Analysis of Digital Village Construction, Economic Growth and Environmental Protection in Rural China. Polish Journal of Environmental Studies. **33** (5), 5925, **2024**.
13. HAN X., FU L., LV C., PENG J. Measurement and spatio-temporal heterogeneity analysis of the coupling coordinated development among the digital economy, technological innovation and ecological environment. Ecological Indicators. **151**, 110325, **2023**.
14. LI H., ZHANG Y., LI Y. The impact of the digital economy on the total factor productivity of manufacturing firms: Empirical evidence from China. Technological Forecasting and Social Change. **207**, 123604, **2024**.
15. YAN Z., CHENG-LING D. The Expansion of the Application Fields of Modern Hi-Tech–The Application Prospects of "Digital Glob"Technology in the Economic Development of Sichuan Province. Resource Development

& Market. **2002**.
16. JIANG P., YANG Y., YE W., LIU L., GU X., CHEN H., ZHANG Y., MA M.C. Study on the Efficiency, Evolutionary Trend, and Influencing Factors of Rural–Urban Integration Development in Sichuan and Chongqing Regions under the Background of Dual Carbon. Land. **13** (5), 696, **2024**.
17. LI W., CUI W., YI P. Digital economy evaluation, regional differences and spatio-temporal evolution: Case study of Yangtze River economic belt in China. Sustainable Cities and Society. **113**, 105685, **2024**.
18. FENG C., LIU Y.Q., YANG J. Do energy trade patterns affect renewable energy development? The threshold role of digital economy and economic freedom. Technological Forecasting & Social Change. **203**, **2024**.
19. ZHAO C., DONG K., LIU Z., MA X. Is digital economy an answer to energy trilemma eradication? The case of China. Journal of Environmental Management. **349** (2), 119369, **2024**.
20. ZAGOROVSKIY M.A., SHABAROV A.B., STEPANOV S.V. Cluster Capillary Core Model for the Calculation of the Relative Phase Permeability for Oil and Water Filtration. Mathematical Models and Computer Simulations. **16** (3), 383, **2024**.
21. DAI D., FAN Y., XIE Z.J. The Empirical Effectiveness of China Digital Economy Enhancing Environmental Governance. Polish Journal of Environmental Studies. **32** (6 Pt.1), 4995, **2023**.
22. HU J., ZHAO X., WU D., WU W. Digital economy and environmental governance performance: empirical evidence from 275 cities in China. Environmental Science and Pollution Research International. **30** (10), 26012, **2022**.
23. WANG G., ZHANG G., GUO X., ZHANG Y. Digital twin-driven service model and optimal allocation of manufacturing resources in shared manufacturing. Journal of Manufacturing Systems. **59**, 165, **2021**.
24. QAHAR A. Energy Efficient Resource Allocation and Utilization in Future Heterogeneous Cellular Network. Computing Technology Towards a Sustainable Society. 9 (3-11), **2017**.
25. XIN L.I., DE-MING D., WAN-BIN S., HUI-ZHE Q. Fundamental Issues for the Green-National-Economic Accounting. Scientia Geographica Sinica. **27** (2), 163, **2007**.
26. SASS T.R., SEMYKINA A., HARRIS D.N. Value-added models and the measurement of teacher productivity. Economics of Education Review. **38**, 9, **2014**.
27. QIANG X. International Comparison of CPI Compilation in OECD Countries and Its Reference. Statistical Research. **2013**.
28. MUSTAFIN M.G., SON T. Method for determining the normal heights from satellite data, taking into account the deviations of the plumb lines. Geodesy and Cartography. **937** (7), 2, **2018**.
29. CUNHA-ZERI G., GUIDOLINI J.F., BRANCO E.A., OMETTO J.P. How sustainable is the nitrogen management in Brazil? A sustainability assessment using the Entropy Weight Method. Journal of Environmental Management. **316**, 115330, **2022**.
30. GAO Y., QIN R., JIN G., ZHANG R., CHEN S., XU Y. Comprehensive evaluation of Chinese baijiu solid-state distillation operating conditions effect on aroma compounds distillation based on entropy weight-TOPSIS analysis. Food Bioscience. **58**, 103705, **2024**.
31. WANG Q., SU M. The effects of urbanization and industrialization on decoupling economic growth from carbon emission – A case study of China. Sustainable Cities and Society. **51**, 101758, **2019**.
32. ZHA J., DAI J., MA S., CHEN Y., WANG X. How to decouple tourism growth from carbon emissions? A case study of Chengdu, China. Tourism Management Perspectives. **39**, 100849, **2021**.
33. LIU T., YANG T. Study on Carbon Emission and Its Influencing Factors in China's Tourism Industry. Polish Journal of Environmental Studies. **33** (6), 6259, **2024**.
34. ZHANG T., ZHANG C., WANG Q., YANG C., ZHANG J., ZHANG C., ZHANG Q., LI M.E. Research on Sustainable Land Use in Alpine Meadow Region Based on Coupled Coordination Degree Model—From Production–Living–Ecology Perspective. Sustainability. **16** (12), 5213, **2024**.
35. LI J., DING J. Analysis of Spatiotemporal Changes, Influencing Factors, and Coupling Coordination Degree of Urban Human Settlements Efficiency: A Case Study of Megacities and Supercities in China. Journal of Urban Planning and Development. **150** (1), 11, **2024**.
36. JING H. Environmental Pollution and Industrial Structure:An Analysis Based on Divisia Index Decomposition Method. Statistical Research. **2009**.
37. HUANG Y., WANG Y., PENG J., LI F., ZHU L., ZHAO H., SHI R. Can China achieve its 2030 and 2060 CO2 commitments? Scenario analysis based on the integration of LEAP model with LMDI decomposition. Science of The Total Environment. **888**, 164151, **2023**.
38. INSHAKOVA A. Law as the Basis of Infrastructure Support of the Digital Economy and Technology of the Internet of Things. Legal Concept. **2019**.
39. CHE C.V. Analyzing the Legal and Ethical Implications of Digital Technologies on Businesses in Cameroon as a Developing Country. Open Access Library Journal. **11** (6), 18, **2024**.
40. TANOMVORSIN V., SAN-UM W. A Holistic Architecture of Internet of AI-Centric as a Conceptual Framework for Supporting Thailand Digital Economy. International Journal of Future Computer and Communication. **7** (4), 91, **2018**.
41. LZROIU G. Digital Pedagogies, Educational Big Data, and Smart Learning Analytics in the Intelligent Economy. Encyclopedia of Educational Innovation. **2020**.
42. ANSONG E., TURKSON C. COVID-19 Pandemic and the Small- and Medium-Sized Enterprise: Digital Strategies for Surviving in a Developing Economy. In book: Digital Innovations, Business and Society in Africa. Advances in Theory and Practice of Emerging Markets, 1st Edition, pp.215-227, Springer Publisher, **2022**.
43. GEORGIEVSKY A.B. Creating Ecosystem Value Proposition Based On Selling Solutions in the Post-Covid-19 Digital Economy. Proceedings of �never The 3rd International Conference on Business, Management and Finance. **2021**.
44. SHAH W.U.H., HAO G., YASMEEN R., YAN H., QI Y. Impact of agricultural technological innovation on total-factor agricultural water usage efficiency: Evidence from 31 Chinese Provinces. Agricultural Water Management. 299, **2024**.
45. LARSSON A., TEIGLAND R. The Digital Transformation of Labor: Automation, the Gig Economy and Welfare. Macroeconomics: Employment, Routledge, **2019**.
46. URBABLIFE A. The smart solution for cities Transforming power-hungry urban areas into low-carbon smart cities via the creative use of technologies. www.Arup.com/urbanlife. Arupsurban, 1–28, **2011**.

47. YANG P., LV Y., CHEN X., LV J., EGGERT R.G. Digital finance, natural resource constraints and firms' low-carbon behavior: Evidence from listed companies. Resources Policy. **89**, **2024**.
48. CHEN Y., JI X., ZHAO G. Does digital infrastructure construction impact urban carbon emission reduction? Evidence from China's smart city construction. Environmental Science and Pollution Research. **31** (27), 39481, **2024**.
49. YU J., CHEN F., GUAN K., ZHANG Y. Building mutual trust in collaborative green NPD: Evidence from China's digital infrastructure. Industrial Marketing Management. **97**, 245, **2021**.
50. KHASHAN O.A. Aligning security and energy-efficiency using change detection and partial encryption for wireless camera networks. Engineering Science and Technology, an International Journal. **53**, **2024**.
51. KHAN W.U., JAMSHED M.A., LAGUNAS E., CHATZINOTAS S., LI X., OTTERSTEN B. Energy Efficiency Optimization for Backscatter Enhanced NOMA Cooperative V2X Communications Under Imperfect CSI. IEEE Transactions on Intelligent Transportation Systems. **11**, 24, **2023**.
52. CASTRO L.G. Leveraging Big Data and AI technologies to improve cancer survivors follow-up decision-making (PERSIST project). International Journal of Integrated Care. **22**, **2022**.
53. MAHALAKSHMI J., KUPPUSAMY K., KALEESWARI C., MAHESWARI P. IoT Sensor-Based Smart Agricultural System. In book: Emerging Technologies for Agriculture and Environment , pp.39, Springer Nature Singapore, **2020**.
54. ZOU Q., ZHANG Z., YI X., YIN C. The direction of promoting smallholders' adoption of agricultural green production technologies in China. Journal of Cleaner Production. **415** (117), 137734, **2023**.
55. PEREZ O. The New Universe of Green Finance: From Self-Regulation to Multi-Polar Governance. Social Science Electronic Publishing. **2007**.
56. TRZCIŃSKI M., UKASIK S., GANDOMI A.H. Optimizing the Structures of Transformer Neural Networks Using Parallel Simulated Annealing. Journal of Artificial Intelligence and Soft Computing Research. **14** (3), 267, **2024**.
57. DAS G., LI S., TUNIO R.A., JAMALI R., ULLAH I., FERNANDO K.W.T.M. The implementation of green supply chain management (GSCM) and environmental management system (EMS) practices and its impact on market competitiveness during COVID-19. Environmental Science and Pollution Research International. **30**, 68387 **2023**.
58. WAN X., WANG Y., ZHANG W. The spatial and temporal situation of China's digital technology innovation and its influencing factors. PLoS One. **19** (1), **2024**.