Research Progress on the Digital Transformation in the Process of Building "Zero-waste Cities"

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Abstract: Carrying out the construction of "Zero-waste Cities" is an important measure for building a Beautiful China. Governing waste through digitalization is of great significance to advancing the construction of Zero-waste Cities in China. This paper analyzes and summarizes the application progress of digital technologies in four major sectors: industry, agriculture, residential life, and transportation. It systematically summarizes the significance of digital empowerment in building Zero-waste Cities, and offers recommendations from three aspects: industrial structure upgrading, new models of environmental protection, and technological empowerment, providing a reference for the development of digital technologies in the process of building Zero-waste Cities.
Keywords: Zero-waste City, Digitalization, Industrial sector, Agricultural sector, Residential sector, Transportation sector

1. Introduction

As the first developing country to implement the innovative practice of building "Zero-waste Cities," solid waste pollution prevention and control has become increasingly important in China. Meanwhile, the annual increase of solid waste in the fields of industry, residential life, agriculture, and construction in China amounts to about 11 billion tons, while the cumulative storage has reached as high as 60 to 70 billion tons [2], posing a huge challenge to the promotion of Zero-waste Cities. To this end, the newly revised Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Waste further consolidates the principles of reduction, resource recovery, and harmless disposal of solid waste, the principle of polluter responsibility, and the extended producer responsibility system.

Figure 1. Cellular Cluster Diagram of "Zero-waste Cities"

The concept of "Zero-waste Cities" is an important component of China's practice of ecological civilization and the promotion of building a Beautiful China [1]. According to a document issued by the General Office of the State Council, a Zero-waste City is a city development model guided by the new development philosophy of innovation, coordination, green development, openness, and sharing. It aims to continuously promote the reduction of solid waste at the source and resource recovery through fostering green development and lifestyles, minimizing landfill disposal, and reducing the environmental impact of solid waste to the lowest possible level. Actively developing new types of productive forces, effectively reducing urban solid waste generation, and expanding resource recovery of solid waste are of great significance to the construction of Zero-waste Cities.

Digital empowerment facilitates the advancement of Zero-waste City construction. During the pilot phase of Zero-waste City initiatives, digital technologies such as big data, the Internet, and the Internet of Things were extensively integrated into local information platforms to coordinate functions including enterprise information reporting, government environmental supervision, online waste trading, technology transfer, and public monitoring. Examples include the "Urban Solid Waste Resource Symbiosis Network System" in Shaoxing, Zhejiang Province [3], the three-tier urban solid waste management platform model in the Sino-Singapore Tianjin Eco-City [4], and the full lifecycle digital management model of industrial solid waste in the Beijing Economic-Technological Development Area [5]. These practical cases demonstrate that the promotion and application of digital technologies have significant practical implications for Zero-waste City construction. With the accelerated innovation of digital technologies and the continuous expansion of digital application scenarios, digital technologies are increasingly involved in urban governance, providing new momentum for advancing Zero-waste City construction and offering new ideas to support high-level development and innovative construction models of Zero-waste Cities.

2. Technological Progress

The construction of Zero-waste Cities is a large and complex system project, characterized by long construction cycles, numerous indicators, wide-ranging information sources, and difficult decision-making bases. Digital technologies provide convenient tools for this process, and various experts and scholars have explored it from different perspectives.

2.1 Digital Empowerment for the "Zero-waste" Transformation of Industrial Enterprises

The industrial sector is the main source of bulk and hazardous solid waste, accounting for approximately 33% of the annual solid waste generation, with bulk industrial solid waste exceeding 10 million tons per year. It is an important "cell" of Zero-waste Cities. The green transformation of the industrial sector is a key link in the construction of Zero-waste Cities. The report of the 19th National Congress of the Communist Party of China pointed out the need to promote the deep integration of the Internet, big data, and artificial intelligence with the real economy, accelerate the building of a strong manufacturing nation, and support the transformation and upgrading of traditional industries.

Luna [6] studied the impact of digitalization on the green development of Chinese manufacturing enterprises. Based on the "triple bottom line" under the framework of domestic and international dual circulation, the study examined the economic, environmental, and social benefits of digital-driven green development. Digitalization was categorized into four underlying technologies—artificial intelligence, blockchain, cloud computing, and big data—and applications of digital technologies. Using relevant econometric models, the study empirically tested the effects, pathways, and boundary conditions of digitalization on energy saving and emission reduction, green innovation, and green upgrading in manufacturing enterprises.

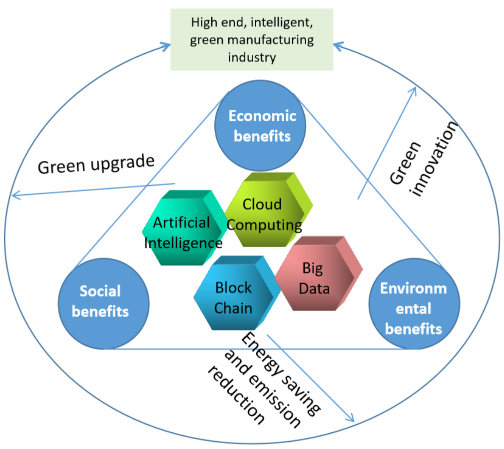

Figure 2. Digital Technologies Driving High-end, Intelligent, and Green Development of Manufacturing

Xiaogang He et al. [7], based on the experience of Chinese industrial enterprises, studied the mechanisms and pathways through which digitalization empowers enterprises' green upgrading. For each standard deviation increase in the degree of digital transformation, SO_2 emissions of enterprises decreased by 18.35%. The emission reduction effect of digital transformation mainly originates from source prevention rather than end-of-pipe treatment. In state-owned enterprises, pollution-intensive enterprises, and large-scale enterprises, the pollution reduction effect of digital transformation is more significant, and the differences in these effects are closely related to the choice of emission reduction methods by different types of enterprises.

Jian et al. [8] developed a new decision-making framework combining q-order Rough Orthopair Fuzzy Sets (q-ROFS), entropy rank-sum weighting method (RSWM), and the full multiplicative form of ratio analysis-based multi-objective optimization (MULTIMOORA). Blockchain technology, by providing various applications in fields such as finance, healthcare, the food industry, and supply chains, can significantly improve the efficiency and transparency of sustainable supply chain management (SSCM).

Atul Kumar Singh et al. [9] incorporated blockchain into circular economy-driven construction material supply chains, achieving sustainable development goals while ensuring transparency, traceability, and efficiency. Comprehensive literature analysis was conducted on PESTEL factors (Political, Economic, Social, Technological, Environmental, and Legal) to identify Critical Success Factors (CSFs). A questionnaire was developed and distributed online to collect information from industry and academic experts. The collected data were analyzed using the fuzzy DEMATEL algorithm. By matching these CSFs with theoretical concepts, the study highlights the theoretical significance of the positive synergy among technology, sustainability, and stakeholder engagement [10].

Tao Liu et al. [11] explored the application of machine learning technologies in smart cities to strengthen circular economy practices in green supply chains. By introducing the gravitational algorithm to optimize parameter selection in support vector machine models, the accuracy and effectiveness of predictive models were improved. A nationwide predictive model for green supply chain economic development efficiency was constructed, with minimum mean squared error (MSE) and root mean squared error (RMSE) values of 0.007 and 0.103, respectively, indicating the great potential of machine learning technologies in optimizing supply chain and circular economy management. This provides valuable insights for decision-makers and researchers in the field of sustainable development.

M. Ramirez-Pea et al. [12] studied how Industry 4.0 promotes the reuse of waste through resource recovery, establishing a model via supply chains to improve performance and sustainability in the shipbuilding industry. The study aimed to link each key Industry 4.0 technology with the most important supply chain paradigms: lean, agile, resilient, and green. The research showed that the green supply chain paradigm connects the social aspects required by the Industry 4.0 performance model. Similarly, lean represents the most important paradigm, including resilience, while agility is considered an intrinsic attribute of shipbuilding. By identifying the key factors in the conceptual model, the study concluded that shipbuilding supply chains should be green and lean.

Theofilos D. Mastos et al. [13] investigated the use of Industry 4.0 and the Internet of Things (IoT) for sustainable supply chain management (SSCM) of scrap metals. Based on the assessment framework developed by Manavalan and Jayakrishna (2019), the study demonstrated that Industry 4.0 has the potential to improve economic, environmental, and social sustainability in supply chain management.

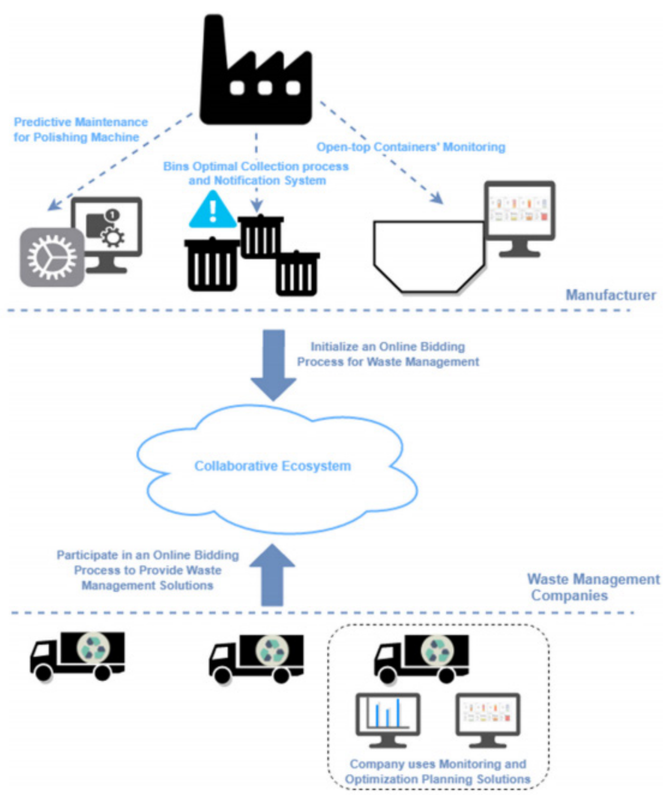

Figure 3. High-level Architecture of IoT-based Solutions for Scrap Metal Management [13]

Building a "zero-waste supply chain" has great application potential for achieving ecological and environmental protection and preventing waste pollution at the source. The "14th Five-Year Plan for Zero-waste City Construction" requires that Zero-waste City construction should "establish green supply chains to achieve source reduction." However, environmental and social changes increase uncertainty and risks in supply chains. Network technology platforms based on traceability can improve the sustainability of supply chain environments. Green supply chains have a significant impact on Zero-waste Cities. Environmental and social changes increase uncertainty and risks in supply chains, and the establishment of a network technology platform based on supplier and product traceability can improve supply chain environmental sustainability [14], enhance user experience [15], break down "information silos," reconstruct value networks, and effectively address risk challenges [16].

2.2 Digital Technologies Driving Efficient and Green Development in Agriculture

The national "14th Five-Year Plan" emphasizes "promoting the green transformation of agriculture and strengthening environmental protection and governance in production areas." However, problems such as excessive use of agricultural inputs, non-point source pollution, and agricultural carbon emissions have become increasingly prominent, significantly affecting the promotion of green agricultural transformation and development. In this context, advancing digital transformation in agriculture has become an effective approach to overcoming resource and environmental constraints and promoting high-quality agricultural development.

Lin Yumei et al. [17] studied the impact of agricultural digital transformation on green growth in agriculture. Using provincial panel data from China for 2013–2019, and employing fixed effects models, mediation effect models, and threshold effect models, they applied the entropy method and the SBM_GML index to measure digital agriculture and agricultural green total factor productivity indicators. Their study demonstrated that digital technologies can innovate modern agricultural production techniques, optimize the allocation of scientific and technological resources, and build a resource-saving and environmentally friendly green development system.

Li Xingyao et al. [18] investigated how digitalization supports green development in mountainous agriculture. Addressing issues such as insufficient smart production and management inputs, underdeveloped green supply chains, and low recognition of green brands, the study proposed using digital technologies to enhance the modernization of specialty mountain agriculture, improve the operational efficiency of green agricultural supply chains, and support the development of green agricultural brands, providing practical feasibility for promoting high-efficiency and green development in modern mountainous agriculture.

Huang Xiaohui et al. [19] explored the mechanisms through which digitalization drives green transformation in agriculture. Within the framework of sustainable livelihood capital theory, the study focused on human, social, natural, and financial capital to analyze theoretically how digital technologies enhance farmers' capital endowments, overcome capital constraints, and drive low-carbon green transformation in agriculture.

Lv Yuntao [20], starting from the theoretical logic of digital technologies supporting the healthy development of emerging rural industries, analyzed the theoretical logic, existing challenges, and scientific strategies for empowering high-quality development of rural emerging industries through digital technologies. The study investigated current limiting factors that affect the release of digital technology potential and explored approaches such as leveraging information infrastructure, improving institutional guarantees in rural areas, and constructing new frameworks for cultivating digital talent in rural areas, aiming to promote connotative and high-quality development of rural emerging industries.

Zhao Baoguo et al. [21] concluded that key issues in enabling high-quality agricultural development through digital technologies include the relative scarcity of digital technology talent in rural areas, suboptimal digital technology support environments, and incomplete support systems. Based on this problem analysis, they proposed corresponding pathways, emphasizing guidance and cultivation of digital technology talent, strengthening digital infrastructure, enhancing multi-level guarantees, and improving the integration of digital technologies with agricultural industries to empower high-quality agricultural development.

2.3 Digital Technologies Supporting Urban Household Waste Management

Urban household waste management is an important aspect of urban ecological civilization construction. With the emergence of large and mega-cities, the amount of household waste has surged, and more than half of cities face the major challenge of being surrounded by waste. Digital technologies offer significant advantages in managing household waste.

Liu Manqin et al. [22] used evolutionary game analysis to study waste sorting and disposal behaviors. The deepened application of digital technologies in urban household waste management can reduce regulatory costs, improve supervision efficiency, strengthen neighborhood connectivity, enhance community integration, and thereby reinforce residents' ecological ethics. The study found that under the traditional community model, closed communities implementing waste sorting systems eventually evolve toward an ideal stable state, whereas the transformation of green behaviors in open communities is difficult to achieve. In digital community models, both closed and open communities exhibit widespread adoption of “green low-waste” behaviors, indicating that data technologies can facilitate the popularization of sustainable lifestyles.

Chen Jiehao [23] conducted in-depth empirical analyses using deep learning algorithms, genetic algorithms, and other methods to study different applications of digital technologies across the stages of household waste generation, collection and transportation, and final disposal. Application of digital technologies at the front-end stage effectively improves residents’ participation rate and sorting accuracy. Using IoT and deep learning technologies, future waste generation trends can be predicted with an error controlled at 21.94%. Applications at the mid-end stage optimize inefficiencies in traditional waste collection and transportation, and genetic algorithms are used to plan optimal collection routes, achieving multi-objective optimization of economic cost, carbon emissions, and collection efficiency. Applications at the end-stage enhance the overall benefits of waste treatment, achieving net efficiency improvements of 8.23%–39.72%. By integrating front-end, mid-end, and end-stage management within a full-chain approach, this framework aims to improve the recycling rate of typical urban wastes and promote sustainable urban waste management.

Xie Qi [24] studied the implementation of household waste sorting policies in Nanchang City. Based on Smith’s policy implementation model and using literature review and survey methods, the study emphasized the need to gradually improve urban household waste sorting policies, particularly by clarifying fee standards, strengthening financial support, and improving relevant laws and regulations. The functions of policy implementation bodies should be enhanced to increase their status and effectiveness, strengthen training for policy implementers, and activate multiple stakeholders in waste sorting policies. Efforts should also be made to increase residents’ participation by promoting and popularizing waste sorting knowledge, establishing public reporting systems for residents’ sorting behaviors, and stimulating residents’ initiative. Finally, the policy implementation environment should be improved by simultaneously promoting economic development and upgrading urban waste sorting technologies.

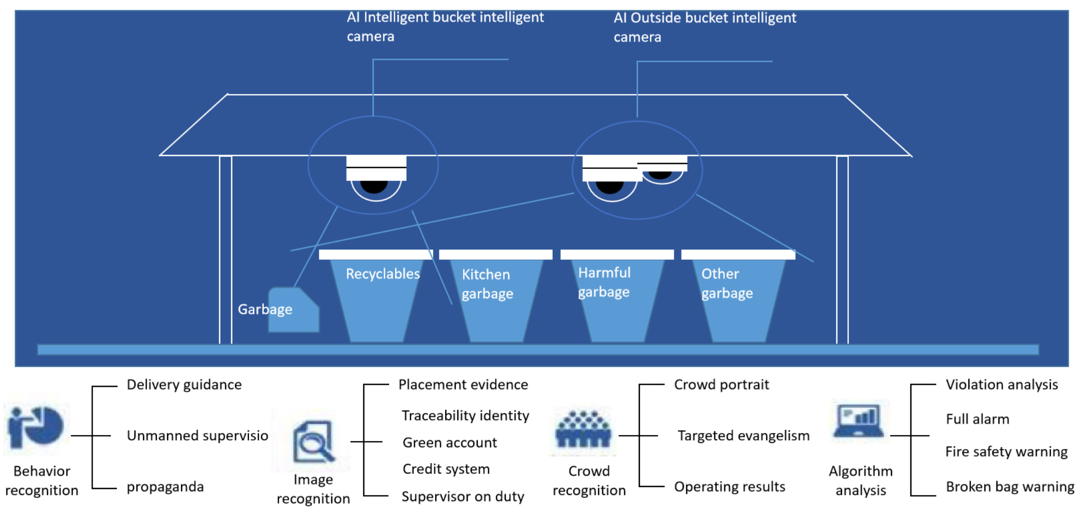

Figure 4. AI-based Solutions for Household Waste Sorting [24]

Research on the application of digital technologies in household waste management in developed countries abroad predates domestic studies and is relatively mature. For example, the application of digital technologies in waste data monitoring, intelligent collection, sorting and classification, and transportation optimization contributes to improving the recycling efficiency of household waste [25–27]. In addition, digital technologies such as intelligent solid waste management platforms can provide a series of analytical services related to resource allocation and optimization, promote circular reuse of waste, and effectively drive urban sustainable development [28–29].

2.4 Digital Technologies Accelerating Logistics Chain Optimization in the Transportation Sector

In the context of the digital economy, a large number of new transportation business models have emerged, bringing new opportunities for the transformation and optimization of the transportation industry, gradually becoming a core driver of domestic circulation. Relying on digital business models to build a modern transportation system is of great significance for “zero-waste” transportation.

Chen Ling [30] noted that the gradual integration of the digital economy and the circulation industry promotes industrial optimization and upgrading. The emergence of the digital economy accelerates the circulation time in China's characteristic circulation industry and significantly reduces circulation costs, with digital resources playing a highly positive role. At the same time, issues of monopoly arising from digital platforms have become increasingly prominent, necessitating stronger antitrust regulation.

Li Guangning [31], based on an analysis of the impact of the digital economy on cost management in logistics enterprises' value chains, identified insufficient application of digital technologies in current value chain cost management and proposed targeted recommendations, including strengthening the integration of enterprise value chains with digital technologies and establishing intelligent systems.

Wang Caihong [32], combining the current status of G Railway Group's digital transformation, used NVivo 12 qualitative analysis software and followed grounded theory analysis steps to code and classify collected data, constructing a model describing the factors influencing G Railway Group's digital transformation, and proposed strategies and safeguard measures for digital transformation.

Tang Yan [33] took B Railway operations as a case study and employed literature review and interviews to analyze the driving factors, existing problems, and underlying causes of the company's logistics digital transformation. The study provides new ideas for overcoming information silos in railway logistics, reducing logistics costs, and improving logistics efficiency through digital development.

3. Conclusions and Recommendations

The construction of Zero-waste Cities requires systematic overall planning and multi-sectoral coordination. It is not a matter of each department acting independently, but necessitates the creation of a coupled and symbiotic network across multiple domains. Systematic and comprehensive management should be implemented throughout the entire process, including waste generation, sorting, collection and transportation, resource utilization, and harmless disposal, to avoid disruptions in the regulatory chain between the various stages of storage, transportation, and treatment of solid waste. Therefore, digital transformation is a crucial scientific management and guidance approach in the construction of Zero-waste Cities. Based on this, the following recommendations are proposed for promoting Zero-waste Cities through digital transformation:

First,Promoting Industrial Structure Transformation and Upgrading:To address the insufficient endogenous driving force for industrial digital transformation and upgrading, efforts should be made to enhance the deep integration of digital and physical systems, stimulate the value of data elements and digital technologies, and strengthen the multi-dimensional application and promotion of digitalization across industrial chains, projects, and products. This will continuously improve the technical support of digitalization for industrial structure upgrading.

Second,Rapidly Optimizing the Structure of Ecological and Environmental Protection Industries:To overcome difficulties in data integration and sharing among various fields of ecological and environmental protection, efforts should focus on promoting data standardization, normalization, and the accelerated construction of data-sharing platforms. This will facilitate the development of new environmental service systems and business models, such as Internet+ and smart environmental protection, and accelerate the intelligence of the ecological and environmental protection industry.

Third,Strengthening Technological Empowerment:To address bottlenecks in key core technologies that cause delays in technological updates, efforts should be intensified in scientific research and technology promotion, advancing the domestic development of critical constraints in digital transformation such as chips, high-end sensors, and industrial software. The promotion of IoT, big data, cloud computing, and especially AI large models should be emphasized to support the construction of a modern Zero-waste Cities system network and realize digital empowerment.

References

[1] Huang Huimin, Zhang Shengjun, Mei Rongwu. Ideas on informatization construction of "Zero-waste Cities" under digital transformation [J]. Resources Conservation and Environmental Protection, 2024, 30:15-23.

[2] Chen Xiaolong, Di Qianbin, Wu Hongyu. Spatiotemporal evolution and influencing factors of pollution reduction and carbon reduction synergy in China's coastal city clusters [J]. Tropical Geography, 2023, 43(11):2060-2074.

[3] Qi Yangjian, Kong Weize, Wang Xiaoyan. Research on "Zero-waste Cities" construction based on urban solid waste resource symbiosis network: A case study of Shaoxing City [J]. Environmental Pollution and Prevention, 2020, 42(12):1549-1552.

[4] Chen Guisheng, Xu Mingchen. Smart city governance under power, technology, and institutional framework: A case

study of Sino-Singapore Tianjin Eco-city [J]. Theory and Modernization, 2022(04):51-62.
[5] Ministry of Ecology and Environment. Pilot highlights of "Zero-waste City" construction in Beijing Economic-Technological Development Area [EB/OL]. (2021-02-08) [2021-02-08]. https://www.mee.gov.cn/home/ztbd/2020/wfcsjssdgz/sdjz/ldms/202102/t20210208_820929.shtml
[6] Lu Na. Study on the impact of digitalization on green development of Chinese manufacturing enterprises [D]. 2024, Yunnan University of Finance and Economics.
[7] He Xiaogang, Zhong Xiangfei. Mechanisms and pathways of digital empowerment for enterprises' "green upgrading": Evidence from Chinese industrial enterprises [J/OL]. Journal of Management, 1-19 [2023-10-13].
[8] Jian Zhang, Xuanjian Zhang, Wei Li, et al. Critical success factors of blockchain technology to implement the sustainable supply chain using an extended decision-making approach [J]. Technological Forecasting & Social Change, 2022, 182:121881.
[9] Atul Kumar Singh, V.R. Prasath Kumar. Integrating blockchain technology success factors in the supply chain of circular economy-driven construction materials: An environmentally sustainable paradigm [J]. Journal of Cleaner Production, 2024, 460:142577.
[10] Yadav S, Singh S P. Blockchain critical success factors for sustainable supply chain [J]. Resources, Conservation and Recycling, 2020, 152:104505.
[11] Tao Liu, Xin Guan, Zeyu Wang, et al. Optimizing green supply chain circular economy in smart cities with integrated machine learning technology [J]. Heliyon, 2024, 10:29825.
[12] Ramirez-Peña M, Sánchez Sotano A J, Pérez Fernandez V, et al. Achieving a sustainable shipbuilding supply chain under I4.0 perspective [J]. Journal of Cleaner Production, 2019, 244:118789.
[13] Mastos T D, Nizamis A, Vafeiadis T, et al. Industry 4.0 sustainable supply chains: An application of an IoT enabled scrap metal management solution [J]. Journal of Cleaner Production, 2020, 269:122377.
[14] Papetti A, Marconi M, Rossi M, et al. Web-based platform for eco-sustainable supply chain management [J]. Sustainable Production and Consumption, 2019, 17(1):215-228.
[15] McQuillan H. Make use V2: Digital textile technology for user modifiable zero waste fashion [R]. Auckland: Auckland University of Technology, 2016.
[16] Giusto D, Lera A, Morabito G, et al. The internet of things: 20th Tyrrhenian workshop on digital communications [C]. Berlin: Springer Science & Business Media, 2010.
[17] Lin Yumei, Li Chenghan. The impact of agricultural digital transformation on agricultural green growth [J/OL]. China Agricultural Resources and Regional Planning, 2024:1-16.
[18] Li Xingyao, Lin Qiang. Digital technology empowers green development of modern mountain specialty agriculture [J]. Rural Economy and Technology, 2024, 35(15):69-72.
[19] Huang Xiaohui, Nie Fengying. Study on the mechanism of digital-driven low-carbon green transformation of farmers' agriculture [J]. Journal of Northwest A&F University (Social Sciences Edition), 2023, 23(1):30-37.
[20] Lü Yuntao. Theoretical logic, practical dilemma and implementation path of digital technology empowering high-quality development of rural emerging industries [J]. Agricultural Economy, 2024(09):117-119.
[21] Zhao Baoguo, Yang Hanlu. Digital technology empowers high-quality agricultural development: Intrinsic logic and implementation path [J]. Rural·Agriculture·Farmers, 2024(17):16-18.
[22] Liu Manqin, Yin Jinge, Li Lingling. Digital technology empowers ecological civilization construction: A case study of urban household waste sorting [J]. China Soft Science, 2024, 6:66-78.
[23] Chen Jiehao, Hu Yupeng, Fei Fan, et al. Construction and case study of full-chain urban waste sorting model based on digital technology [J]. Resources Science, 2024, 46(4):667-698.
[24] Xie Qi. Study on policy implementation of urban household waste sorting in Nanchang under carbon neutrality: Based on Smith policy implementation model [D]. 2022, Nanchang Hangkong University.
[25] Tseng M L, Tan R R, Chiu A S F, et al. Circular economy meets Industry 4.0: Can big data drive industrial symbiosis [J]. Resources, Conservation and Recycling, 2018, 131:146-147.
[26] Abinaya, Kaustoob R, Vatsa M, et al. IoT based smart garbage and waste collection bin [J]. International Journal of Advance Research, Ideas and Innovations in Technology, 2018, 4(2):522-524.
[27] Vu D D, Kaddoum G. A waste city management system for smart cities applications [C]// Proceedings of the 2017 Advances in Wireless and Optical Communications (RTUWO). Riga, Latvia: IEEE, 2017:225-229.
[28] Vafeiadis T, Nizamis A, Pavlopoulos V, et al. Data analytics platform for the optimization of waste management procedures [C]// 2019 15th International Conference on Distributed Computing in Sensor Systems (DCOSS). Santorini, Greece: IEEE, 2019.
[29] Vafeiadis T, Nizamis A, Apostolou K, et al. Intelligent information management system for decision support: Application in a lift manufacturer's shop floor [C]// 2019 IEEE International Symposium on Innovations in Intelligent Systems and Applications (INISTA). Sofia, Bulgaria: IEEE, 2019.
[30] Chen Ling. Study on high-quality development of circulation industry with Chinese characteristics empowered by

digital economy: From the perspective of Marx's circulation theory [D]. 2023, Shanghai University of Finance and Economics.
[31] Li Guangning, Zheng Ruixi. Analysis of logistics enterprise value chain cost management under the background of digital economy [J]. Logistics Platform, 2024, 20:54.
[32] Wang Caihong. Research on influencing factors and strategies of digital transformation in G large railway group [D]. 2024, Beijing University of Chemical Technology.
[33] Tang Yan. Research on digital transformation strategies of B railway company logistics business [D]. 2024, Hebei University of Economics and Business.