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| RESEARCH ARTICLE

A study on digital-intelligence integration on synergy of pollution and carbon reduction in Fuzhou's Private Enterprises

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| ABSTRACT
Against the backdrop of the "dual carbon" goals and the rapid development of the digital economy, promoting synergies between pollution control and carbon emission reduction has become a key pathway to achieving green, high-quality development. Digital-intelligent integration, through the deep convergence of digital and intelligent technologies, provides new technical support for corporate green transformation and environmental governance.This paper takes private enterprises in Fuzhou as its research subjects. Based on the theoretical logic of digital-intelligent convergence and the synergistic effects of pollution control and carbon reduction, it analyzes the characteristics of digital-intelligent convergence in Fuzhou as well as changes in pollutant and carbon emission levels, and systematically explores the mechanism through which digital-intelligent convergence drives these synergistic effects.The study found that from 2011 to 2023, the level of digital-intelligent integration in Fuzhou showed an overall trend of continuous improvement, while pollutant and CO_2 emission levels generally declined, indicating a solid foundation for the integration of digital transformation and green development.Further analysis indicates that the integration of digital and intelligent technologies primarily drives synergistic benefits in pollution reduction and carbon emission reduction through pathways such as optimized resource allocation, green technological innovation, intelligent production processes, and coordinated environmental governance. Based on these findings, this paper proposes policy recommendations, including strengthening the construction of digital-intelligent infrastructure, improving the green technological innovation system, advancing digital environmental governance, and guiding private enterprises toward differentiated transformation, with the aim of providing a theoretical reference for the green and low-carbon development of local enterprises.

| KEYWORDS

Digital-intelligence integration, private enterprises, pollution and carbon reduction

| ARTICLE INFORMATION

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1. Introduction

Against the backdrop of increasingly severe global climate change and ecological and environmental constraints, promoting the green transformation of economic development models has become a core issue of widespread concern among nations. The Chinese government attaches great importance to environmental pollution control and greenhouse gas emission reduction, strategically planning development pathways for carbon emission reduction and pollutant reduction (Guo et al., 2024; Wang et al., 2025).Since proposing the "carbon peak" and "carbon neutrality" goals, China has gradually transitioned from single-issue pollution control to "synergistic pollution and carbon reduction management."However, due to factors such as an energy structure characterized by "abundant coal but scarce oil and natural gas," the transregional transport of pollutants, and pressures to restructure the industrial sector, China still faces significant challenges in pollution control and carbon reduction. There is an urgent need to explore new technology-enabled pathways for the coordinated advancement of pollution and carbon reduction (Liu Huajun et al., 2023).

Digital-intelligent integration—a new development model formed by the deep integration of cutting-edge technologies such as big data, artificial intelligence, and the Internet of Things—is emerging as a key driver of green economic and social transformation, providing new technological support for environmental governance and energy conservation and emissions reduction. Zhang Zhengyan et al. (2022) point out that, against the backdrop of tightening resource and environmental constraints, digital-intelligent integration has already demonstrated positive effects in areas such as ecological governance, environmental monitoring, and pollution early warning.Unlike traditional digital transformation, which primarily focuses on information transmission and process optimization, the integration of data and intelligence achieves improved efficiency in the allocation of production factors and more precise environmental governance through the integration of data resources, the application of intelligent algorithms, and the dynamic optimization of production processes, thereby offering new possibilities for promoting the synergistic achievement of pollutant reduction and carbon emission reduction.However, research on how the integration of data and intelligence influences the synergistic enhancement of pollution reduction and carbon emission reduction remains in its exploratory phase, and there is still a lack of systematic analysis regarding its mechanisms of action, impact pathways, and applicability in different corporate contexts.

The private sector in Fujian Province contributes approximately 70% of the province's tax revenue. As a major city on the southeastern coast, Fuzhou boasts a robust foundation for private-sector development, with a total of 11 enterprises ranked among the 2025 Top 500 Chinese Private Enterprises (Fuzhou Municipal People's Government, 2025).At the same time, private enterprises are numerous and span a wide range of industries. During their green transition, they generally face issues such as insufficient technological innovation capabilities, high costs of green investments, and limited environmental management capabilities, which create certain obstacles to the coordinated advancement of pollution reduction and carbon reduction. Against the backdrop of the "Dual Carbon" goals and the digital economy development strategy, exploring the implementation mechanisms through which digital-intelligent integration empowers the green transition of private enterprises is of great significance for enhancing enterprises' pollution control capabilities, promoting the formation of low-carbon production models, and achieving regional green and high-quality development.

Accordingly, this paper takes private enterprises in Fuzhou as its research subject. Focusing on the core question of "how the integration of digital and intelligent technologies promotes synergistic benefits in pollution reduction and carbon reduction," it constructs an analytical framework at the theoretical level—namely, "integration of digital and intelligent technologies—mechanism of action—synergistic benefits in pollution reduction and carbon reduction"—to systematically reveal the intrinsic logic by which this integration influences corporate green transformation. Furthermore, it provides a theoretical basis for local governments to advance digital empowerment of green development and formulate targeted policies.

2. Literature Review

Regarding the measurement of the level of synergy between pollution reduction and carbon reduction, scholars generally analyze the level of coordinated governance across different regions by constructing comprehensive evaluation indicator systems.

Regarding research on influencing factors, existing literature primarily explores aspects such as technological innovation, industrial structure, energy efficiency, and environmental governance capacity.Research generally agrees that technological progress can improve resource utilization efficiency and promote the application of clean production technologies, serving as a key driver for enhancing synergies between pollution reduction and carbon reduction (Tian et al., 2025). In addition, the digital economy (Xin et al., 2026), environmental regulations, and improved governance capabilities are also considered crucial safeguards for promoting synergies between pollution reduction and carbon reduction.

In recent years, with the rapid development of digital and intelligent technologies, the integration of digital and intelligent technologies has gradually emerged as a new pathway for promoting synergistic pollution and carbon reduction governance. Relevant studies indicate that this integration can enhance the level of regional synergies in pollution and carbon reduction by improving the efficiency of information acquisition, promoting green technological innovation, optimizing energy allocation, and driving industrial restructuring.Li and Diao (2025) found that digital infrastructure can significantly influence the level of coordinated pollution and carbon reduction governance in cities; Zhang Jie and Liu Yaqi (2025) further pointed out that the integration of digital and intelligent technologies not only directly promotes coordinated pollution and carbon reduction governance but also exerts indirect effects through technological innovation and the optimization of energy production structures.Xu Yuan's (2026) study further found that the integration of digital and intelligent technologies plays a significant role in promoting pollution reduction and carbon reduction, with multiple pathways of action including green technological innovation, energy conservation, and industrial upgrading. At the same time, the development of emerging technologies such as artificial intelligence has provided new technical support for pollution reduction and carbon reduction; relevant studies have

found that factors such as industrial robots have varying degrees of impact on the synergy between pollution reduction and carbon reduction (Xu et al., 2025) .

Overall, existing research provides an important foundation for understanding the influencing factors and implementation pathways of synergistic pollution and carbon reduction, but certain shortcomings remain: On the one hand, existing studies primarily focus on macro-level scales such as regions and cities, with insufficient attention paid to the mechanisms of pollution and carbon reduction during the green transition of micro-level entities—particularly private enterprises;on the other hand, existing research tends to emphasize the role of digital-intelligent integration in promoting regional green development, while the intrinsic mechanisms through which such integration strengthens synergies between pollution reduction and carbon reduction require further exploration.

3. Current Status of Digital-Intelligence Integration and Pollution and Carbon Reduction Levels in Fuzhou

3.1 Measurement of Digital-Intelligence Integration Levels

Drawing on the study by Wang & Su ((2025)), this research constructs a digitalization level based on four dimensions: digital infrastructure, digital industry development, digital inclusive finance, and digital awareness. The level of intelligentization is characterized by the number of artificial intelligence patent applications in the city, and the level of digital-intelligent integration is characterized using the entropy method based on these indicators. The results are shown in Figure 1.

The overall trend shows a sustained upward trajectory, indicating that Fuzhou's level of digital-intelligence integration continued to improve between 2011 and 2023. Specifically, indicator growth was relatively stable in the early stages; as digital infrastructure improved, the scope of digital technology applications expanded, and the digital transformation of industries advanced, the level of digital-intelligence integration entered a phase of rapid growth. Although there were brief fluctuations in the middle and later stages, the overall growth trend remained unchanged, demonstrating that Fuzhou's digital-intelligence integration development exhibits strong sustainability and resilience.Overall, Fuzhou is gradually forming a development model characterized by the deep integration of data elements, intelligent technologies, and the real economy, providing a solid technological foundation for the digital transformation of private enterprises and the synergistic enhancement of pollution reduction and carbon emission reduction.

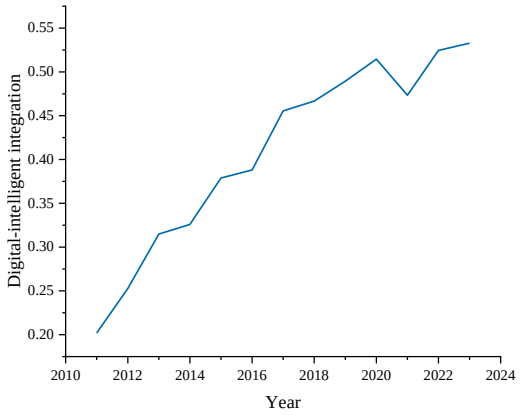


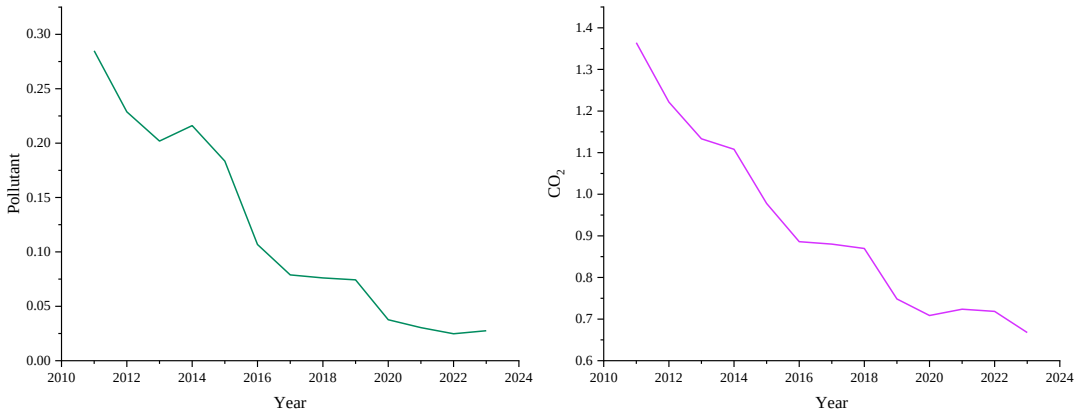
Figure 1 Level of Digital-Intelligence Integration in Fuzhou

3.2 Measurement of Pollution Reduction and Carbon Emission Reduction Levels

Drawing on the research by Zhu et al. , Dian et al. (, and other studies, and taking data availability into account, we adopted industrial sulfur dioxide emissions, industrial solid waste, industrial chemical oxygen demand (COD) emissions, industrial ammonia nitrogen emissions, and the ratio of industrial particulate matter to GDP as pollutant measurement indicators. These were then integrated into a single indicator using the entropy method.Carbon emissions were measured using CO_2emissions per unit of GDP. The product of these two indicators represents the level of synergistic benefits from pollution reduction and carbon reduction; it should be noted that this indicator is negative.

As shown in Figures 2(a) and (b), both pollutant emission levels and CO_2 emission levels in Fuzhou exhibited an overall downward trend during the study period, indicating that regional pollution control and low-carbon development have achieved certain results. In particular, pollutant emission levels showed a sustained downward trend, reflecting Fuzhou's continuously improving pollution control capabilities as a result of strengthened environmental regulations, industrial restructuring, and the promotion and application of green technologies.Although CO_2 emission levels fluctuated to some extent in certain years, the long-term trend remains downward, indicating that improved energy efficiency and the green transformation of industries have played a positive role in carbon emission reductions. Overall, Fuzhou has gradually achieved the synergistic advancement of

pollution control and carbon emission reduction during its economic development, providing a practical foundation for further exploring how the integration of digital and intelligent technologies can enhance synergies in pollution control and carbon reduction.



(a) The level of pollutant emissions (b) The level of CO_2 emission

Figure 2 The level of pollutant and CO_2 emission

4. Analysis of the Multidimensional Mechanisms by Which Digital-Intelligence Integration Drives Pollution and Carbon Reduction

As shown in Figures 1 and 2 above, Fuzhou's level of digital-intelligent integration has continued to improve, while pollutant and CO_2 emissions have generally shown a downward trend, indicating that the potential of digital-intelligent integration to empower green development is gradually emerging.However, the integration of digital and intelligent technologies does not simply rely on technological investment to directly reduce pollutant emissions; rather, it exerts a systemic impact on pollution and carbon reduction through multiple pathways, including changes in enterprises' resource allocation methods, innovation models, production processes, and environmental governance systems. Therefore, it is necessary to further analyze the intrinsic mechanisms by which the integration of digital and intelligent technologies drives synergistic benefits in pollution and carbon reduction from the perspective of these pathways.

4.1 Mechanism for Optimizing Resource Allocation

In traditional production systems, information asymmetry and market imperfections often lead to misallocation of resources, resulting in the long-term persistence of energy-intensive and inefficient production methods. In Fuzhou, where private enterprises are numerous and predominantly small and medium-sized, capital constraints and limited access to information are widespread issues, further exacerbating resource misallocation and low energy efficiency.

Through data integration and intelligent analysis, the convergence of digital and intelligent technologies significantly reduces the costs of information acquisition and processing, enabling enterprises to allocate resources with greater precision. Against the backdrop of Fuzhou's ongoing efforts to advance digital infrastructure development, enterprises can leverage industrial internet platforms and data service systems to monitor energy usage in real time and utilize algorithms to optimize production schedules, thereby reducing energy waste and redundant inputs. This "precise allocation" directly lowers energy consumption per unit of output, leading to a simultaneous reduction in both pollutants and carbon emissions.

Furthermore, within Fuzhou's industrial system—characterized by manufacturing and an export-oriented economy—the industrial chains are closely interconnected. Data sharing driven by the integration of digital and intelligent technologies can effectively reduce information friction between upstream and downstream sectors, enhance supply chain coordination efficiency, and thereby optimize resource allocation on a larger scale, leading to systematic emission reductions at the regional level.

4.2 Mechanisms for Green Technological Innovation

The integration of digital and intelligent technologies has significantly transformed the pathways and efficiency of technological innovation. For private enterprises in Fuzhou, traditional green technology innovation often faces challenges such as insufficient R&D investment and high risks, resulting in relatively limited incentives for innovation. Against this backdrop, the integration of digital and intelligent technologies provides enterprises with new pathways for technological innovation by reducing the cost of information acquisition and improving the efficiency of knowledge integration.

On the one hand, big data and artificial intelligence provide enterprises with a richer information base, enabling them to more accurately identify technological directions in the fields of energy conservation, emissions reduction, and clean production; on the other hand, intelligent algorithms can accelerate the R&D process through simulation analysis and data mining, reducing trial-and-error costs and thereby alleviating the resource constraints faced by private enterprises in green technology innovation.

In Fuzhou's efforts to promote industrial transformation and upgrading, this type of technological innovation is primarily reflected in the retrofitting of energy-saving equipment, the optimization of clean production processes, and the application of pollution control technologies. Through technological substitution, enterprises can reduce energy consumption and pollution emissions while maintaining output levels, thereby achieving "relative decoupling."

Furthermore, by leveraging the resources of local universities and research institutions, the integration of digital and intelligent technologies promotes the diffusion of green technologies through knowledge spillover effects, enabling the wider adoption of innovative achievements and further amplifying the effects of pollution and carbon reduction.

4.3 Mechanisms for Smart Production Processes

Production processes are the direct sources of pollutants and carbon emissions. Some traditional manufacturing sectors in Fuzhou still suffer from extensive production methods and relatively low equipment efficiency, resulting in high energy consumption and emission intensities. Through the application of smart manufacturing and the Industrial Internet, the integration of digital and intelligent technologies endows production processes with real-time monitoring and dynamic adjustment capabilities, thereby providing a technical foundation for enterprises to achieve process-level emissions reductions.

For example, through sensors and data analysis systems, enterprises can monitor equipment operating status in real time and adjust production parameters based on data feedback, thereby reducing energy consumption and emission intensity. This dynamic optimization mechanism not only improves production efficiency but also significantly reduces environmental externalities. In the long term, against the backdrop of promoting high-quality development in Fuzhou's manufacturing sector, the intelligent transformation of production processes will drive enterprises to transition from traditional "extensive production" to "lean and low-carbon production," establishing a stable, low-emission production model.

4.4 Collaborative Mechanisms for Environmental Governance

The integration of digital and intelligent technologies not only impacts enterprises internally but also reshapes the relationship between the government and businesses. As Fuzhou City continues to advance the development of a digital government, environmental governance is gradually transitioning toward data-driven and intelligent approaches. Through environmental data platforms, the government can monitor corporate emissions in real time, thereby improving the efficiency and accuracy of regulation. This "digital regulation" increases compliance pressure on private enterprises, prompting them to proactively pursue green transformation.At the same time, data-sharing mechanisms have increased the transparency of policy implementation and reduced regulatory failures caused by information asymmetry.

More importantly, at the regional governance level, the integration of digital and intelligent technologies has facilitated information connectivity and collaborative interaction among the government, enterprises, and society, shifting environmental governance from being led by a single entity to a multi-stakeholder collaborative approach, thereby enhancing the overall effectiveness of pollution reduction and carbon reduction policies.

5. Conclusions and Policy Implications

5.1 Conclusions

Focusing on private enterprises in Fuzhou, this paper systematically analyzes the mechanisms through which the integration of digital and intelligent technologies drives green transformation, with an emphasis on how such integration enhances the synergistic effects of pollution reduction and carbon emission reduction. The analysis combines Fuzhou's level of digital-intelligent integration with trends in pollutant and CO_2 emissions.The study found that from 2011 to 2023, the level of digital-intelligent integration in Fuzhou showed an overall trend of continuous improvement. The enhancement of digital infrastructure, the deepening of digital technology applications, and the strengthening of intelligent innovation capabilities have provided a crucial technological foundation for enterprises' green transition. At the same time, pollutant emission levels and CO_2 emission intensity have generally shown a downward trend, indicating that Fuzhou has achieved positive results in optimizing industrial structure, improving energy efficiency, and strengthening environmental governance, laying a solid practical foundation for the coordinated advancement of pollution reduction and carbon reduction.

Further analysis indicates that the integration of digital and intelligent technologies does not directly influence pollution reduction and carbon reduction through the application of a single technology, but rather exerts its influence through multiple

mechanisms, including optimized resource allocation, green technological innovation, intelligent production processes, and coordinated environmental governance. Specifically, the integration of digital and intelligent technologies reduces corporate energy consumption and resource waste by improving the efficiency of information utilization and the precision of resource allocation;by promoting the research, development, and diffusion of green technologies, it enhances enterprises' capabilities for pollution control and low-carbon production; through smart manufacturing and dynamic monitoring, it optimizes production processes to achieve precise control over emissions; and by leveraging digital governance platforms, it strengthens information coordination among the government, enterprises, and society, thereby improving the efficiency of environmental governance. Overall, the integration of digital and intelligent technologies provides Fuzhou's private enterprises with new technical pathways and development models to overcome constraints in green transformation and achieve synergistic benefits in pollution reduction and carbon reduction.

5.2 Policy Implications

Based on the above analysis, the integration of digital and intelligent technologies provides a systematic pathway for Fuzhou's private enterprises to achieve synergistic benefits in pollution reduction and carbon reduction by optimizing the allocation of information resources, promoting green technological innovation, advancing the intelligent transformation of production processes, and strengthening coordination in environmental governance. Therefore, the policy framework should be refined in areas such as digital infrastructure development, support for green innovation, digital governance systems, and the enhancement of enterprises' transformation capabilities.

First, efforts should continue to improve the construction of digital and intelligent infrastructure to provide fundamental support for the green transition of private enterprises. Fuzhou is home to a large number of private enterprises, many of which are small and medium-sized enterprises (SMEs) that face challenges such as insufficient capital investment and limited technical application capabilities during their digital transformation. Therefore, efforts should be accelerated to advance the development of the industrial internet, data service platforms, and intelligent infrastructure, while improving mechanisms for the open sharing of data resources to reduce the costs for enterprises in accessing digital technologies and applying intelligent tools.At the same time, through policy subsidies and technical service support, the enthusiasm of small and medium-sized enterprises to participate in digital and intelligent transformation should be enhanced, promoting the wider application of digital technologies in production management and energy utilization.

Second, incentive mechanisms for green technology innovation should be strengthened to enhance enterprises' intrinsic motivation for green transformation. Green technology innovation is a key pillar for achieving synergistic benefits in pollution reduction and carbon emission reduction, but private enterprises often face constraints such as insufficient R&D investment and high innovation risks. To address this, innovation costs for enterprises should be reduced through fiscal subsidies, tax incentives, and green finance, while collaboration between universities, research institutions, and enterprises should be strengthened to promote the commercialization and widespread adoption of green technologies, thereby improving the accessibility of energy-saving and emission-reduction technologies for enterprises.

Third, efforts should be made to advance the development of a digital environmental governance system to improve the precision of pollution and carbon reduction management. Building on the development of digital government and smart environmental protection initiatives, capabilities for collecting, monitoring, and analyzing data on pollutant and carbon emissions should be strengthened to shift environmental oversight from traditional ex post management to dynamic and precise governance. At the same time, data sharing among government, enterprises, and social entities should be promoted to enhance the efficiency of environmental policy implementation and foster a multi-stakeholder collaborative governance framework.

Finally, a categorized implementation strategy should be adopted based on differences in the scale, industry type, and digital infrastructure of private enterprises. For enterprises with a solid digital foundation, they should be encouraged to serve as models for smart manufacturing and green transformation, thereby creating a ripple effect for the dissemination of best practices. For small and medium-sized enterprises (SMEs) with weaker digital capabilities, training, technical services, and transformation guidance should be strengthened to lower the barriers to green transformation. This will guide more enterprises to actively integrate into the system of digital-intelligent convergence, achieving a synergistic balance between enhanced economic benefits and improved environmental outcomes.

5.3 Limitations and Future Directions

Although this paper analyzes the mechanism by which the integration of digitalization and intelligence drives synergistic benefits in pollution reduction and carbon reduction from a theoretical perspective, there remains room for further exploration.First, this paper primarily relies on a theoretical framework for its analysis and lacks empirical testing using micro-level enterprise data; future research could further validate the mechanism by incorporating enterprise-level data. Second, this paper does not fully

account for differences among enterprises of varying sizes, industries, and technological levels; subsequent studies could conduct further heterogeneity analyses. Finally, as digital and intelligent technologies continue to evolve, future research could focus on the impact of new technologies—such as artificial intelligence and the Industrial Internet—on the pollution and carbon reduction mechanism to expand the boundaries of related research.

Statement and Declarations

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