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Configurational Pathways Linking Digital Economy Development to Regional Comprehensive Environmental Pollution in China: A Multi-Period Fuzzy-Set Qualitative Comparative Analysis

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Abstract: Against the backdrop of increasingly severe regional environmental pollution and the nationwide promotion of environmental governance, the digital economy has become an important factor associated with regional environmental pollution and green sustainable development. However, the impact of the digital economy on regional environmental pollution presents complex and non-linear characteristics, and traditional net-effect regression analysis cannot identify multiple pathways formed by the synergistic combination of various digital factors. This study aims to identify multiple configurational patterns through which digital economy conditions are associated with high or low levels of regional comprehensive environmental pollution, so as to provide a theoretical basis and practical reference for differentiated regional environmental governance. Taking 30 provincial-level regions in China from 2022 to 2024 as research samples, this paper constructs an analytical framework covering digital infrastructure, digital industry development, and digital innovation input, and adopts a multi-period configurational analysis based on fuzzy-set qualitative comparative analysis (fsQCA) to explore the configurational paths linking digital economy conditions to regional comprehensive environmental pollution. The results identify five paths leading to high regional comprehensive environmental pollution and two paths leading to low regional comprehensive environmental pollution in the pooled analysis. The annual analyses identify six configurations in 2022 and three configurations in both 2023 and 2024, revealing both continuity and changes in the configurational pathways over time. A low level of broadband access is frequently present in high-pollution configurations, while combinations involving e-commerce activity, innovation expenditure, and research and development (R&D) personnel recur across the three years. These findings indicate that digital development does not inherently produce pollution-abatement effects; rather, its environmental implications are jointly determined by the presence and absence of multiple conditions. The research shows that the relationship between the digital economy and regional comprehensive environmental pollution exhibits clear equifinality, causal asymmetry, and configurational complexity, which means that regions should formulate differentiated digital-development and environmental-governance strategies according to their specific development conditions. This paper provides a new configurational perspective for understanding the complex environmental implications of the digital economy and supplies empirical evidence for optimizing regional digital economy policies and environmental governance practices.

Keywords: Digital economy; Regional comprehensive environmental pollution; Configurational analysis; Multi-period fsQCA; Regional environmental governance

1 Introduction

Against the backdrop of increasingly prominent regional environmental pollution pressures and accelerated green governance transformation, environmental pollution control has become a core task of regional sustainable development. In response to mounting environmental challenges, China has continuously introduced stringent environmental pollution-control policies to restrict wastewater discharge, sulfur dioxide emissions, and industrial solid-waste generation., and has imposed higher requirements for industrial structure transformation, energy efficiency improvement and resource allocation optimization [1, 2]. In this context, the digital economy, as a new economic form supported by digital technology, data elements and information networks, provides new support for regional environmental governance and green transformation through technological innovation, resource allocation optimization and industrial upgrading [3].

The impact of the digital economy on regional environmental pollution is complex rather than unidirectional. On the one hand, digital infrastructure construction, digital industry development, and digital innovation input can reduce environmental pollution by improving production efficiency, optimizing energy utilization, and promoting the diffusion of clean and green technologies. On the other hand, the operation of data centers, the expansion of the platform economy, and the rapid growth of consumption-side digitalization may create additional energy demand and environmental pressure, forming a typical digitalization–environment paradox [4, 5]. Therefore, whether the digital economy can effectively reduce regional environmental pollution depends on the synergistic matching among different digital factors and the specific development conditions of each region. Existing studies have extensively examined the pollution-control mechanisms of the digital economy from the perspectives of energy efficiency, industrial structure, and technological spillovers, but most studies focus on the independent net effect of a single variable, which cannot fully reveal the multi-condition linkage, path diversity, and asymmetric causality of the digital economy as a complex system.

On this basis, this paper selects 30 provincial-level regions in China over the period 2022–2024 as research objects and constructs an analytical framework based on "digital infrastructure–digital industry development–digital innovation input." A multi-period configurational analysis based on fuzzy-set qualitative comparative analysis (fsQCA) is adopted to identify the multiple configurational pathways associated with high and low levels of regional comprehensive environmental pollution and to examine their temporal evolution. Specifically, this study addresses two questions: which combinations of digital economy conditions are associated with high and low regional comprehensive environmental pollution, and how do these configurations evolve across different years? This study extends existing research from the examination of individual net effects to the analysis of cross-dimensional configurational relationships, enriches the understanding of the environmental implications of the digital economy, and provides an empirical basis for differentiated regional digital-development and environmental-governance strategies.

2 Literature Review

2.1 Environmental Effects of the Digital Economy

The understanding of the digital economy concept in existing research has undergone a progressive expansion, from the technological level to the economic system level, and from static conceptualization to dynamic evolutionary processes. Early investigations were primarily focused on digital technologies themselves and their industrial applications. Tapscott [6] was among the first to systematically articulate the concept of the "digital economy," which was defined as a new economic form driven by information and communication technologies as the core driving force. As the depth of integration between digital technologies and the real economy continued to increase, the research perspective on the digital economy gradually extended from single technological applications to broader domains, including industrial transformation, resource allocation, and governance capacity. Xin et al. [7] further conceptualized the digital economy as an economic system in which data function as a central production resource, digital networks provide the essential infrastructure, and the integration of information and communication technologies supports broader economic and industrial transformation. This definition captures the key features of the digital economy in terms of production inputs, technological infrastructure, and industrial integration, and provides a representative operational basis for related research.

A large number of empirical studies have examined how the digital economy influences regional environmental quality, with many reporting its potential to reduce pollution [8–11]. Digital technology can improve enterprise production efficiency, optimize resource utilization, and reduce pollutant generation. Zhang and Ran [12] found that digital economy development significantly reduced industrial dust, industrial sulfur dioxide, and carbon dioxide emissions in Chinese cities. Zhao et al. [13] further showed that the digital economy could promote the synergistic reduction of $PM_{2.5}$ and carbon emissions, although these effects exhibited regional heterogeneity. However, some studies have also found that digital industry expansion may create new environmental pressures [5, 14, 15]. From a broader perspective, Sibt-e-Ali et al. [16] showed that digitalization, financial technology, governance quality, and climate-related policy commitments jointly influence environmental conservation in emerging economies. The environmental effect of the digital economy is realized through multiple intermediary mechanisms, such as technological innovation, industrial structure adjustment, and the green transformation of supply chains [17–19]. Technological innovation is an important channel through which digitalization may reduce pollution, as digital technology can reduce the research and development (R&D) costs associated with green technology and accelerate the diffusion of clean production equipment. At the same time, the pollution-abatement effect of the digital economy exhibits obvious spatial and regional heterogeneity. Du et al. [20] identified a U-shaped relationship between digital economy development and carbon-emission efficiency across China's major urban agglomerations, highlighting the nonlinear and regionally heterogeneous environmental effects of digitalization. Ding and Luo [21] used a spatial Durbin model and found that digital development can not only reduce local pollution but also produce positive spillover effects in neighboring regions through technology diffusion.

In general, prior research has generated substantial evidence on the environmental implications of the digital economy. Nevertheless, its emphasis on the average net effects of individual digital factors offers limited insight into why similar levels of digital development may be associated with contrasting pollution outcomes across regions. A configurational perspective is therefore needed to examine how different combinations of digital conditions correspond to regional environmental pollution.

2.2 Configurational Effects of the Digital Economy on Regional Environmental Pollution

For complex environmental problems driven by multiple interacting factors, such as digital transformation and environmental pollution control, configurational analysis can better explain differences in outcomes under different combinations of conditions. Different from traditional regression analysis, which focuses on the net effects of independent variables, QCA methods emphasize multi-factor synergy, causal asymmetry, and equifinality, making them suitable for analyzing the phenomenon of "different paths leading to the same pollution level" in regional environmental governance.

In the field of digital economy and environmental governance research, some scholars have begun to adopt configurational approaches to examine how combinations of multiple conditions shape green development outcomes. Li et al. [22] analyzed the spatiotemporal configuration paths underlying the coordinated development of the digital economy and green logistics. Xu [23] further showed that regional green innovation performance may result from different combinations of formal and informal institutional conditions. These studies suggest that green development outcomes are shaped by the joint effects of multiple interdependent conditions rather than by any single factor [22, 23]. Using dynamic fsQCA, Li et al. [24] identified the evolving configuration pathways associated with carbon-emission reduction in energy-intensive industries, demonstrating the value of a multi-period configurational approach for capturing temporal changes in complex environmental mechanisms.

In regional environmental governance, the pollution level of a region may be jointly influenced by digital infrastructure, industrial digitalization, innovation input, energy efficiency, and the policy environment. Ignoring the synergistic relationships among these factors may lead to a biased explanation of regional differences in pollution levels. FsQCA breaks through the limitations of single-variable causal inference, identifies multiple equivalent paths leading to high or low pollution, and reveals asymmetric configurational relationships [25, 26]. On this basis, this paper adopts a multi-period fsQCA approach, drawing on previous dynamic configurational applications [22, 24], and constructs an analytical framework for examining how combinations of digital economy conditions are associated with regional comprehensive environmental pollution. Compared with the existing literature, this paper not only discusses whether the digital economy is associated with lower environmental pollution, but also focuses on the combination patterns of digital elements in regional environmental governance and their temporal evolution, thereby supplementing theoretical research on digital environmental governance from a configurational perspective.

3 Research Design

3.1 Data Collection and Indicator Construction

Thirty provincial-level regions in China, excluding Tibet, Hong Kong, Macao, and Taiwan, were selected for the analysis, covering the period from 2022 to 2024. The outcome variable was defined as the level of regional comprehensive environmental pollution. Following Liu and Lin [27], the entropy-weight method was used to construct a composite pollution index based on wastewater discharge, sulfur dioxide emissions, and industrial solid-waste generation, thereby reducing the potential for subjective weighting bias. The condition variables represent digital economy development and cover three dimensions: digital infrastructure, digital industry development and digital innovation input, following Zhao et al. [28]. Original data were collected from China Statistical Yearbook [29], China Statistical Yearbook on Environment [30], China Science and Technology Statistics Yearbook [31] and Economy Prediction System database [32]. Specific indicators are shown in Table 1.

3.2 Variable Measurement and Calibration

Before the necessity and sufficiency analyses were performed, all condition variables and the outcome variable underwent calibration. Drawing on existing studies and considering the case context and data distribution, the direct calibration method was applied to all condition variables and the outcome variable [25]. The calibration anchors were set at the 95th, 50th, and 25th percentiles, corresponding to full membership, the crossover point, and full non-membership, respectively [33]. To prevent cases whose calibrated membership scores were exactly equal to 0.5 from being excluded from the truth-table analysis, a small constant of 0.001 was added only to those calibrated membership scores; the original raw data remained unchanged [24]. The variable descriptions and calibration anchors are presented in Table 2.

Table 1. Indicator system for digital economy development and regional comprehensive environmental pollution level

Primary Indicator	Secondary Indicator	Indicator Content
Digital economy	Digital infrastructure	Length of long-distance fiber optic cable lines (km)
		Number of internet broadband access ports per 10,000 persons
	Digital industry development	E-commerce sales revenue
		Software business revenue (10,000 CNY)
	Digital innovation input	Science and technology innovation investment (10,000 CNY)
		Full-time equivalent of R&D personnel in industrial enterprises above designated size
Regional environmental pollution level	Comprehensive environmental pollution index	Total wastewater discharge (10,000 tons)
		Sulfur dioxide emissions in waste gas (10,000 tons)
		Generation of general industrial solid waste (10,000 tons)

Note: CNY = Chinese Yuan; R&D = research and development.

Table 2. Calibration anchors for the outcome and condition variables

Variable	Code	Description	Calibration		
			Full Membership	Crossover Point	Full Non-Membership
Outcome variable	Y	Comprehensive environmental pollution level	20.704	11.921	2.276
Condition variables	X1	Length of long-distance fiber optic cable lines	14.039	10.298	6.883
	X2	Number of internet broadband access ports per 10,000 persons	25.209	21.414	15.462
	X3	E-commerce sales revenue	34.214	28.791	20.435
	X4	Software business revenue	48.927	38.476	33.358
	X5	Science and technology innovation investment	59.530	51.278	40.132
	X6	Full-time equivalent of research and development (R&D) personnel in industrial enterprises above designated size	69.463	58.202	46.181

To improve methodological transparency, the detailed implementation of the multi-period fsQCA was specified as follows:

1. **Case unit and sample size:** The unit of analysis was the province–year observation. The study used a balanced panel covering 30 provinces from 2022 to 2024, yielding a total of 90 observation cases.
2. **Pooled and annual analyses:** A two-stage analytical design was adopted. First, a pooled full-sample fsQCA was conducted using all 90 province–year observations to identify general and relatively stable configurational pathways. Second, separate fsQCA analyses were conducted for 2022, 2023, and 2024 to examine the intertemporal evolution of the configurations.
3. **Unified cross-year calibration:** The raw observations from all three years were pooled to determine common calibration anchors at the 25th, 50th, and 95th percentiles. The same anchors were then applied to both the pooled and annual analyses, thereby ensuring cross-year comparability and reducing inconsistencies arising from separate year-specific calibration.
4. **Assessment of configurational stability:** The configuration results for 2022, 2023, and 2024 were compared to identify persistent, newly emerging, and disappearing pathways. This comparison was used to assess the temporal evolution of the configurational pathways through which digital economy conditions were associated with regional environmental pollution.

4 Data Analysis and Empirical Results

4.1 Necessary Conditions Analysis

Following Fiss et al. [26], necessity analysis was performed to determine whether the presence or absence of any individual condition was required for high or low regional comprehensive environmental pollution (Y). A condition was considered necessary when its consistency exceeded 0.90 and its coverage exceeded 0.50. As shown in Table 3, none of the individual conditions (X1–X6) or their negations satisfied both necessity criteria for high regional comprehensive environmental pollution (High Y), except for ∼X2. Specifically, ∼X2 (low level of internet broadband access ports per 10,000 persons) achieved a consistency of 0.937 and a coverage of 0.749, indicating that insufficient broadband infrastructure was a necessary condition for the occurrence of high environmental pollution. However, this finding should be interpreted as a necessary but not sufficient condition, meaning that high pollution cases rarely occurred without this condition, while ∼X2 alone was insufficient to generate high pollution outcomes.

Table 3. Necessity analysis of individual conditions

Condition Variable	High Y		Low Y	
	Consistency	Coverage	Consistency	Coverage
X1	0.690	0.904	0.609	0.489
∼X1	0.610	0.718	0.881	0.635
X2	0.343	0.948	0.488	0.827
∼X2	0.937	0.749	0.969	0.475
X3	0.648	0.916	0.573	0.496
∼X3	0.644	0.711	0.903	0.611
X4	0.637	0.781	0.702	0.527
∼X4	0.614	0.770	0.708	0.544
X5	0.706	0.866	0.600	0.452
∼X5	0.553	0.693	0.822	0.631
X6	0.746	0.848	0.654	0.455
∼X6	0.521	0.710	0.782	0.654

Note: Y denotes regional comprehensive environmental pollution; High Y and Low Y denote its high and low levels, respectively. X1–X6 represent the condition variables, and "∼" indicates the absence or low level of a condition.

For low regional comprehensive environmental pollution (Low Y), ∼X3 (low level of e-commerce sales revenue) was identified as the only necessary condition, with a consistency of 0.903 and a coverage of 0.611. This result indicates that insufficient e-commerce development was commonly associated with low-pollution cases. Meanwhile, ∼X1 (low level of fiber-optic cable infrastructure) approached the consistency threshold (0.881) but did not meet the criterion of 0.90. Although ∼X2 showed a high consistency of 0.969 for Low Y, its coverage was only 0.475, below the required threshold of 0.50, and therefore it cannot be regarded as a necessary condition. These results suggest that, apart from ∼X2 for High Y and ∼X3 for Low Y, no individual condition or its negation met the necessity criteria. Instead, pollution patterns are likely to result from combinations of multiple conditions, which are further examined through the configurational analysis.

4.2 Configurational Pathway Analysis

For the configurational analysis, the consistency cutoff was specified as 0.80, the proportional reduction in inconsistency (PRI) cutoff as 0.70, and the minimum case frequency as 1. Using fsQCA 4.1, both parsimonious and intermediate solutions were generated [25, 26]. A condition was treated as core when it appeared in both types of solutions, whereas it was regarded as peripheral when it appeared only in the intermediate solution. The analysis identified five configurations associated with high regional comprehensive environmental pollution and two configurations associated with low regional comprehensive environmental pollution, demonstrating equifinality and conjunctural causation. As shown in Table 4, the consistency of every individual configuration exceeded 0.80. The overall solution consistency values were 0.816 for High Y and 0.857 for Low Y, while the corresponding solution coverage values were 0.913 and 0.963, respectively. These results indicate that the identified configurations exhibit satisfactory explanatory consistency and collectively cover a substantial proportion of the observed outcomes.

(1) Interpretation of High-Pollution Configurations

Five configurations were identified for high regional comprehensive environmental pollution. Configuration 1, represented by Guangxi, combines the core presence of X5 and the core absence of X2, together with the peripheral presence of X6 and the peripheral absence of X4. Configuration 2, represented by Gansu and Xinjiang, is characterized by the core presence of X3 and X5, the core absence of X2, and the peripheral presence of X6. These two pathways indicate that relatively strong innovation or e-commerce development may coexist with high environmental pollution when broadband infrastructure remains weak. Configuration 3, represented by Shanghai, combines the core presence of X1 and the core absence of X3, together with the peripheral absence of X4 and X5. Configuration 4, represented by Guizhou, is characterized by the core absence of X1 and the core presence of X3, X4, and X5, together with the peripheral presence of X6. These configurations reflect imbalanced development among digital infrastructure, digital industries, and innovation conditions. Configuration 5, represented by Hunan, combines the core presence of X2 with the core absence of X1, X3, X5, and X6, as well as the peripheral absence of X4, suggesting that broadband access alone may be insufficient when other dimensions of digital development remain weak.

Table 4. Configurational pathways to high and low regional comprehensive environmental pollution

Condition Variable	**High Y**					**Low Y**	
	C1	**C2**	**C3**	**C4**	**C5**	**C1**	**C2**
X1			●	⨂	⨂	⨂	⨂
X2	⨂	⨂			●	⨂	•
X3		●	⨂	●	⨂	⨂	⨂
X4	⊗		⊗	●	⊗	•	•
X5	●	●	⊗	●	⨂	⨂	•
X6	•	•		•	⨂	⨂	•
Raw coverage	0.413	0.333	0.284	0.530	0.442	0.257	0.420
Unique coverage	0.080	0.009	0.018	0.092	0.038	0.017	0.009
Consistency	0.943	0.969	1.000	0.924	0.926	0.975	0.937
Solution consistency			0.816			0.857	
Solution coverage			0.913			0.963	
Representative cases	Guangxi	Gansu Xinjiang	Shanghai	Guizhou	Hunan	Jiangsu	Yunnan

Note: Y denotes regional comprehensive environmental pollution; High Y and Low Y denote its high and low levels, respectively. C1–C5 are the configurations associated with High Y, and C1–C2 denote the configurations associated with Low Y. ● = core condition present; • = peripheral condition present; ⨂ = core condition absent; small ⊗ = peripheral condition absent; blank cell = an irrelevant "do not care" condition, meaning that the variable is not included in the configuration.

(2) Interpretation of Low-Pollution Configurations

Two configurations were identified for low regional comprehensive environmental pollution. Configuration 1, represented by Jiangsu, combines the core absence of X1, X2, X3, X5, and X6 with the peripheral presence of X4. This pathway indicates that low pollution is not necessarily associated with the broad presence of all digital-economy conditions. Configuration 2, represented by Yunnan, combines the core absence of X1 and X3 with the peripheral presence of X2, X4, X5, and X6. This configuration suggests that low pollution may arise from a selective combination of digital conditions rather than uniformly high digitalization across all dimensions.

4.3 Multi-Period Configurational Analysis

The temporal analysis presented in Table 5 reveals the evolution of configurational pathways associated with high regional comprehensive environmental pollution from 2022 to 2024. Six configurations were identified in 2022, while three configurations were identified in both 2023 and 2024. The consistency values of all individual configurations exceeded 0.92. The annual solution consistency values were 0.912, 0.875, and 0.933, and the corresponding solution coverage values were 0.914, 0.925, and 0.929, respectively, indicating satisfactory explanatory consistency and coverage across the three years.

In 2022, the six configurations (C7–C12) exhibited considerable diversity. Configuration 7, represented by Zhejiang, Shanghai, and Fujian, combined the presence of X1 with the absence of X2, X3, X4, and X5, reflecting an infrastructure-oriented pattern with comparatively weak digital-industry and innovation conditions. Configuration 8, represented by Beijing and Tianjin, showed a similar structure but additionally included the presence of X6. Configuration 9, represented by Shaanxi, combined the presence of X3 and X6 with the absence of X1, X2, and X4, indicating that e-commerce activity and R&D human capital could coexist with high environmental pollution under relatively weak infrastructure and software-industry conditions. Configurations 10 and 11 shared the presence of X3, X4, X5, and X6. However, X1 was irrelevant in Configuration 10 and absent in Configuration 11, while X2 was absent in Configuration 10 and irrelevant in Configuration 11. These two configurations, represented mainly by Xinjiang, Qinghai, Gansu, Jilin, and Hainan, suggest that the simultaneous development of digital industries and innovation resources did not necessarily correspond to low environmental pollution. Configuration 12, represented by Hunan, combined the presence of X2 with the absence of X1, X3, X4, X5, and X6, reflecting a pattern in which broadband access was not accompanied by broader digital-industry or innovation development.

In 2023, the number of configurations decreased to three (C4–C6). Configuration 4, represented by Hainan and Jilin, combined the presence of X1, X3, X5, and X6 with the absence of X2. Configuration 5, represented by Xinjiang, Qinghai, and Gansu, included the presence of X3, X4, X5, and X6 together with the absence of X2. This configuration largely continued the digital-industry and innovation combination observed in Configurations 10 and 11 in 2022. Configuration 6, represented by Beijing and Tianjin, combined the presence of X1 and X6 with the absence of X2, X3, X4, and X5, indicating an infrastructure- and R&D-oriented pattern with relatively weak digital-industry development.

Table 5. Multi-period configurational pathways to high regional comprehensive environmental pollution

Condition Variable	2022						2023			2024		
	C7	**C8**	**C9**	**C10**	**C11**	**C12**	**C4**	**C5**	**C6**	**C1**	**C2**	**C3**
X1	✓	✓	×		×	×	✓		✓	✓		✓
X2	×	×	×	×		✓	×	×	×	×	×	×
X3	×	×	✓	✓	✓	×	✓	✓	×		✓	×
X4	×	×	×	✓	✓	×		✓	×	×	×	×
X5	×			✓	✓	×	✓	✓	×	✓	✓	×
X6		✓	✓	✓	✓	×	✓	✓	✓	✓	✓	×
Raw coverage	0.413	0.333	0.284	0.531	0.442	0.257	0.420	0.552	0.320	0.297	0.500	0.404
Unique coverage	0.080	0.009	0.018	0.093	0.038	0.017	0.009	0.166	0.089	0.005	0.288	0.148
Consistency	0.945	0.969	1.000	0.924	0.927	0.975	0.937	0.921	0.940	0.976	0.944	0.936
Solution consistency	0.912						0.875			0.933		
Solution coverage	0.914						0.925			0.929		
Representative cases	Zhejiang Shanghai Fujian	Beijing Tianjin	Shaanxi	Xinjiang Qinghai Jilin Hainan	Gansu Qinghai Xinjiang	Hunan	Hainan Jilin	Xinjiang Qinghai Gansu	Beijing Tianjin	Guizhou Jilin	Gansu Hainan Qinghai Xinjiang	Beijing Shanghai Tianjin

Note: C7–C12, C4–C6, and C1–C3 denote the configurations identified for 2022, 2023, and 2024, respectively. The check mark (✓) indicates the presence or high level of a condition, the cross (×) indicates its absence or low level, and a blank cell indicates an irrelevant or "do not care" condition. Unlike Table 4, this table does not distinguish between core and peripheral conditions. All configurations reported in this table are associated with High Y.

In 2024, three configurations (C1–C3) were again identified. Configuration 1, represented by Guizhou and Jilin, combined the presence of X1, X5, and X6 with the absence of X2 and X4, while X3 was irrelevant. Configuration 2, represented by Gansu, Hainan, Qinghai, and Xinjiang, combined the presence of X3, X5, and X6 with the absence of X2 and X4. This pathway continued the recurring combination of e-commerce activity and innovation resources found in the preceding years, although the role of software-industry development changed from presence in earlier configurations to absence in 2024. Configuration 3, represented by Beijing, Shanghai, and Tianjin, combined the presence of X1 with the absence of X2, X3, X4, X5, and X6, reflecting an infrastructure-oriented pathway in which the other digital conditions remained comparatively weak.

From a temporal perspective, the number of high-pollution configurations declined from six in 2022 to three in both 2023 and 2024, indicating that the configurational pathways became more concentrated over time. A recurring combination involving the presence of X3, X5, and X6 appeared in all three years, although its accompanying infrastructure and software-industry conditions varied. This pattern was repeatedly represented by Gansu, Qinghai, and Xinjiang, suggesting a degree of temporal persistence in these provinces. The absence of X2 appeared in 10 of the 12 annual configurations, which is consistent with the necessity-analysis result identifying $\sim$X2 as a necessary condition for High Y. In addition, X5 and X6 were present in many configurations, indicating that relatively strong innovation input and R&D human capital did not automatically correspond to lower environmental pollution. Their environmental implications appear to depend on how they were combined with digital infrastructure, e-commerce activity, and software-industry development.

Overall, the multi-period results demonstrate both continuity and change in the digital configurations associated with high regional comprehensive environmental pollution. The repeated occurrence of imbalanced combinations among digital infrastructure, digital-industry development, and innovation resources suggests that the environmental implications of digitalization depend less on the isolated presence of individual conditions than on their cross-dimensional alignment and temporal combination.

4.4 Robustness Test

To verify the stability of the configurational results, the configuration consistency threshold was adjusted to 0.75 and 0.85, respectively, and the multi-period fsQCA analysis was repeated. The core combinations of the configurations associated with high and low regional comprehensive environmental pollution remained largely unchanged, with only slight fluctuations in the coverage of individual configurations. These results indicate that the main findings are robust and reliable.

5 Conclusion and Implications

From a configurational perspective, this study examines how different combinations of digital economy conditions are associated with high and low levels of regional comprehensive environmental pollution. Using provincial data from China for 2022–2024, the study conducts a pooled fsQCA analysis and separate annual analyses to identify both general configurational patterns and their temporal evolution. This approach complements conventional net-effect analyses by revealing equifinality, causal asymmetry, and conjunctural relationships among multiple conditions. The necessity analysis shows that a low level of internet broadband access ports per 10,000 persons (∼X2) is a necessary condition for high regional comprehensive environmental pollution, whereas a low level of e-commerce sales revenue (∼X3) is a necessary condition for low regional comprehensive environmental pollution under the adopted consistency and coverage thresholds. No other individual condition or its absence satisfies both necessity criteria. These findings indicate that regional environmental pollution outcomes cannot generally be explained by the isolated presence of a single digital economy condition.

The pooled configurational analysis identifies five pathways associated with high regional comprehensive environmental pollution and two pathways associated with low regional comprehensive environmental pollution. The high-pollution pathways include several different combinations of digital infrastructure, e-commerce activity, software-industry development, science and technology expenditure, and R&D human capital. Some pathways combine relatively strong innovation-related conditions with weak broadband infrastructure, whereas others combine developed infrastructure with comparatively weak digital-industry or innovation conditions. These results suggest that the environmental implications of digital development depend on the alignment among different digital economy dimensions rather than on the expansion of any single dimension. The low-pollution configurations also demonstrate causal asymmetry. Low regional comprehensive environmental pollution is not simply the inverse of the configurations associated with high pollution. Instead, it arises from distinct combinations of present and absent digital conditions. The pooled results represented by Jiangsu and Yunnan indicate that low pollution does not necessarily require uniformly high levels of all digital economy conditions. However, because industrial structure, energy composition, environmental regulation, and other contextual factors are not included as conditions in the present model, their possible contributions should be regarded as contextual interpretations rather than directly verified mechanisms.

The multi-period analysis further reveals both continuity and change in the configurations associated with high regional comprehensive environmental pollution from 2022 to 2024. The number of identified configurations decreased from six in 2022 to three in both 2023 and 2024, indicating that the configurational pathways became more concentrated during the study period. A combination involving the presence of e-commerce sales revenue, science and technology expenditure, and R&D personnel appeared repeatedly across the three years, although the accompanying roles of digital infrastructure and software-industry development varied. In addition, the absence of a high level of broadband access appeared in most annual configurations, which is consistent with the necessity-analysis result for High Y. Innovation expenditure and R&D human capital were also present in many high-pollution configurations. This does not demonstrate that innovation directly increases pollution or that innovation resources are necessarily directed toward pollution-intensive industries. Rather, it indicates that innovation-related inputs alone do not guarantee lower environmental pollution and that their environmental implications may depend on how they are combined with other digital and regional conditions.

These findings provide several policy implications. First, regional digital development policies should move beyond the simple pursuit of digital scale and place greater emphasis on coordination among digital infrastructure, digital-industry development, technological investment, and human capital. Expanding one dimension of the digital economy without complementary development in other dimensions may not produce the expected environmental benefits. Second, local governments should evaluate the environmental performance of digital development according to regional circumstances. Digital infrastructure construction, software-industry development, e-commerce expansion, and innovation investment should be coordinated with environmental objectives rather than treated as independent development targets. Environmental assessment mechanisms may also be incorporated into major digital infrastructure and digital-industry projects to identify potential increases in energy use, logistics demand, and resource consumption. Third, differentiated digital-development strategies should be formulated for regions with different economic and environmental conditions. Provinces should identify the combinations of digital conditions that are most compatible with their development stage rather than uniformly pursuing comprehensive digitalization. Regions with relatively weak digital infrastructure may prioritize coordinated infrastructure improvement, whereas regions with developed digital industries may place greater emphasis on improving the environmental orientation and resource efficiency of digital activities. Fourth, the repeated coexistence of innovation-related conditions and high environmental pollution indicates that the quantity of innovation input should not be the sole policy focus. Greater attention should be paid to the direction, application, and environmental outcomes of science and technology expenditure and R&D activities. This may help strengthen the role of innovation in cleaner production, resource efficiency, and environmental management.

This study nevertheless has several limitations. First, the analysis is conducted at the provincial level, and substantial heterogeneity within provinces cannot be captured. The relationships among digital development, industrial activity, and environmental pollution may differ across cities, industries, and enterprises. Second, the measurement systems for both the digital economy and regional environmental pollution remain relatively limited. The outcome variable is constructed from wastewater discharge, sulfur dioxide emissions, and industrial solid-waste generation and therefore does not cover all dimensions of environmental pollution. Moreover, several indicators are measured using aggregate provincial quantities, which may partly reflect differences in provincial economic size and population rather than only differences in digital development or environmental pressure. Third, important contextual conditions—including industrial structure, energy composition, environmental regulation, economic development, and clean-energy availability—are not incorporated into the configurational model. Consequently, these factors cannot be treated as empirically verified explanations for the representative provincial cases. Fourth, the study covers only the period from 2022 to 2024. The relatively short time span limits the ability to identify long-term configurational evolution. In addition, the annual analyses contain 30 provincial cases and six condition variables, which may result in limited empirical diversity and make some configurations sensitive to threshold selection. Finally, although fsQCA is suitable for identifying multiple sufficient and necessary combinations, it cannot directly estimate marginal effects, effect sizes, causal transmission mechanisms, or spatial spillovers. The configurational findings should therefore be interpreted as set-theoretic associations rather than as definitive evidence of isolated causal effects.

Future research may extend the present analysis in several directions. First, city-, industry-, and enterprise-level panel data could be used to examine spatial and sectoral heterogeneity more precisely. Second, future indicator systems could incorporate pollution intensity, carbon emissions, data-center energy consumption, digital logistics activity, artificial intelligence applications, and green-oriented innovation outputs. Standardized or intensity-based indicators may also be introduced to reduce the influence of regional scale. Third, industrial structure, energy composition, environmental regulation, clean-energy availability, and economic development could be incorporated as additional configurational conditions. Fourth, longer observation periods and more advanced longitudinal QCA designs could be used to examine the stability and evolution of configurational pathways. Finally, fsQCA could be combined with spatial econometric models, panel regression, or case-based process analysis to evaluate spatial spillovers, marginal relationships, and the mechanisms underlying the identified configurations. Such extensions would provide a more comprehensive understanding of the relationship between digital economy development and regional environmental sustainability.

Author Contributions

Conceptualization, Y.H.Y. and G.N.W.; methodology, Y.H.Y.; software, G.N.W.; validation, Y.H.Y., G.N.W. and C.L.L.; formal analysis, G.N.W.; investigation, C.L.L.; resources, Y.H.Y.; data curation, G.N.W.; writing—original draft preparation, Y.H.Y.; writing—review and editing, Y.H.Y. and C.L.L.; visualization, G.N.W.; supervision, Y.H.Y.; project administration, Y.H.Y.; funding acquisition, Y.H.Y. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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