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From "Harmony Between Humans and Nature" to Green Development: The Mechanism of Traditional Chinese Ecological Culture Empowering Regional Low-Carbon Economies

从“天人合一”到绿色发展：传统中国生态文化赋能区域低碳经济的作用机制

Yuhao Gu^{a,*}^a International Institute of Management and Business, Minsk 220086, Belarus**Keywords:**

Traditional Chinese Ecological Culture;
Low-Carbon Economy;
Cultural Capital; Synergistic Empowerment;
Digital Technology; S
Ustainable Built Environment;
Regional Development;
Modern Transformation

关键词:

传统中国生态文化; 低碳经济;
文化资本; 协同赋能;
数字技术; 可持续建成环境;
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Abstract: Amid China's "dual carbon" goals and the ecological civilization agenda, the contemporary value of traditional Chinese ecological culture—centered on "harmony between humans and nature"—is being renewed. As the digital economy and artificial intelligence integrate with the real economy, they accelerate regional low-carbon transitions while also bringing challenges such as labor-market restructuring, skill mismatches, and inadequate adaptability of the built environment. This study argues that traditional ecological culture, as a form of "cultural capital" with value guidance and practical resilience, can synergize with emerging technological and economic factors to support regional low-carbon development. Based on literature across philosophy, economics, geography, the digital economy, and sustainable development, the study constructs an analytical framework of "Cultural connotations → Modern transformation → Synergistic empowerment → Regional practice → Optimization pathways," and summarizes three conclusions: (1) traditional ecological culture can be transformed into modern low-carbon cultural capital through value ethics, institutional rules, and practical behaviors; (2) it works in synergy with digital technology, SMEs, and sustainable built environments, promoting low-carbon transition via value constraint, technological drive, subject adaptation, and spatial guarantee across firm, industry, and regional governance levels; and (3) current practices include "culture + education and communication," "culture + spatial governance," and "culture + policy integration," but still face fragmented cognition, weak regional coordination, and shallow technology-culture integration.

摘要: 在“双碳”目标与生态文明建设背景下，以“天人合一”为核心的传统生态文化正被重新激活。数字经济与人工智能深度融入实体经济，一方面加速区域低碳转型，另一方面也带来劳动力结构调整、技能错配与建成环境适配不足等挑战。本文认为，传统生态文化可作为具有价值引领与实践韧性的“文化资本”，与新技术、新经济要素协同，支撑区域低碳发展。基于跨学科文献，构建“文化内涵—现代转化—协同赋能—区域实践—优化路径”框架，并提出三点结论：传统生态文化可经由价值伦理、制度规则与实践行为转化为低碳文化资本；其与数字技术、中小企业及可持续建成环境形成协同机制，通过“价值约束、技术驱动、主体适应、空间保障”推动企业、产业与区域治理层面的转型；当前实践主要包括“文化+传播教育”“文化+空间治理”“文化+政策整合”，但仍受文化认知碎片化、区域协同不足与技术—文化融合浅表化等制约。

Introduction

Research Background

Ecological crises triggered by global climate change have become a pressing shared challenge for humanity, making low-carbon development an inevitable choice

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for countries to overcome ecological constraints and achieve sustainable growth. As the world's largest developing economy and a major carbon emitter, China has explicitly articulated its strategic goals of reaching peak carbon emissions by 2030 and achieving carbon neutrality by 2060, positioning regional low-carbon economic development as a core vehicle and key driver of ecological civilization construction.

Unlike Western low-carbon development pathways that predominantly rely on technological innovation and mandatory institutional constraints, China's low-carbon transition is inherently embedded with the genes of traditional ecological culture. From the cosmic view of "harmony between humans and nature" and the resource philosophy of "moderation in taking," to the symbiotic ideas integrating Confucianism, Taoism, and Buddhism, traditional ecological culture provides a unique value core and practical wisdom for regional low-carbon development. Its inherent characteristics—holism, inclusiveness, and sustainability—align closely with the essence of low-carbon development.

Meanwhile, the vigorous development of the digital economy and the widespread application of artificial intelligence are profoundly reshaping the production factors, industrial forms, and governance models of regional economic development. On one hand, artificial intelligence boosts production efficiency and drives green technological innovation, while the digital economy breaks geographical barriers to optimize the allocation of low-carbon resources [12]. On the other hand, technological transformation gives rise to issues such as income polarization in the labor market [11], skill mismatches in SMEs [12], and inadequate adaptability of the built environment to low-carbon industries [13], adding new complexities to regional low-carbon transitions. Against this backdrop, relying solely on technological drive or institutional constraints is insufficient to address multifaceted contradictions. There is an urgent need to tap into the empowering potential of traditional Chinese ecological culture and construct an integrated development model characterized by "cultural leadership, technological support, subject synergy, and spatial adaptation."

Research Questions and Core Logic

Existing studies have explored related themes from multiple perspectives: At the philosophical level, scholars have elaborated on the modern ecological ethical value of traditional ideas such as "harmony between humans and nature" [1, 3]; at the empirical level, research has verified the positive impact of cultural capital on corporate green innovation and regional green efficiency [5, 7]; at the practical level, studies have

mapped the implementation pathways of ecological culture in regional low-carbon transitions [8]; in the field of emerging economies, scholars have focused on the impacts of artificial intelligence, the digital economy, and the built environment on enterprise operations and regional development [11, 12, 13].

However, existing research exhibits notable gaps: First, it lacks a systematic examination of the full-chain empowerment mechanism linking "ecological culture → modern transformation → regional low-carbon development," failing to clearly reveal the transmission logic of cultural capital from value concepts to practical outcomes. Second, it inadequately integrates the regulatory role of emerging technologies and economic forms in this mechanism, overlooking the synergistic relationships between culture, technology, enterprises, and space. Third, it lacks targeted analysis of the bottlenecks and breakthrough pathways of cultural empowerment in practice, resulting in insufficient connection between theory and application.

Based on these gaps, this study focuses on three core research questions: How does traditional Chinese ecological culture transform into cultural capital adapted to low-carbon development through modernization? How does this cultural capital synergize with emerging economic factors (digital technology, SMEs, built environment) to empower regional low-carbon economies? How can practical pathways be optimized to address the realistic bottlenecks of cultural empowerment? Centering on these questions, this study constructs a logical framework of "Cultural Connotations → Modern Transformation → Synergistic Empowerment → Regional Practice → Optimization Pathways," aiming to systematically uncover the complete mechanism through which traditional Chinese ecological culture empowers regional low-carbon economies and provide theoretical support and practical reference for regional low-carbon development.

Research Significance

Theoretical Significance

This study makes three key theoretical contributions: First, it constructs a comprehensive logical framework for the empowerment of regional low-carbon economies by traditional Chinese ecological culture, filling the gap in full-chain research on "traditional ecological culture → modern low-carbon development." Second, it integrates theories from cultural economics, regional economics, digital economy, and other disciplines, proposing a "culture-technology-enterprise-space" four-dimensional synergistic empowerment model that enriches the sustainable development theory system. Third, it

expands the application boundary of cultural capital theory, extending traditional ecological culture from the philosophical realm to the practical level of regional low-carbon governance and providing a new application scenario for cultural capital theory.

Practical Significance

The practical value of this study lies in three aspects: First, it offers new insights for regional governments in formulating low-carbon development policies, promoting a shift from "technology-oriented" and "institution-oriented" policy design to a model of "cultural leadership + multi-factor synergy." Second, it provides a roadmap for enterprises—especially SMEs—in their low-carbon transition, guiding them to integrate ecological culture into their development strategies and leverage digital technology to enhance transition efficiency. Third, it offers cultural support for fostering public low-carbon behaviors, guiding the formation of low-carbon lifestyles through the dissemination of ecological culture and consolidating the social foundation for regional low-carbon development (Figure 1).

Theoretical Foundation: Core Connotations and Modern Transformation Logic of Traditional Chinese Ecological Culture

Traditional Chinese ecological culture is not a static historical legacy but evolves into a value system and governance resource adapted to modern regional low-carbon development through a three-stage transformation—value ethics, institutional rules, and practical behaviors. Drawing on literatures such as Tu (2001), Pan (2014), Lu (2016), and Zhang & Zhang (2023), this section clarifies its core connotations and constructs a logical framework for modern transformation.

Core Connotations: an Ecological Wisdom System Centered on "Harmony Between Humans and Nature"

Traditional Chinese ecological culture encompasses the value concepts, behavioral norms, and practical wisdom formed by the Chinese nation in long-term production and living practices, focusing on the relationship between humans and nature. Its core is the idea of "harmony between humans and nature," which is not a simplistic call for "harmonious coexistence between humans and nature" but emphasizes the holism, interconnectedness, and symbiosis of "humans-nature-society," opposing the unrestrained exploitation and conquest of nature by humans [1]. Tu Weiming [1] points out that the essence of "harmony between humans and

nature" lies in extending individual moral cultivation ("self-cultivation") to responsibility for nature, forming an ecological ethics of "caring for people and loving all things." This transcends the dichotomy between Western "anthropocentrism" and "ecocentrism," providing a holistic value guide for modern low-carbon development.

This core idea is enriched and deepened through the integration of Confucianism, Taoism, and Buddhism, forming a trinity ecological wisdom system:

- 1) Confucianism: Centered on "moderation," "frugality," and "caring for people and loving all things," it emphasizes the moderation and moral constraints of human economic behaviors, opposes excessive consumption and resource waste, and incorporates ecological responsibility into the moral system of "self-cultivation, family governance, state governance, and world peace" [2];
- 2) Taoism: Focused on "following the way of nature" and "governing by non-interference," it advocates that humans act in accordance with natural laws, reject development activities that violate ecological logic, and pursue the inherent harmony between humans and nature [3];
- 3) Buddhism: Based on "equality of all beings" and "karma," it strengthens reverence for life and nature, advocates a circular and symbiotic lifestyle, and forms behavioral norms of "non-harm, resource conservation, and environmental protection" [3].

Together, they constitute an ecological wisdom system of "respecting nature, following nature, and protecting nature," with core characteristics summarized as: holistic thinking (emphasizing the indivisibility of humans, nature, and society), the principle of moderation (opposing over-development and over-consumption), responsible ethics (regarding ecological protection as a moral responsibility of humans), and circular concept (advocating the sustainable use of resources). These characteristics are highly consistent with the core requirements of modern low-carbon development, laying a value foundation for regional low-carbon transitions.

Modern Transformation: a Three-Stage Logic From Philosophical Thought to Governance Resource

The modern transformation of traditional Chinese ecological culture is a prerequisite for its empowerment of regional low-carbon economies. Essentially, it involves converting traditional ecological wisdom from philosophical thought into the value ethics, institutional rules, and practical behaviors of modern society, real-

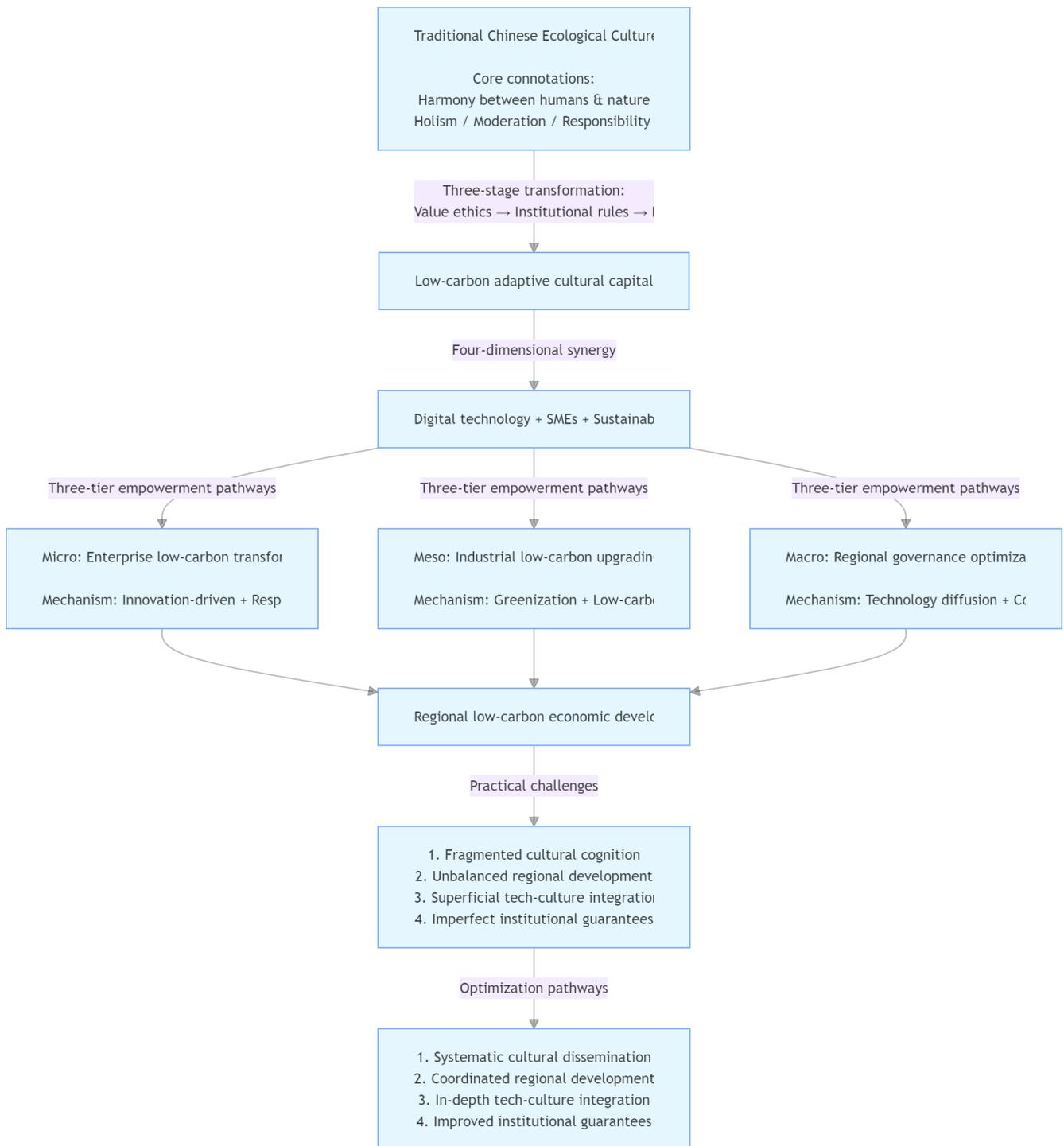


Figure 1 | Conceptual framework of traditional Chinese ecological culture empowering regional low-carbon economies



Figure 2 | Three-stage modern transformation of traditional Chinese ecological culture

Note: Traditional Chinese ecological culture achieves the leap from philosophical thought to governance resource through three-stage transformation, laying a foundation for regional low-carbon development.

ized through a three-stage logic (Figure 2):

Stage 1: Value-Ethical Transformation—From Traditional Ecological Concepts to Modern Low-Carbon Values

The core of this transformation is integrating traditional ecological concepts such as "harmony between humans and nature" and "frugality and caring for others" with modern sustainable development concepts and low-carbon development goals, forming time-specific low-carbon values. Neo-Confucianism transforms "harmony between humans and nature" into modern ecological humanism [1], emphasizing that humans must assume responsibility for nature while pursuing economic development, incorporating ecological protection into the core dimension of human civilization progress. Scholars such as Lu Feng [3] interpret Confucian, Taoist, and Buddhist wisdom to propose low-carbon lifestyle solutions for addressing the crises of industrial civilization, converting traditional concepts such as "frugality" and "simplicity" into modern low-carbon consumption values. In the context of the digital economy, this transformation further extends to a value orientation of "technology for good," guiding emerging factors such as artificial intelligence and digital technology to tilt toward green and low-carbon fields, avoiding the disconnection between technological development and ecological protection.

Stage 2: Institutional-Rule Transformation—From Traditional Behavioral Norms to Modern Governance Tools

The behavioral norms in traditional ecological culture are transformed into institutional rules and policy tools for modern environmental governance through policy

construction. Pan Yue [2] systematically sorts out the empowering role of traditional Chinese culture in ecological civilization systems, pointing out that ecological norms in Confucian "ritual system" (such as "worship of mountains and rivers" and "hunting seasons") can be converted into modern environmental regulatory systems, Taoist "circular concept" into resource recycling policies, and Mohist "frugality" thought into energy conservation and emission reduction policies. Zhang Kai and Zhang Ying [4] propose a "three-dimensional transformation framework," integrating traditional ecological wisdom into the development concept of "lucid waters and lush mountains are invaluable assets," ecological clauses in village regulations and people's conventions, and ecological protection red line systems, realizing in-depth integration with the contemporary governance system. Meanwhile, the policy construction process fully considers the impact of the digital economy on employment and income distribution [11], as well as the role of SMEs in low-carbon transitions [12], making the institutional rules transformed from ecological culture more practically adaptable.

Stage 3: Practical-Behavioral Transformation—From Traditional Lifestyles to Modern Low-Carbon Behaviors

Through educational dissemination and social guidance, the transformed low-carbon values and institutional rules are internalized into conscious low-carbon behaviors of the public and enterprises. At the public level, traditional concepts of "frugality" and "simplicity" are converted into daily behaviors such as low-carbon consumption and green travel; at the enterprise level, the moral norm of "caring for people and loving all things" is transformed into operational behaviors such

as green production, pollution reduction, and green innovation; at the government level, the governance concept of "harmony between humans and nature" is converted into administrative behaviors such as low-carbon policy formulation, green spatial planning, and ecological protection [8]. This transformation process is consistent with the requirements of sustainable built environments [13], promoting the formation of a collaborative low-carbon behavior system involving "government-enterprises-public."

Synergistic Empowerment Mechanism: Core Pathways of Traditional Chinese Ecological Culture Driving Regional Low-Carbon Economies

Through modern transformation, traditional Chinese ecological culture forms "cultural capital," which constitutes a "four-dimensional synergistic" empowerment system with digital technology, SMEs, and sustainable built environments. It constructs a multi-dimensional and multi-level empowerment mechanism across three tiers: micro-level enterprise transformation, meso-level industrial upgrading, and macro-level regional governance. Drawing on empirical literatures such as Du et al. (2022), Xu et al. (2021), and Li et al. (2023), combined with emerging economic research by Gu et al. (2025), this section reveals its core functional pathways.

Composition of the Four-Dimensional Synergistic Empowerment System (Figure 3)

Core Leadership: Traditional Chinese Ecological Cultural Capital

As the core of the empowerment system, traditional Chinese ecological cultural capital provides value leadership and moral constraints, specifically reflected in: at the value level, guiding the transformation of regional development concepts from "economic priority" to "ecological priority and green development"; at the moral level, strengthening the ecological responsibility awareness of enterprises and the public; at the behavioral level, regulating low-carbon production, consumption, and governance behaviors.

Technological Support: Digital Economy and Artificial Intelligence

The digital economy and artificial intelligence provide technological empowerment for low-carbon transitions, specifically manifested as: efficiency improvement—optimizing resource allocation through big data and the Internet of Things to reduce emission reduction costs; technological innovation—promoting the R&D

and promotion of green technologies; information dissemination—facilitating the rapid diffusion of low-carbon concepts and technologies [12].

Subject Adaptation: Small and Medium-Sized Enterprises (SMEs)

As an important component of the regional economy, SMEs play a "bridge" role in low-carbon transitions, specifically reflected in: bridging skill mismatches—addressing talent gaps in low-carbon industries through flexible skill training and talent adaptation [12]; filling industrial chain gaps—providing products and services in segmented areas of the low-carbon industrial chain; promoting regional balance—driving low-carbon economic development in central and western regions and county areas.

Spatial Guarantee: Sustainable Built Environments

Sustainable built environments provide spatial support for low-carbon transitions, specifically manifested as: optimizing spatial layout—realizing the rational allocation of production, living, and ecological spaces; improving building energy efficiency—reducing carbon emissions from urban operations; improving green transportation systems—reducing carbon emissions in the transportation sector [13].

Three-Tier Empowerment Pathways

Micro-Level: the "Dual-Drive + Dual-Support" Mechanism for Promoting Corporate Low-Carbon Transformation

As the core subject of regional low-carbon economies, enterprises' green transformation relies on the synergistic effect of "cultural leadership + technological support + subject adaptation + spatial guarantee," forming a "dual-drive" of "innovation-driven and responsibility-constrained," coupled with a "dual-support" of "technological empowerment and spatial adaptation":

- 1) Innovation-Driven Effect: Confucian thought of "caring for people and loving all things" enhances managers' ecological moral responsibility, reduces short-term profit-seeking behaviors, and encourages enterprises to incorporate green innovation into their development strategies; the concept of "frugality" promotes enterprises to optimize production processes, reducing resource consumption and carbon emissions [5]. Digital technology provides technical support for corporate green innovation, such as artificial intelligence optimizing production processes and big data accurately matching green resources; SMEs accelerate the application and diffusion of green technologies within enterprises by bridging skill mismatches [12]. Empirical research shows that in regions with a strong Confucian cultural at-

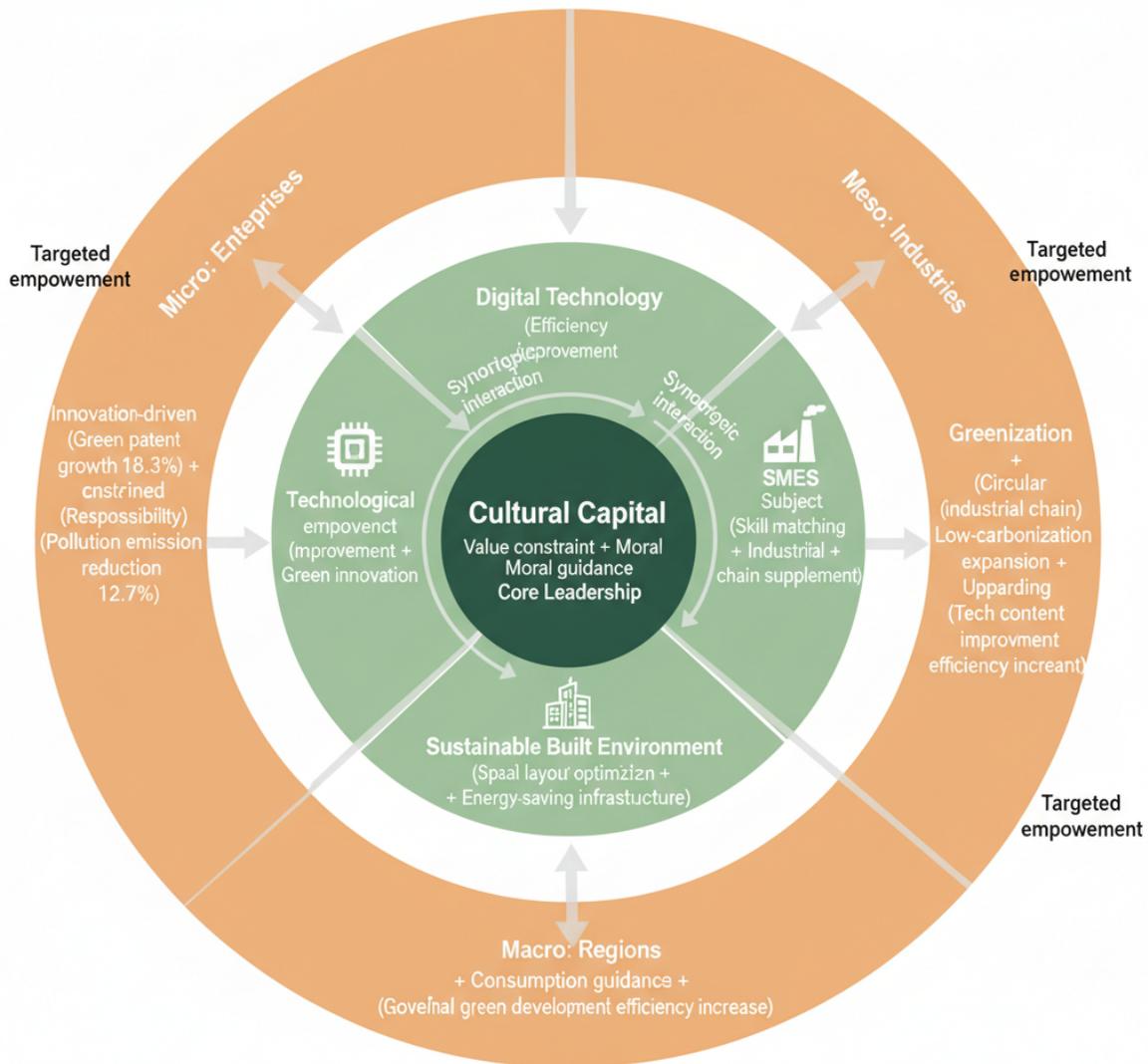


Figure 3 | Four-dimensional synergistic empowerment mechanism

mosphere, the number of green patent applications by enterprises increases by an average of 18.3% [5], and the application of digital technology can further amplify this effect.

- 2) Responsibility-Constrained Effect: Traditional culture restricts corporate pollution behaviors through a "social reputation mechanism"—in regions with a strong cultural atmosphere, corporate pollution behaviors are prone to condemnation by community public opinion, increasing reputation costs and forcing enterprises to reduce emission intensity [6]. Confucian "integrity" and Taoist "reverence for nature" form dual moral constraints, while sustainable built environments regulate enterprise location selection and production layout from the spatial level [13], forming a dual guarantee of "moral constraints + spatial constraints." Research by Xu et al. [6] shows that for

each one-standard-deviation increase in the traditional culture index, the intensity of corporate pollution emissions decreases by 12.7%.

Meso-Level: the "Three-Oriented + Three-Synergistic" Mechanism for Promoting Industrial Low-Carbon Upgrading

Industrial low-carbon upgrading is a core link in regional low-carbon economic development. Traditional Chinese ecological cultural capital guides the "greenization, low-carbonization, and upgrading" of industries, forming a "three-synergistic" mechanism with digital technology, SMEs, and built environments:

- 1) Industrial Greenization: The holistic thinking of "harmony between humans and nature" guides the adaptation of regional industrial layout to the natural environment, avoiding the excessive agglomeration of high-pollution and high-energy-consuming industries;

the concept of "circular symbiosis" promotes the circular development of industries, forming a circular industrial chain of "resources-products-waste-recycled resources." Digital technology provides technical support for industrial circularization, such as the Internet of Things enabling precise management and control of resource recycling; SMEs promote the implementation of circular economic models by participating in segmented links of the circular industrial chain.

- 2) **Industrial Low-Carbonization:** The concept of "frugality" guides industries to reduce energy consumption and carbon emissions, promoting the transformation and upgrading of high-energy-consuming industries; low-carbon consumption culture drives demand for low-carbon industries, guiding market resources to tilt toward low-carbon industries such as new energy and energy conservation and environmental protection. The digital economy promotes cross-border integration of low-carbon industries, such as the integration of low-carbon agriculture with rural tourism and the integration of green manufacturing with modern service industries; sustainable built environments provide spatial carriers for low-carbon industries, such as the construction of low-carbon industrial parks and green industrial parks [13].
- 3) **Industrial Upgrading:** Traditional concepts of "innovation" and "progress" (such as Confucianism's "If one can improve oneself in one day, do so each day, and keep doing so") drive enterprises to increase investment in green technology R&D, promoting the upgrading and intelligent transformation of low-carbon industries. Digital technologies such as artificial intelligence and big data enhance the technological content and added value of low-carbon industries; through technological innovation and model innovation, SMEs inject vitality into the upgrading of low-carbon industries [12].

Macro-Level: the "Three-Dimensional + Three-Guarantee" Mechanism for Improving Regional Green Development Efficiency

At the regional level, traditional Chinese ecological cultural capital provides three-dimensional support for green development efficiency through technology diffusion, consumption guidance, and governance optimization, while forming three guarantees with digital technology, SMEs, and built environments:

- 1) **Technology Diffusion Support:** In regions with a strong ecological cultural atmosphere, enterprises' green innovation achievements are more likely to diffuse across subjects and industries, forming "innovation clusters" and reducing the overall regional emission reduction costs. Digital technology breaks

geographical restrictions, promoting the sharing and adaptation of green technologies on a larger scale; as important carriers of technology diffusion, SMEs accelerate the extension of green technologies to county and rural areas [12].

- 2) **Consumption Guidance Support:** Traditional ecological concepts of "frugality" and "simplicity" are transformed into public low-carbon consumption behaviors through educational dissemination, driving demand for regional low-carbon industries and guiding market resources to tilt toward green industries. The digital economy facilitates the dissemination of low-carbon consumption information, making it easier for consumers to supervise enterprises' low-carbon behaviors and further strengthening the guiding role of low-carbon consumption in industrial structure; sustainable built environments promote the formation of low-carbon consumption behaviors by optimizing consumption scenarios (such as green shopping malls and low-carbon communities) [13].
- 3) **Governance Optimization Support:** The traditional governance concepts of "harmony in diversity" and "collaborative governance" guide regions to construct a multi-stakeholder collaborative low-carbon governance system involving "government-enterprises-public-social organizations." Digital technology improves governance efficiency, such as big data enabling precise monitoring of carbon emissions and blockchain ensuring the transparency of carbon trading; the extensive participation of SMEs and the public enhances the relevance and effectiveness of low-carbon governance; sustainable built environments provide spatial platforms for multi-stakeholder collaborative governance, such as the construction of community deliberation spaces and ecological protection collaboration platforms.

Empirical research by Li Wei et al. [7] shows that there is a significant positive correlation between cultural capital and regional green development efficiency, presenting a "marginal effect increasing" characteristic. Meanwhile, the level of digital technology, SME development, and built environment quality all have a positive regulatory effect on this correlation.

Regional Practice: Models, Challenges, and Optimization Pathways of Ecological Culture Empowering Low-Carbon Transitions

The value of theories and mechanisms is ultimately reflected through regional practice. Drawing on literatures such as Zuo et al. (2021), Wang et al. (2018), and Chen & Pan (2017), combined with emerging economic

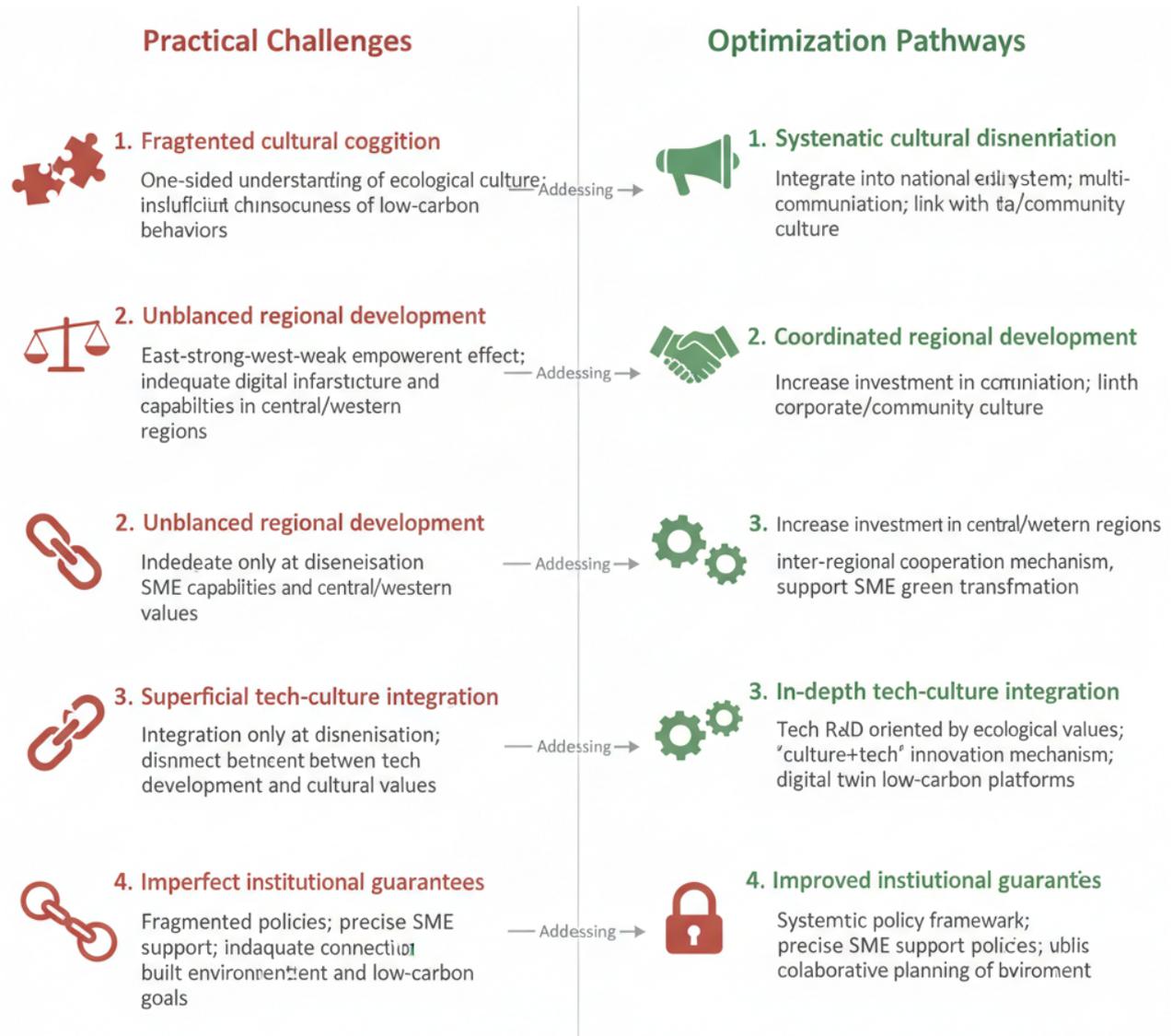


Figure 4 | Practical challenges and corresponding optimization pathways

research by Gu et al. (2025), this section sorts out the typical practice models, realistic challenges, and targeted optimization pathways of ecological culture empowering regional low-carbon transitions (Figure 4).

Typical Practice Models

"Culture + Education and Communication" Model: Cultivating the Social Foundation for Low-Carbon Development

This model integrates traditional Chinese ecological culture into public cognition through a three-dimensional system of basic education, higher education, and social education, transforming it into low-carbon behaviors. At the basic education stage, primary and secondary schools incorporate ecological knowledge from

the "Twenty-Four Solar Terms" and ancient environmental protection stories (such as "Mencius opposing over-hunting") into courses such as "Morality and Rule of Law" and "Science," fostering low-carbon awareness among young people [8]; at the higher education stage, universities offer interdisciplinary courses such as "Traditional Ecological Wisdom and Low-Carbon Development," cultivating "ecology + technology" compound talents to meet the skill demands brought about by the digital economy [12]; at the social education stage, ecological concepts such as "harmony between humans and nature" and "frugality and caring for others" are disseminated through community cultural walls, village regulations and people's conventions, and digital media, guiding the public to form low-carbon lifestyles. For example, Anji in Zhejiang Province combines "bamboo

culture" with low-carbon industries, guides residents to participate in green production and living through community education and digital platforms, and collaborates with SMEs to carry out skill training, bridging skill mismatches in low-carbon industries.

"Culture + Spatial Governance" Model: Building Spatial Carriers for Low-Carbon Development

This model combines the "spatial harmony" concept in traditional ecological wisdom with the requirements of sustainable built environments, optimizes regional spatial layout, and builds spatial carriers for low-carbon development. At the urban level, it preserves "mountains and rivers patterns" (such as Suzhou's water towns and Beijing's central axis greening), constructs green transportation systems and low-carbon building clusters, and reduces carbon emissions from urban operations [9]; at the county level, it develops low-carbon tourism and ecological agriculture relying on ecological and cultural resources, achieving a win-win situation of "ecological protection + economic development"; at the industrial park level, it builds circular economic parks to realize resource sharing and waste recycling, in line with the traditional concept of "circular symbiosis" [13]. For example, Huangshan in Anhui Province integrates "Taoist ecological wisdom" into scenic area planning and management, constructs green transportation systems, implements garbage classification and resource recycling, and builds a low-carbon scenic area integrating "ecology-tourism-culture."

"Culture + Policy Integration" Model: Constructing Institutional Guarantees for Low-Carbon Development

This model integrates traditional Chinese ecological culture into the regional low-carbon policy framework, promoting the transformation of cultural capital into low-carbon development momentum through policy guidance and institutional constraints. At the national level, the concept of "harmony between humans and nature" is transformed into the development goal of "harmonious coexistence between humans and nature," and the idea of "frugality" is converted into policies such as total energy consumption control and energy conservation and emission reduction [10]; at the local level, the inheritance of ecological culture and the effectiveness of low-carbon development are included in the assessment indicators of local governments, and policies supporting SMEs' participation in low-carbon transitions are introduced (such as financial subsidies and tax incentives) to encourage enterprises to apply green technologies and carry out skill training [12]; at the community level, traditional village regulations and people's conventions are combined with modern low-carbon

norms to formulate community low-carbon conventions, strengthening the constraints on public low-carbon behaviors. For example, Suzhou in Jiangsu Province integrates "Confucian integrity culture" into the enterprise environmental credit evaluation system, providing policy inclinations for enterprises with good environmental credit and forcing enterprises to fulfill their low-carbon responsibilities.

Realistic Challenges

Despite certain achievements in ecological culture empowering regional low-carbon transitions in China, four major realistic challenges persist:

Fragmented Cultural Cognition and Inadequate Value Transformation

Some regions have a one-sided understanding of the core connotations of traditional Chinese ecological culture, simply equating it with "ecological tourism promotion" or "traditional cultural performances," while neglecting its modern transformation at the levels of value ethics and institutional rules; the public has insufficient understanding of the inherent connection between ecological culture and low-carbon development, and low-carbon behaviors lack cultural consciousness, mostly relying on external constraints, making it difficult to form a long-term mechanism.

Unbalanced Regional Development and Gaps in Synergistic Empowerment

Eastern regions are leading central and western regions in terms of cultural capital transformation, digital infrastructure, SME development level, and built environment quality, resulting in an "east-strong-west-weak" pattern in the empowering effect of ecological culture [7]; central and western regions have weak digital infrastructure, insufficient green transformation capabilities of SMEs, and poor adaptability of built environments, which restrict the synergistic empowerment of cultural capital and emerging factors.

Superficial Integration Between Technology and Culture and Low Empowerment Efficiency

The current integration of digital technology and ecological culture mostly remains at the dissemination level (such as digital media disseminating ecological culture), with insufficient integration in core areas such as green technology innovation, low-carbon industrial upgrading, and regional governance optimization; there is a certain disconnect between technological development and cultural values, and some digital technology applications still prioritize "efficiency," neglecting the cultural connotation of ecological protection.

Imperfect Institutional Guarantees and Obstacles to Practical Implementation

The institutional design for ecological culture empowerment lacks systematicness, with fragmented and inconsistent policies; support policies for SMEs' participation in low-carbon transitions are not precise enough, and the support for skill training and technological R&D is insufficient [12]; the connection between built environment planning and low-carbon policies, as well as cultural inheritance, is not close enough, making it difficult to balance the ecological rationality and economic sustainability of spatial layout [13].

Optimization Pathways

In response to the above challenges, combined with the theoretical and mechanism analysis above, the following optimization pathways are proposed:

Strengthen Systematic Cultural Dissemination and Deepen Value Transformation

Construct an ecological culture dissemination system led by the government, supported by academic circles, linked with the media, and participated by the public. Systematically disseminate the core connotations of traditional Chinese ecological culture through compiling popular readers, producing special programs, and organizing cultural activities; incorporate ecological culture into the national education system, forming a complete curriculum chain from basic education to higher education, and cultivating "culture + low-carbon" compound talents; promote the in-depth integration of ecological culture with corporate culture and community culture, transforming concepts such as "harmony between humans and nature" and "frugality and caring for others" into corporate business philosophy and public behavioral norms.

Coordinate Regional Development and Narrow the Gap in Empowerment

Increase policy inclination and resource investment in central and western regions, improve digital infrastructure construction, and enhance the accessibility of green technologies; support the development of SMEs in central and western regions, strengthen their green transformation capabilities and skill adaptation capabilities through skill training, technology incubation, and financial support [12]; develop characteristic industries such as low-carbon tourism and ecological agriculture based on the unique ecological and cultural resources in central and western regions, realizing a virtuous cycle of "cultural resources - economic development - ecological protection"; establish a coordination mechanism between eastern and central-western re-

gions to promote the cross-regional flow of cultural capital, digital technology, and green industries.

Promote in-Depth Integration Between Culture and Technology and Improve Empowerment Efficiency

Guided by ecological cultural values, promote the focus of digital technology on green and low-carbon fields, such as using artificial intelligence to optimize green technology R&D, big data to achieve precise carbon emission control, and blockchain to improve the carbon trading system; develop innovative "culture + technology" products and services, such as low-carbon lifestyle APPs based on traditional ecological wisdom and digital twin low-carbon community platforms; establish a "culture-technology-industry" integrated innovation mechanism, encouraging cooperation between enterprises, universities, and research institutions to develop low-carbon technologies and products with both cultural connotations and technological content.

Improve the Institutional Guarantee System and Strengthen Practical Implementation

Construct a systematic institutional framework for ecological culture empowerment, incorporating ecological culture inheritance, digital technology application, SME support, and built environment optimization into regional low-carbon development plans; introduce precise policies to support SMEs' participation in low-carbon transitions, focusing on skill training, green technology R&D and application, and low-carbon industrial chain integration [12]; establish a collaborative planning mechanism between built environments, low-carbon development, and cultural inheritance, integrating ecological cultural connotations into urban spatial layout, architectural design, and transportation system construction to improve spatial adaptability [13]; improve the assessment and evaluation system, incorporating indicators such as cultural empowerment effectiveness, regional coordinated development, and technology-culture integration into local government assessments, and strengthening policy implementation supervision.

Conclusions

By integrating core literatures from multiple disciplines, this study constructs a comprehensive analytical framework of "Cultural Connotations → Modern Transformation → Synergistic Empowerment → Regional Practice → Optimization Pathways," systematically revealing the intrinsic logic and core mechanisms of traditional Chinese ecological culture empowering regional low-carbon economies. The key conclusions are as follows:

- 1) Centered on "harmony between humans and nature," traditional Chinese ecological culture forms an ecological wisdom system with holism, moderation, responsibility, and circularity. Through a three-stage transformation of "value ethics - institutional rules - practical behaviors," it becomes a cultural capital adapted to modern low-carbon development;
- 2) Ecological cultural capital forms a "four-dimensional synergistic" empowerment system with digital technology, SMEs, and sustainable built environments. It achieves all-round empowerment of regional low-carbon economies through four pathways—"value constraint, technological drive, subject adaptation, and spatial guarantee"—across three tiers: micro-level enterprise transformation, meso-level industrial upgrading, and macro-level regional governance;
- 3) Three typical practice models have been formed in China: "culture + education and communication," "culture + spatial governance," and "culture + policy integration." However, challenges such as fragmented cultural cognition, unbalanced regional development, superficial integration between technology and culture, and imperfect institutional guarantees persist;
- 4) By strengthening systematic cultural dissemination, coordinating regional development, promoting in-depth integration between culture and technology, and improving the institutional guarantee system, the realistic bottlenecks can be effectively addressed, and the efficiency and sustainability of ecological culture empowering regional low-carbon economies can be enhanced.

Future research can be further deepened in three directions: First, conduct quantitative research to construct an evaluation index system for ecological cultural capital, digital technology, SME development, and built environment quality, and empirically test the effectiveness and boundary conditions of the four-dimensional synergistic empowerment mechanism; second, focus on specific regions or industries to carry out case stud-

ies, in-depth analyzing the differences and adaptability of ecological culture empowerment models in different regions and industries; third, expand the international comparative perspective, exploring the uniqueness and universality of traditional Chinese ecological culture empowering low-carbon development, and providing a more referenceable "Chinese solution" for global sustainable development.

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Research Article

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AI Empowerment Logic in the Digital Transformation of Chinese Language Education: From Tool Application to Ecological Reconstruction

人工智能赋能汉语教育数字化转型的逻辑：从工具应用到生态重构

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Chinese Language Education;
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关键词:

汉语教育; 人工智能;
数字化转型; 生态重构;
人机协同; 教育治理

Abstract: With the coupled development of Generative Artificial Intelligence (GAI) and big data technologies, Chinese language education—especially international Chinese language education—is experiencing a critical leap from "information-assisted teaching" to "digital transformation." This study delves into the inherent evolutionary logic of AI empowerment in Chinese language education, arguing that its transformation path follows a three-stage progression: from efficiency-driven tool application in individual links, to full-process human-AI collaborative innovation, and ultimately to the systematic reconstruction of the educational ecosystem. The research elaborates on AI's profound impacts in reshaping learning paradigms, redefining teaching time and space, and enhancing teacher evaluation. It highlights that the essence of digital transformation lies in the reorganization of educational elements and the digital extension of educational sovereignty. Drawing on transnational cases and authoritative studies, this paper deconstructs the implementation paths of ecological reconstruction across four core dimensions: learning paradigms, resource development, evaluation systems, and governance mechanisms. Additionally, it offers forward-looking reflections on ethical challenges and technological boundaries in the current transformation, providing theoretical support and practical insights for building a high-quality, sustainable global digital ecosystem for Chinese language education.

摘要: 随着生成式人工智能 (GAI) 与大数据技术的融合发展, 汉语教育, 尤其是国际中文教育, 正在从“信息化辅助教学”迈向“数字化转型”的关键阶段。本文聚焦AI赋能汉语教育的内在演进逻辑, 认为其转型路径呈现三阶段递进: 由单一环节的效率型工具应用, 发展到全流程的人机协同创新, 最终走向教育生态的系统性重构。研究指出, AI正在重塑学习方式, 重构教学的时空组织, 并提升教师评价与改进的效能。数字化转型的本质在于教育要素的再组织, 以及教育治理能力在数字空间的延伸。基于跨国案例与权威研究, 本文从学习范式、资源开发、评价体系与治理机制四个维度梳理生态重构的实施路径, 并对当前转型中的伦理风险与技术边界进行反思, 为构建高质量、可持续的全球国际中文数字教育生态提供理论与实践参考。

Introduction

Amid the global wave of "educational digital transformation" advocated by UNESCO, the degree of digitalization in Chinese language education—an essential

carrier for language dissemination and cultural exchange—has become a core indicator of educational modernization [9]. Data from the Center for Language Education and Cooperation (CLEC) shows that the

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global number of Chinese learners has exceeded 200 million. However, international Chinese language education has long grappled with three structural dilemmas: first, a severe shortage of qualified teachers, with high-quality educators concentrated in China and a handful of developed countries, resulting in a student-teacher ratio exceeding 1:50 in many developing nations; second, the high threshold for Chinese character acquisition, as the uniqueness and cultural load of pictographic characters leave overseas learners struggling with "difficulty in reading/writing and superficial understanding"; third, the lack of authentic cross-cultural communication contexts, leading to the phenomenon of "being able to learn but unable to apply" [2].

Traditional information-based methods, such as static multimedia courseware and recorded lectures, only improve dissemination efficiency without touching the deep-seated transformation of educational logic. For instance, early Chinese learning websites primarily presented static knowledge points, achieving cross-regional resource dissemination but retaining the traditional "teacher-centered" model, which fails to meet the needs of personalized learning and interactive communication [8]. The explosive development of AI, particularly Generative AI represented by Large Language Models (LLMs), has provided an opportunity for bottom-up reconstruction in Chinese language education. AI is no longer merely a "scaffolding" for teaching but has gradually evolved into the "gene" of the educational ecosystem—it not only addresses efficiency issues but also reshapes teaching relationships, resource forms, and evaluation logic [6]. Exploring the evolutionary logic of AI empowerment is theoretically and practically significant for constructing a high-quality, sustainable global Chinese language education system, aligning with the core agenda of "technology empowerment and cross-cultural competence development" in transnational education research [11].

The Evolutionary Path of AI Empowerment in Chinese Language Education: a Three-Stage Logic

Initial Stage: Efficiency Enhancement Under Instrumental Logic

At this stage, AI primarily enters the teaching process as an "assistant," with its core logic centered on **"technology substituting for efficiency"**—replacing teachers' repetitive tasks through technical tools to reduce teaching costs and improve the efficiency of basic links [10]. Technological application at this stage is characterized by "single-point breakthroughs and ex-

ternal empowerment," without altering the core structure of traditional teaching.

In practical terms, it focuses on the intelligent upgrading of three types of basic tasks: first, auxiliary tools for language input and output, such as Optical Character Recognition (OCR) technology for digitizing and retrieving paper textbooks and ancient documents, helping learners quickly look up rare or polyphonic characters; Text-to-Speech (TTS) technology for generating standard Mandarin, Cantonese, and other accent streams to provide pronunciation references for overseas learners; and Automatic Speech Recognition (ASR) technology for developing Putonghua proficiency test simulation systems that real-time correct pronunciation issues such as tones and phonological changes [5]. Second, basic teaching management tools—for example, AI essay grading systems can automatically identify Chinese character writing errors and grammatical mistakes, generating basic revision suggestions to free teachers from heavy homework grading; course management platforms use AI to track attendance and learning duration, simplifying teaching administration. Third, resource retrieval tools, such as digital textbook and question banks that support quick filtering by knowledge points and difficulty levels, addressing the inefficiency of resource searching in traditional teaching [8].

At a deeper level, technological application at this stage is essentially "tool substitution"—AI acts as an externally inserted auxiliary means to solve high-repetition, low-creativity tasks in teaching. At this point, the physical field (classroom) and logical field (teachers imparting knowledge) of teaching remain unchanged; technology only plays a role in "improving efficiency and reducing burden," primarily alleviating the burden of "teaching" but failing to address core pain points of "learning," such as meeting personalized needs and constructing cultural contexts [3]. This logic of instrumental application is consistent with the principle of "complementarity between economic and teaching activities" in educational institutions, achieving a balance between improved teaching efficiency and resource cost control through technological optimization [12].

Developmental Stage: Human-AI Collaboration Under Integration Logic

With the maturity of adaptive algorithms and Natural Language Processing (NLP) technology, AI has begun to deeply intervene in the "learning" process, shifting its core logic from "efficiency substitution" to **"data-driven precision"**, realizing the initial reorganization of teaching elements and process reengineering [1]. At this stage, AI is no longer an isolated tool but forms a col-

laborative relationship with teachers and students, becoming an indispensable core element in the teaching process.

In practice, AI's application scenarios have expanded from "teaching assistance" to "learning empowerment": first, personalized learning path planning—constructing Chinese grammar and vocabulary systems based on knowledge graph technology, accurately identifying learners' knowledge gaps (such as preposition usage errors and Chinese character stroke order issues) through entrance assessments, and dynamically adjusting learning content and difficulty gradients [10]. For example, the AI system of an international Chinese education platform can strengthen tone discrimination training for Southeast Asian learners who struggle with tone perception, and push stroke order animations and interactive writing exercises for European and American learners who face difficulties in Chinese character writing. Second, intelligent Q&A and companion learning—Chinese intelligent teaching assistants developed based on large language models can provide 24/7 real-time responses, answering learners' questions about vocabulary, grammar, and cultural backgrounds, and even simulating real dialogue scenarios for oral practice [6]. Third, teaching decision support—by analyzing learners' learning behavior data (such as answer accuracy, learning duration, and interaction frequency), AI generates learning situation analysis reports for teachers, highlighting key knowledge points that require emphasis and student groups that need attention, enabling teachers to implement precise teaching [4].

At a deeper level, the core transformation at this stage is the "reconstruction of teaching relationships": the teaching process has shifted from "group uniformity" to "large-scale personalization." AI acts as a digital twin of teachers, undertaking tasks such as learning situation diagnosis, personalized push, and basic Q&A, while teachers focus on high-level links such as teaching design, cultural guidance, and emotional support [7]. Data has become the blood connecting teachers, students, and resources, forming a teaching closed loop of "diagnosis-push-feedback-optimization," marking the transformation of Chinese language education from "experience-driven" to "data-driven" [3]—a shift that also provides a new path for "precision competence development" in cross-cultural Chinese learning [11].

Advanced Stage: Systematic Reconstruction Under Ecological Logic

This is the ultimate goal of digital transformation. AI is no longer an isolated module but a technical foundation integrated into the educational ecosystem, with its

core logic centered on "**digitally endogenous paradigm reshaping**", achieving a leap from teaching link optimization to comprehensive educational system reconstruction [2]. At this stage, the logic of technological empowerment has transcended tool application itself, rising to profound changes in organizational structure, evaluation logic, educational boundaries, and educational sovereignty.

In practical terms, ecological reconstruction is reflected in three types of innovative scenarios: first, the construction of immersive and collaborative learning environments—creating "digital twin classrooms" through VR/AR technology, allowing global learners to jointly participate in Chinese teaching activities in virtual reality. For example, simulating traditional Chinese festival scenarios (such as pasting Spring Festival couplets and making zongzi during the Dragon Boat Festival) to learn language and experience culture through interactive experiences; using multimodal interaction technology to achieve real-time cross-regional collaboration, enabling overseas learners to team up with Chinese students for project-based Chinese learning (such as co-producing Chinese Vlogs and conducting cross-cultural research) [6]. Second, the construction of a decentralized resource ecosystem—building an open-source Chinese education platform based on AI, encouraging teachers and learners worldwide to participate in resource creation and optimization. AI is responsible for semantic annotation, quality review, and precise distribution of resources, forming a "co-construction, sharing, and dynamic evolution" resource ecosystem [5]. Third, the construction of a new educational governance system—establishing a blockchain and AI-based academic credit certification and evaluation system to realize the mutual recognition of Chinese learning achievements among different institutions and countries; using AI to monitor the fair distribution of educational resources, promoting the tilt of high-quality digital resources toward developing countries [9].

At a deeper level, the educational ecosystem at this stage has transformed from "closed and hierarchical" to "open and platform-based": school boundaries have blurred, with informal learning (such as short-video Chinese learning and AI companion practice) deeply integrating with formal learning (classroom teaching and credit courses); educational subjects have diversified, with governments, schools, enterprises, and learners jointly participating in ecological construction; educational sovereignty has achieved digital extension—China enhances its discourse power and influence in global Chinese language education by exporting digital standards, core technologies, and high-quality resources [2]. This process of ecological reconstruction

fully reflects the "in-depth complementarity between economic and teaching activities" in educational institutions—the economic attributes of technical platforms provide sustainable support for teaching activities, while the high-quality output of teaching activities feeds back the optimization of the platform ecosystem [12].

Core Dimensions and Logical Implementation of Ecological Reconstruction

Reconstruction of Learning Paradigms: From "Acquisition" to "Symbiosis"

Traditional Chinese learning emphasizes rote memorization and repetitive practice, with learners often in a passive receptive state, making it difficult to form genuine language competence and cultural perception [8]. Ecological reconstruction empowered by AI advocates **"embodied learning" and "adaptive learning"**, realizing a fundamental transformation of learning paradigms [4].

The core of embodied learning is "situationalization and experientialization." Through multimodal interaction technology, AI can create authentic communication contexts for students, transforming Chinese learning from mere symbol memory to semantic understanding and cultural perception. For example, for business Chinese learners, AI can simulate workplace scenarios such as job interviews, business negotiations, and product introductions, allowing learners to interact with AI through multimodal methods (voice, text, body language) to master professional vocabulary and communication etiquette in practice; for adolescent learners, AI can construct Chinese adventure game scenarios where learners advance through solving language puzzles and completing Chinese tasks, improving language application ability in immersive experiences [10]. Adaptive learning emphasizes "personalization and dynamic adjustment"—based on learners' cognitive characteristics, learning progress, and interests, AI real-time adjusts learning content and methods. For visual learners, it pushes more image and video resources; for auditory learners, it strengthens audio materials and oral practice; for fast-progressing learners, it adds extended content; for learners facing difficulties, it provides step-by-step guidance and encouraging feedback [6].

This paradigm shift transforms learners from passive recipients into active explorers and creators in the digital environment. Chinese learning changes from "being forced to learn" to "wanting to learn," and from "learning to know" to "learning to use," truly realizing the synchronous improvement of language competence and

cultural literacy [2]—aligning with the core perspective of "cultivating cross-cultural competence through situational learning" in transnational education research [11] (**Figure 1**).

Reconstruction of Resource Development: From "Static Textbooks" to "Dynamic Semantic Libraries"

Traditional Chinese education resources are centered on paper textbooks, with three limitations: first, outdated content updates, as textbook content often fails to keep up with the real-time development of Chinese and social hot topics; second, serious homogenization, making it difficult to meet the personalized needs of different regions and learning objectives; third, weak interactivity, with learners only able to passively read without in-depth participation [5]. Digital transformation requires resources to be highly interactive and semanticized. AI technology provides core support for the reconstruction of resource development [1].

AI-empowered resource development presents three major transformations: first, the shift in resource production logic from "expert compilation and one-way distribution" to "AI-assisted, multi-stakeholder co-construction, and dynamic generation." By capturing real-time Chinese corpora from the entire network, AI can dynamically generate Chinese reading materials suitable for learners' proficiency levels, completely solving the problem of outdated textbooks and content disconnected from real life [10]. For example, for learners interested in China's technological development, AI can automatically screen recent Chinese technology news, simplify complex sentence structures, and label key vocabulary before pushing; for learners preparing for the HSK exam, AI can generate simulation questions that match the exam difficulty and question types. Second, the diversification of resource forms—shifting from single text and image resources to multimodal, interactive resources. AI can transform classic literary works into audio books, animated short films, or interactive scripts, and Chinese character teaching into stroke order games and radical puzzles, enhancing resource attractiveness and participation [8]. Third, the precision of resource distribution mechanisms—achieving "one-size-fits-one" resource push based on knowledge graph and user portrait technology. Chinese education platforms can automatically match the most suitable learning resources according to learners' progress (such as mastered vocabulary and grammar points), learning objectives (such as HSK exams, business communication, or cultural experience), and interests (such as sports, art, and food), preventing learners from "getting lost" in massive resources [3].

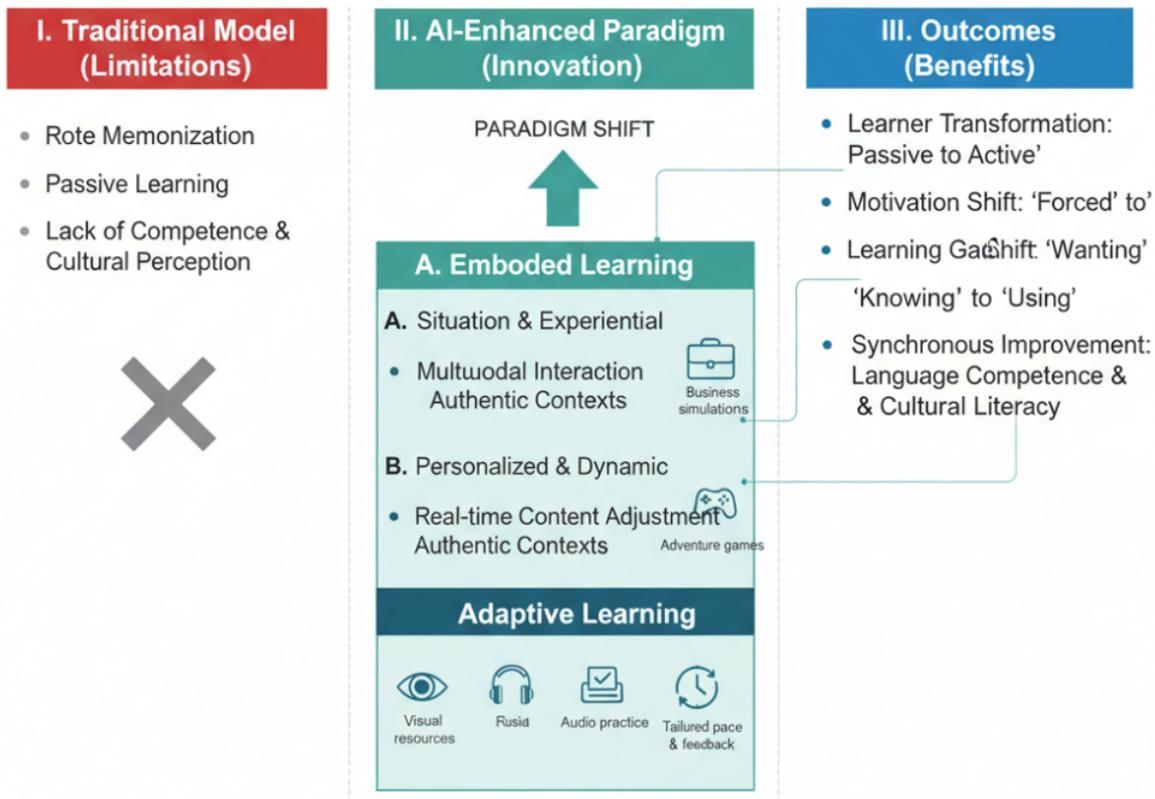


Figure 1 | AI-Empowered Transformation of Chinese Language Learning

The construction of such dynamic semantic libraries enables Chinese education resources to break through time and space constraints, achieving unlimited expansion and precise supply, laying the foundation for the balanced development of global Chinese language education [9]. Meanwhile, it realizes the precise alignment between teaching activities and market demands through "dynamic resource updates," reflecting the complementarity between economic and teaching activities in educational institutions [12] (Figure 2).

Reconstruction of Evaluation Systems: From "Summative Scores" to "Full-Process Profiles"

Traditional Chinese education evaluation is centered on summative assessments (such as the HSK exam and final classroom exams), with a single evaluation standard and closed evaluation process. It is difficult to fully reflect learners' language competence and learning processes, and suffers from the drawbacks of "valuing knowledge over ability" and "valuing results over processes" [4]. The development of AI technology provides technical support for the reconstruction of evaluation systems, making "full-process, multi-dimensional, and personalized" evaluation possible [7].

The reconstruction of AI-empowered evaluation systems is reflected in three dimensions: first, the comprehensive collection of evaluation data—AI can real-time track micro-data during learners' language input, output, and interaction processes, including pronunciation accuracy, vocabulary richness, grammatical correctness, and expression fluency. It can even capture non-verbal information such as facial expressions and body language through cameras, comprehensively reflecting learners' language competence and learning status [6]. For example, in oral evaluation, AI can not only identify pronunciation errors but also analyze phonological changes, intonation fluctuations, and emotional expression, providing a more comprehensive assessment; in writing evaluation, AI can analyze multiple dimensions such as content completeness, logical coherence, language standardization, and expression innovation, rather than merely focusing on grammar and spelling errors [10]. Second, the dynamicization of evaluation methods—shifting from "one-exam-determines-all" to "full-process continuous evaluation." By continuously collecting learners' learning data, AI generates dynamically updated "Chinese proficiency profiles," clearly showing learners' strengths and weaknesses, progress trajectories, and development potential, enabling learn-

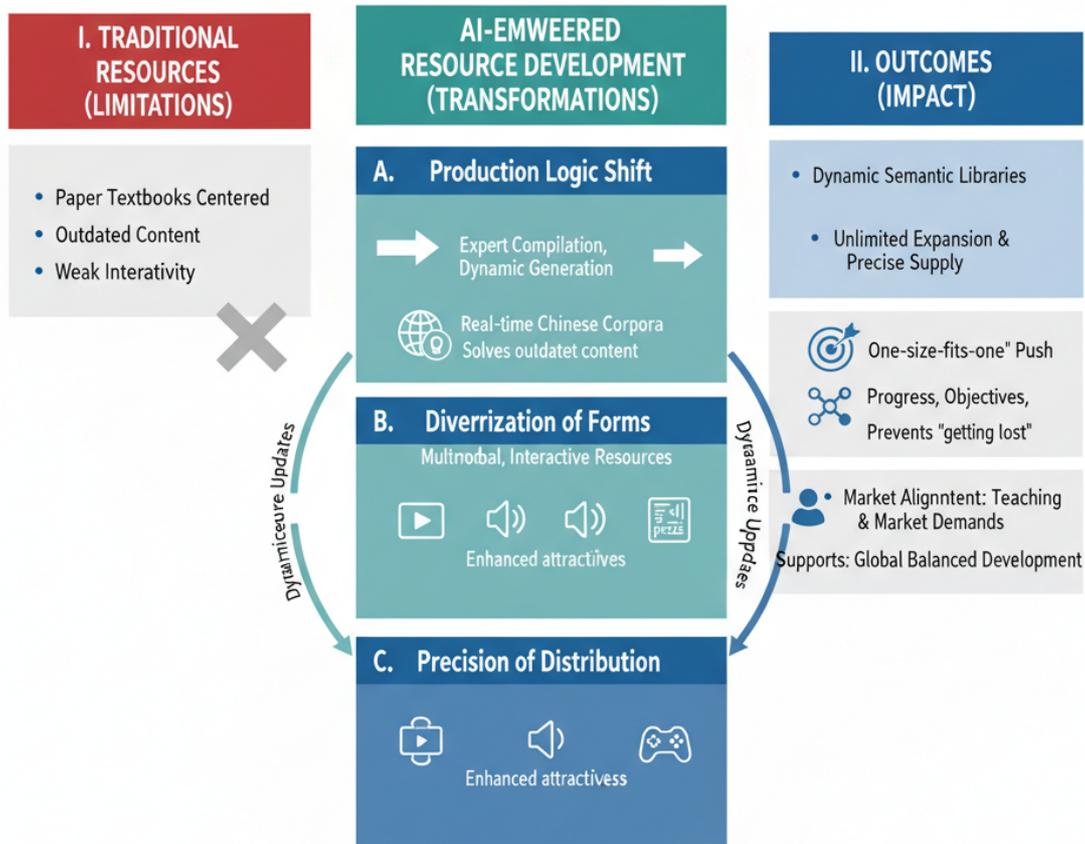


Figure 2 | AI-Empowered Resource Development for Chinese Language Education

ers and teachers to timely understand learning effects and adjust learning and teaching strategies [3]. Third, the transformation of evaluation functions—from "screening and differentiation" to "diagnosis and empowerment." Evaluation results are no longer merely scores and rankings but specific ability analysis reports and personalized improvement suggestions. For example, AI can recommend relevant grammar explanations and exercises for learners' preposition usage errors, and push targeted pronunciation training resources for pronunciation problems, making evaluation an important link to promote learning [4].

This reconstruction of the evaluation system shifts the focus of Chinese language education from "knowledge indoctrination" to "ability cultivation," and from "result-oriented" to "process-oriented," truly realizing the deep integration of evaluation and teaching [2], and providing technical support for "precise ability profiling" of cross-cultural Chinese learners [11] (Figure 3).

Reconstruction of Governance Mechanisms: From "Single Management" to "Multi-Stakeholder Collaboration"

Traditional Chinese education governance takes governments and schools as core subjects, with a relatively closed governance model characterized by delayed decision-making, uneven resource distribution, and supervision difficulties [9]. Ecological reconstruction empowered by AI promotes the transformation of governance mechanisms from "single management" to "multi-stakeholder collaboration," constructing a new governance system of "government guidance, market-driven, school-led, and social participation" [1].

Specifically, the reconstruction of governance mechanisms is reflected in three levels: first, the digital transformation of government governance—governments build big data platforms for Chinese language education to real-time monitor the global development of Chinese language education (such as learner scale, teacher distribution, and resource usage), providing data support for policy formulation; they formulate application standards, ethical norms, and data security rules for AI in Chinese language education to guide the orderly devel-

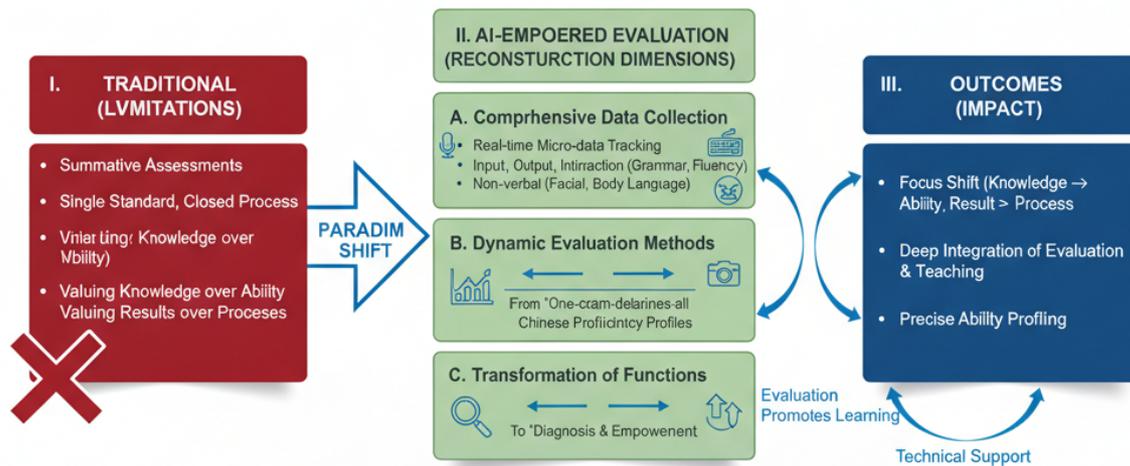


Figure 3 | AI-Empowered Evaluation System Reconstruction for Chinese Language Education

opment of digital transformation [9]. For example, the "Action Plan for International Chinese Online Education (2021-2025)" issued by the CLEC clearly proposes to "establish an international Chinese education digital standard system and regulate the application of AI technology" [9]. Second, the collaborative governance between markets and schools—deep cooperation between AI enterprises and Chinese education institutions, with enterprises focusing on technology R&D and resource supply, and schools focusing on teaching innovation and talent training, forming a "demand-oriented, complementary advantage" cooperation mechanism [6]. For example, technology companies and universities collaborate to develop specialized large models for Chinese language education, combining universities' teaching experience with enterprises' technological advantages to create intelligent products more in line with teaching needs; schools obtain high-quality resources and technical support through the use of enterprise digital platforms, while providing teaching scenarios and data feedback for enterprises to promote technological iteration [3]. This cooperation model not only optimizes teaching effects but also realizes the market-oriented efficient allocation of educational resources, fully reflecting the complementarity between economic and teaching activities in educational institutions [12]. Third, the widespread participation of society—encouraging Chinese teachers, scholars, and learners worldwide to participate in the formulation of Chinese education standards, resource construction, and quality supervision through open-source communities and crowdsourcing platforms, forming a "co-construction, co-governance, and shared" governance pattern [5].

This multi-stakeholder collaborative governance mechanism breaks the closedness and hierarchy of traditional governance, improving the precision, efficiency, and fairness of Chinese language education governance, and providing institutional guarantee for the global digital transformation of Chinese language education [2] (Figure 4).

Challenges and Reflections: the Boundaries of Technological Rationality

Despite the clear logic and broad prospects of AI empowerment in Chinese language education, three core challenges remain in practice, requiring us to grasp the boundaries of technological rationality and achieve a balance between technological empowerment and humanistic care [4].

The Challenge of Digital Divide and Educational Equity

Unequal distribution of technical resources may widen the "gap between the rich and the poor" in global Chinese language education, exacerbating educational inequality [9]. On one hand, there is a significant gap in hardware facilities—learners in developed countries generally have access to high-speed networks and intelligent terminals, while some regions in developing countries still face insufficient network coverage and equipment shortages, making it difficult to access AI-empowered high-quality educational resources. On the other hand, there is a clear gap in digital literacy—teachers and learners in different regions vary in AI tool application capabilities, data literacy, and critical thinking. Some teachers may struggle to effectively use AI

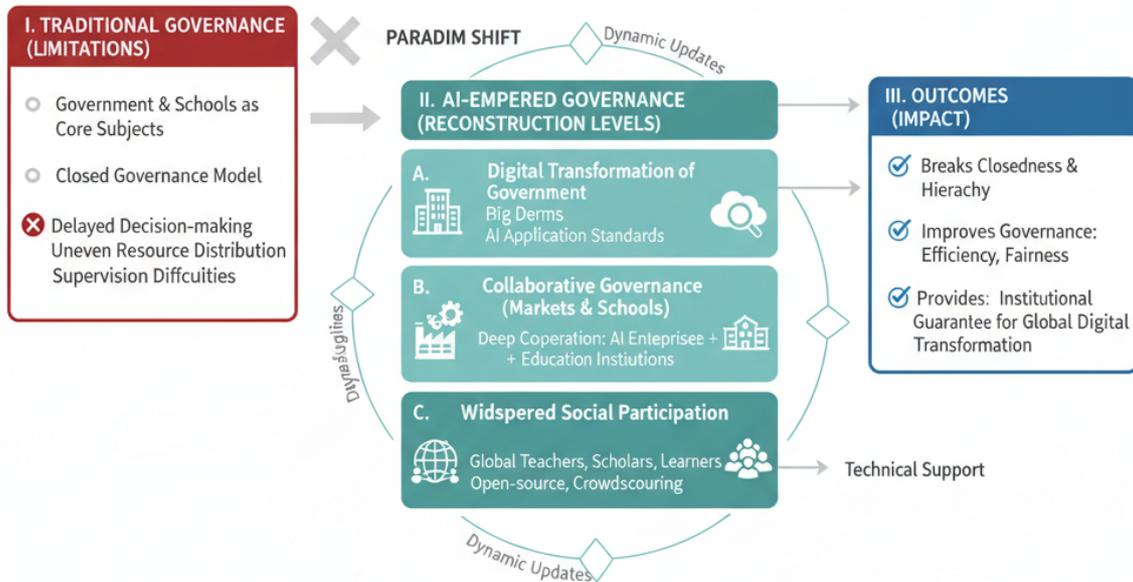


Figure 4 | AI-Empowered Governance Reconstruction for Chinese Language Education

technology due to insufficient digital literacy, while some learners may fall into "technological dependence" without guidance [7]. This digital divide may further expand the development gap in Chinese language education, violating the basic concept of "educational equity" [2] and affecting the foundation of "equal participation" in transnational Chinese education [11].

The Risk of Losing Cultural Subjectivity

Chinese language education is not only language teaching but also an important carrier for cultural dissemination, with its core goal of cultivating learners' Chinese competence and Chinese cultural literacy [8]. Over-reliance on AI algorithms for content generation may lead to the oversimplification or misinterpretation of the profound cultural connotations behind Chinese—AI-generated Chinese materials may only focus on the correctness of language forms while ignoring the transmission of cultural connotations; AI-simulated communication scenarios may lack authentic cultural contexts, resulting in learners' superficial understanding of Chinese [5]. More seriously, if AI algorithms' training data contains Western-centric cultural biases, it may subtly influence learners' perception of Chinese culture, weakening the cultural communication function of Chinese language education [6]. How to uphold cultural subjectivity in technological empowerment and avoid "language instrumentalization and cultural superficialization" is a core issue that must be addressed in the digital transformation of Chinese language education [2]

—a problem that is particularly prominent in transnational education scenarios [11].

The Ethical Dilemma of Algorithmic Bias and Privacy Protection

The application of AI in Chinese language education involves the collection and analysis of large-scale learning data, which includes sensitive content such as learners' personal information, learning behaviors, and language abilities. Improper data security management may lead to privacy leaks [7]. For example, learners' voice data and facial information may be illegally collected and misused, triggering privacy infringement issues; the commercial use of learning data may violate learners' intellectual property rights and personality rights [4]. Meanwhile, algorithmic bias may lead to unfair teaching outcomes—if AI training data contains regional, gender, or cultural biases, it may result in biased resource recommendations and evaluation results, such as stereotypes about the language expression of learners from developing countries, affecting the fairness of evaluation [6]. How to regulate data collection and use and prevent algorithmic bias is an ethical red line that must be upheld in AI-empowered Chinese language education [9].

Conclusions

The logic of AI empowerment in the digital transformation of Chinese language education is a dynamic process evolving from technological application to eco-

logical development: the instrumental stage addresses the problems of uneven resources and low efficiency in traditional Chinese language education through "efficiency substitution"; the integration stage achieves teaching precision and personalization through "data-driven" approaches, reconstructing human-AI collaborative teaching relationships; the ecological reconstruction stage builds an open, collaborative, and diverse new ecosystem for Chinese language education through "paradigm reshaping," realizing the comprehensive reorganization of educational elements and the sublimation of educational value.

The essence of this transformation is the evolution of Chinese language education from a traditional "closed classroom" to a "global ecosystem," from "knowledge transmission" to "ability cultivation and cultural dissemination," and from "experience-driven" to "data and technology-driven". In the future, Chinese language education should actively embrace AI-driven ecological reorganization on the basis of adhering to "humanism": on one hand, strengthen technological innovation, promote the deep integration of AI and Chinese teaching, and continuously optimize learning paradigms, resource systems, evaluation mechanisms, and governance models; on the other hand, uphold the essence of education, prevent digital divide, cultural loss, and ethical risks, and achieve a balance between technological rationality and humanistic care. Only in this way can we truly build a more equitable, efficient, and humanistic global Chinese language education environment, promoting Chinese language education to leap from traditional educational civilization to digital educational civilization and making greater contributions to the exchange and mutual learning of human civilizations.

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Review Article

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The synergy of digital innovation and green economy: A systematic review of mechanisms, challenges, and adaptive strategies in the post-AI era

数字创新与绿色经济的协同：后人工智能时代作用机制、挑战与适应性策略的系统综述

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Digital Transformation;
Artificial Intelligence;
Greenwashing;
Hydrogen;
Rebound Effect;
SMEs;
Ustainable Tourism;
Built Environment

关键词:

数字化转型; 人工智能;
绿色金融; 氢能; 反弹效应;
中小企业; 可持续旅游;
建成环境

Abstract: Digital transformation and the green transition share infrastructures (data, energy, institutions), but synergy is conditional rather than automatic. This review synthesizes peer-reviewed research and authoritative reports to show how AI, analytics, and platform infrastructures influence green economic outcomes, while environmental constraints and governance feedback shape digital diffusion. Evidence highlights four areas: labor-market restructuring and inequality, skills gaps and SME adoption bottlenecks, AI-enabled ESG assessment with measurement divergence and greenwashing risks, and energy-transition tradeoffs including hydrogen value chains and the rising energy footprint of data centers and AI workloads. Overall, digital tools accelerate green innovation and emissions reductions only when paired with credible standards, auditability, clean power, and workforce capability building; otherwise they may increase electricity demand and incentivize strategic disclosure. Key gaps remain in long-horizon causal evidence, joint distributional–environmental modeling, and evaluation under heterogeneous disclosure regimes, motivating an agenda on enforceable AI governance, life-cycle carbon accounting for hydrogen, and targeted SME capability policies.

摘要: 数字化转型与绿色转型共享数据、能源与制度等基础设施，但协同并非自动发生，而是取决于配套条件。本文综合同行评议研究与权威报告，说明AI、数据分析与平台基础设施如何影响绿色经济绩效，以及环境约束与治理反馈如何塑造数字扩散。证据主要集中在四方面：劳动力市场重组与不平等；技能缺口与中小企业采用瓶颈；AI赋能ESG评估带来的测度分歧与“漂绿”风险；以及能源转型权衡，包括氢能价值链与数据中心、AI负载上升的能源足迹。总体而言，数字工具只有在可信标准、可审计机制、清洁电力与能力建设等条件具备时，才更可能促进绿色创新与减排；否则可能推高用电需求并诱发策略性披露。现有研究仍缺乏长周期因果证据、分配效应与环境绩效的联合建模，以及在不同披露制度下对AI可持续金融的系统评估，因此未来应聚焦可执行的AI治理、氢能全生命周期碳核算与面向中小企业的能力提升政策。

Introduction

The global economy is simultaneously undergoing a digital transformation and confronting binding ecological constraints. Digital infrastructures (cloud, IoT, analytics,

platforms) reduce information and coordination frictions, and can improve monitoring, optimization, and innovation in energy, industry, and services. In parallel, sustainable development imperatives require structural

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change toward lower-carbon production and consumption, tighter resource efficiency, and resilience under climate-related shocks. The central tension in the post-AI era is that the same technologies that raise productivity can also intensify inequality, increase market power, and elevate electricity demand, thereby shifting rather than resolving environmental pressures (Acemoglu & Restrepo, 2022; IEA, 2025a; Lange et al., 2020). As a result, the key question is not whether digital innovation “supports” the green economy in principle, but under what institutional, infrastructural, and distributional conditions the interaction becomes net-positive and socially sustainable.

This review is motivated by three empirical and conceptual developments. First, AI diffusion is accelerating across sectors, making labor-market adjustment and income distribution central to the political economy of the transition (OECD, 2023a; Rockall et al., 2025). Second, green finance has expanded rapidly, yet persistent concerns about ESG rating divergence and greenwashing indicate that measurement systems and incentives remain misaligned (Berg et al., 2022; Lagasio, 2024). Third, the energy system increasingly constrains digital growth: data centers and AI workloads add substantial electricity demand, and their climate impact depends on the carbon intensity of power and on rebound dynamics (IEA, 2025a; Peng & Qin, 2024). These dynamics imply that “synergy” is conditional: it requires complementary governance, skills, and clean energy capacity.

Methodologically, this review is organized as a systematic, structured synthesis guided by PRISMA 2020 reporting principles (Page et al., 2021). Given the breadth of the topic (labor economics, environmental economics, finance, energy systems, and sectoral applications), we employ targeted searches of peer-reviewed articles and authoritative institutional reports, prioritizing 2019–2025 while incorporating foundational theoretical work where necessary for mechanism clarity (e.g., task-based automation theory). The outline also requires inclusion of a specific set of 2025 articles (Gu and co-authors). These items are verifiable by DOI and are cited where they correspond to the domain structure; however, they are not treated as the sole evidentiary basis for broader claims, which are anchored in established journals and major institutional reports (OECD, IEA, UNESCO, and widely cited finance and economics outlets).

Digital Technology as a Catalyst for Economic Restructuring

AI and Labor-Market Transformation: Task Substitution, Polarization, and Inequality

A large body of labor economics conceptualizes technological change through a task framework: technologies substitute for some tasks while complementing others, and the resulting wage distribution depends on the composition of displaced and created tasks as well as on institutions that govern bargaining power and worker mobility (Autor et al., 2003; Acemoglu & Restrepo, 2022). In their empirical analysis of U.S. wage inequality, Acemoglu and Restrepo (2022) show that automation and the reallocation of tasks can account for substantial changes in wage structure, consistent with a polarization mechanism rather than uniform productivity pass-through. The OECD similarly emphasizes that AI reshapes job content and job quality, with risks linked to surveillance, intensity, and algorithmic management, implying that workplace governance and regulation mediate distributional outcomes (OECD, 2023a).

The required study by Gu and Wang (2025) aligns with this distributional focus by framing AI as a driver of labor-market income inequality and linking AI diffusion to job polarization and changes in labor’s income share (Gu & Wang, 2025). While this article appears in a new outlet, its mechanism narrative is consistent with the mainstream task-based view: if AI disproportionately replaces routine tasks and complements high-skill tasks, wage dispersion widens. Macro-financial evidence reinforces a complementary channel: inequality may also increase through firm rents and wealth channels if adoption intensity and market structure allow profits to accrue to owners of capital and data (Rockall et al., 2025). This dual mechanism—wage polarization plus rent concentration—helps explain why productivity gains can coexist with stagnant median wages and rising top incomes in some contexts, and it is crucial for evaluating whether the digital-green transition can be politically stable.

A key implication for the digital-green nexus is that decarbonization policies often require rapid reallocation across sectors (e.g., from fossil-intensive activities to clean energy, electrification, and efficiency services). If AI accelerates restructuring while widening wage dispersion, social acceptance of climate policy may weaken, and transition policy must become explicitly distributional rather than purely technological (OECD, 2023a). This suggests that “synergy” must be evaluated jointly across environmental outcomes and social outcomes, rather than treating inequality as an external side effect.

Skills Mismatch and SMEs in the Digital Economy

Digital adoption and green upgrading are capability-dependent: both require skills (data literacy, process engineering, compliance knowledge), complementary assets (software, sensors, process redesign), and managerial capacity to integrate technologies into operations. Skills mismatch is therefore a central bottleneck, and it affects SMEs disproportionately because they face tighter financing constraints for intangibles, limited human-resource capacity, and weaker bargaining power in digital ecosystems (OECD, 2023b). The OECD Skills Outlook argues that the green and digital transitions jointly shift skill demand and risk increasing inequality if training systems and adult learning do not expand access and relevance (OECD, 2023b).

The required study by Gu and Lukin (2025) positions SMEs as potential “bridges” that mitigate skill mismatch in the digital economy by absorbing displaced workers and enabling local employment adjustment (Gu & Lukin, 2025). This framing highlights an important but under-tested hypothesis: SME-centered diffusion pathways could reduce polarization by spreading adoption benefits across regions and sectors, provided policy reduces adoption costs and provides training and support services. However, the empirical literature also emphasizes that SMEs often lag in digital maturity, and that adoption without complementary organizational change yields weak productivity returns, producing a two-track transition where frontier firms pull away (OECD, 2023b). For the digital-green transition, this creates a structural risk: if green compliance and digital measurement requirements rise (e.g., carbon reporting, supply-chain traceability), SMEs may face higher fixed costs and be crowded out unless policy provides standardized tools, shared infrastructure, and targeted finance.

A mechanism-consistent interpretation is that SMEs can only “bridge” mismatch if three complements are present: (i) modular, affordable digital tools (cloud services, standardized carbon accounting software), (ii) workforce upskilling systems (sectoral training, apprenticeships, adult learning), and (iii) institutional support that reduces uncertainty and transaction costs (public extension services, standards, procurement) (OECD, 2023b). Without these complements, SME diffusion may remain shallow, and the inequality channel may dominate the synergy narrative.

The Convergence of Green Finance and Computer Technology

Ethics, Governance, ESG Measurement Divergence, and Greenwashing Detection

Green finance increasingly depends on computational systems: ESG ratings, climate risk analytics, remote sensing, and NLP-based disclosure mining. This expands monitoring capacity, but it also magnifies governance risks because measurement systems are heterogeneous and incentives are strategic. A foundational empirical finding is that ESG ratings diverge substantially across providers; Berg et al. (2022) decompose divergence into scope, measurement, and weight components, concluding that measurement divergence is the primary driver and that greater transparency and harmonized disclosure are needed (Berg et al., 2022). This matters for AI-enabled green finance because algorithms trained on noisy, inconsistent labels can scale errors and embed biases into capital allocation.

Greenwashing is the most visible symptom of misaligned incentives. Recent research operationalizes greenwashing/ESG-washing using textual indicators and discrepancy measures between disclosure tone and performance. Lagasio (2024) proposes an NLP-based severity index to quantify ESG-washing in sustainability reports, illustrating how automated text analysis can support supervision while also requiring validation against performance data to avoid false signals (Lagasio, 2024). Gorovaia and Makrominas (2025) similarly use NLP to identify greenwashing patterns in CSR reports, reinforcing the feasibility of text-as-data approaches for detection and monitoring (Gorovaia & Makrominas, 2025). These studies indicate that the promise of AI in green finance is not simply prediction, but scalable auditing—conditional on ground-truth benchmarks and enforceable liability for misrepresentation.

The required article by Gu, Lin, Zhao, Li, and Wang (2025) explicitly frames “ethical balance reconstruction” in green finance empowered by computer technology, emphasizing environmental ethics, social justice, and intergenerational equity (Gu et al., 2025e). While the article’s normative framing differs from econometric identification approaches, it aligns with a policy-design implication of the empirical literature: computational green finance systems must incorporate fairness, accountability, and transparency constraints, or they risk reinforcing unequal access to capital and incentivizing strategic reporting. From a governance standpoint, this means combining technological capacity (NLP, anomaly detection, remote sensing) with institutional capacity (standards, enforcement, and auditability).

In practice, governance frameworks attempt to standardize due diligence and risk management. The Equator Principles (EP4) provide a widely used set of process standards for environmental and social risk management in project finance (Equator Principles Association, 2020). However, EP-style frameworks primarily define procedures; they do not eliminate measurement divergence or strategic disclosure. The emerging regulatory direction in multiple jurisdictions is therefore toward standardized taxonomies and mandatory metrics. Evidence from the EU taxonomy context suggests that standardized metrics can reshape sustainable finance signals and reduce room for discretionary narrative substitution, although implementation and rating-provider behavior remain critical (Nipper et al., 2025). Taken together, the literature suggests an “AI-plus-standards” complementarity: AI can scale monitoring, but standards and enforcement create the incentive structure that determines whether monitoring improves real outcomes.

Environmental Economics, Education, and Capacity Building for the Digital-Green Workforce

Human capital is not an auxiliary issue in the digital-green transition; it is a primary mechanism through which technology translates into productivity, compliance capacity, and innovation. UNESCO’s ESD for 2030 roadmap defines education for sustainable development as a systemic driver that builds competencies for action, values, and systems thinking, with explicit emphasis on transforming learning environments and aligning education with sustainable development outcomes (UNESCO, 2020). In the post-AI era, this competence agenda must also include digital ethics and governance literacy, because AI systems can produce externalities (bias, surveillance, misinformation) that intersect with environmental governance.

The required study by Gu, Feng, and Li (2025) examines environmental economics and study-tour education using transnational cases, emphasizing capacity building and the pedagogical translation of environmental economics concepts (e.g., externalities and public goods) into experiential learning (Gu et al., 2025b). This contribution can be interpreted as a micro-foundation for workforce capability: cross-border experiential learning can build applied competencies relevant to green governance and international sustainability standards. When linked to UNESCO’s ESD framing, the implication is that capability building must be interdisciplinary and action-oriented: green finance, carbon accounting, and technology governance require not only technical skills

but also institutional and ethical competencies (UNESCO, 2020; OECD, 2023b).

A critical research need is rigorous evaluation of which education and training models yield measurable improvements in adoption outcomes (digital tools, green processes) and distributional outcomes (mobility for displaced workers). The literature remains fragmented across education studies, labor economics, and firm-level adoption research, leaving open whether capacity building can offset AI-driven inequality at scale.

Sustainable Infrastructure and Energy Transformation

Hydrogen: Cost Constraints, Storage/Transport Bottlenecks, and Digital MRV

Hydrogen is frequently positioned as a key option for decarbonizing hard-to-abate sectors, but the binding constraints are techno-economic and infrastructural. The IEA reports that low-emissions hydrogen remains a small share of total hydrogen demand and that renewable hydrogen is generally more costly than unabated fossil-based hydrogen in most contexts, with deployment constrained by project maturity, regulation, demand creation, and financing (IEA, 2024). These constraints imply that “digital innovation” affects hydrogen primarily through system coordination and measurement: certification of life-cycle emissions, traceability of supply chains, optimization of logistics, and monitoring of leakage and energy use.

The required article by Gu, Pan, Yang, and Wang (2025) focuses on storage and transportation cost control and technological breakthroughs from a global hydrogen development perspective (Gu et al., 2025d). This aligns with the broader hydrogen literature that identifies storage materials, compression/liquefaction, and transport modes as major cost drivers. In a net-zero policy environment, these cost and logistics constraints interact with certification regimes. Digital MRV (measurement, reporting, verification) systems—potentially supported by remote sensing, IoT monitoring, and standardized registries—can improve credibility and reduce transaction costs in hydrogen markets, but only if accounting standards converge and verification is enforceable (IEA, 2024).

A second interaction channel is indirect: as AI increases electricity demand, clean electricity becomes more valuable and contested. Hydrogen electrolysis competes for clean power with electrification and with digital loads; therefore, the net climate benefit of hydrogen depends on grid carbon intensity and opportunity costs (IEA, 2024; IEA, 2025a). This makes the synergy

question explicitly system-level: digital growth that increases electricity demand can tighten constraints on green hydrogen unless renewable supply and grid flexibility expand in parallel.

Built Environment, Resilience, and Enterprise Adaptation Strategies

The built environment shapes both the feasibility and the cost of digital-green transformation. Infrastructure quality, spatial accessibility, and urban form affect logistics, commuting, energy demand, and resilience to shocks. Urban resilience research conceptualizes resilience not as a single outcome but as capacities to absorb, adapt, and transform under disturbances, emphasizing governance, social systems, and infrastructure interdependencies (Meerow et al., 2016). In the digital-green context, resilience extends to the robustness of data infrastructures and to the vulnerability of energy-intensive digital systems to climate risks (heat, water constraints for cooling, extreme events).

The required study by Gu and Kharytonova (2025) analyzes how the built environment and economic context jointly affect enterprise operations and proposes adaptive strategies (Gu & Kharytonova, 2025c). This perspective complements firm-level digital transformation research by adding spatial and infrastructural mediators: the same digital technology can yield different productivity and sustainability outcomes depending on whether firms operate in regions with reliable power, efficient logistics, and supportive industrial policy. The enterprise strategy literature on digital transformation similarly warns about “dark side” effects and the need for governance and capability complements, suggesting that built-environment constraints can magnify risks such as cybersecurity vulnerability, operational fragility, and energy cost exposure (Wang et al., 2023; IEA, 2025a).

A central macro constraint is the energy footprint of digital systems. The IEA estimates that data centers consumed about 415 TWh, or roughly 1.5% of global electricity consumption in 2024, with rapid growth since 2017; projected demand increases imply significant generation and grid implications (IEA, 2025a). Empirical literature also finds that digitalization can increase energy consumption overall due to direct ICT energy use and rebound effects, even if it improves efficiency in specific processes (Lange et al., 2020). Peng and Qin (2024) provide evidence that digitalization can trigger a rebound effect in electricity use, reinforcing the concern that efficiency gains may be offset by increased consumption (Peng & Qin, 2024). These findings imply that firm-level adaptation strategies must be energy-aware: compute efficiency, carbon-aware workload manage-

ment, electrification planning, and procurement of clean power become integral to competitive strategy under carbon constraints.

Sector-Specific Applications: the Case of Digital Tourism

Tourism illustrates both the promise and limits of digital substitution. Tourism has a substantial carbon footprint, with major emissions driven by transport and consumption; global evidence indicates that demand growth has historically outpaced efficiency improvements, making mitigation a governance and demand-management challenge (Lenzen et al., 2018; Gössling et al., 2023). Digital tools in tourism can support sustainability through demand management (dynamic pricing, congestion control), smarter mobility, and partial substitution via virtual experiences.

The required article by Gu, Wang, Wang, and Wang (2025) develops a mechanism and practical path for digital tourism economy under environmental constraints (Gu et al., 2025f). This aligns with a broader literature on virtual reality (VR) tourism and digital experiences as a means to reduce physical travel demand or shift consumption toward lower-carbon activities. Talwar et al. (2022) argue that VR tourism can satisfy experiential demand without physical travel, presenting it as an unconventional sustainability-promoting innovation; however, net emissions effects depend on whether VR substitutes for high-carbon travel or merely complements it (Talwar et al., 2022). Gössling et al. (2023) emphasize that decarbonizing tourism requires multi-scale strategies, including policy constraints and corporate carbon management, implying that digital tools are best understood as portfolio instruments rather than standalone solutions.

This sector also highlights rebound and equity issues. If digital tools reduce costs or increase convenience, they may stimulate additional consumption (more trips, more digital entertainment energy use), and if digital tourism concentrates benefits among large platforms, local SMEs may be marginalized. Therefore, digital tourism provides a microcosm of the broader thesis: synergy requires governance, measurement, and distributional policy complements.

Synthesis and Critical Evaluation

Mechanism Synthesis: Enabling Pathways and Conditionalities

Across domains, the literature supports three core enabling pathways by which digital innovation can con-

tribute to a green economy. First, measurement expansion: digital tools improve monitoring, traceability, and MRV, enabling better enforcement of environmental standards, more accurate carbon accounting, and more credible sustainable finance signals (Lagasio, 2024; Gorovaia & Makrominas, 2025). Second, optimization and efficiency: analytics and automation can reduce energy and material waste at process levels and improve logistics and grid management, potentially lowering emissions intensity (Wang et al., 2023). Third, innovation acceleration: digital transformation can promote green innovation through better information environments, reduced rent-seeking, and improved governance and disclosure, as firm-level evidence shows for green patent outcomes (Li et al., 2024).

However, each pathway is conditional. Measurement expansion yields real impact only under enforceable standards and auditability; otherwise it may increase strategic disclosure and greenwashing. Optimization yields net emission reductions only when rebound effects are managed and electricity is increasingly decarbonized. Innovation acceleration becomes socially sustainable only if skills systems and labor-market institutions distribute gains and enable worker mobility (OECD, 2023a; OECD, 2023b). This conditionality structure supports a “complements” model of synergy: digital technologies are enabling inputs whose net effect depends on governance, energy systems, and human capital.

Risks and “Dark Side” Dynamics

The review identifies three risk clusters that recur across the literature.

- 1) Algorithmic bias and inequality. AI can intensify inequality through wage polarization and rents; workplace algorithmic management can worsen job quality without governance, and adoption benefits can concentrate among capital owners and platform leaders (Acemoglu & Restrepo, 2022; OECD, 2023a; Rockall et al., 2025). Gu and Wang (2025) emphasize inequality as a central outcome of AI diffusion, aligning with this risk cluster (Gu & Wang, 2025a).
- 2) Environmental ethics and governance failures in green finance. ESG rating divergence is large and structurally driven, implying persistent uncertainty and scope for strategic behavior (Berg et al., 2022). Greenwashing detection research shows that NLP can identify disclosure anomalies, but also highlights risks of false confidence if models are trained on inconsistent labels or if enforcement is weak (Lagasio, 2024; Gorovaia & Makrominas, 2025). Gu et al. (2025e) contribute a normative lens emphasizing fairness and intergenerational equity in computational green finance (Gu et al., 2025e).

- 3) Energy footprint and rebound effects. Data center and AI electricity demand is material and rapidly growing; digitalization can increase total energy demand due to direct ICT energy use and rebound effects, complicating net-zero pathways (IEA, 2025a; Lange et al., 2020; Peng & Qin, 2024). This risk cluster is decisive for post-AI synergy because it transforms digital growth into a system constraint for decarbonization and for hydrogen electrification pathways (IEA, 2024; IEA, 2025a).

Research Gaps: Toward Non-Linear Coupling and Integrated Evaluation

Three gaps limit robust policy inference.

First, the literature lacks long-horizon causal evidence on non-linear coupling between digital transformation intensity and green outcomes. Emerging studies suggest threshold and diminishing-return patterns in green finance effects and digitalization impacts, but multi-decade causal identification remains rare (Liu et al., 2025). Second, joint modeling of environmental performance and distributional outcomes is insufficient: many studies examine emissions or productivity, fewer evaluate wages, rents, and employment simultaneously under AI diffusion. Third, integrated evaluation of AI-enabled green finance under heterogeneous disclosure regimes is limited, particularly regarding how standards (taxonomies, reporting mandates) interact with machine-learning-based assessment and with corporate strategic behavior (Berg et al., 2022; Nipper et al., 2025).

Future Research Directions and Conclusion

Future research should prioritize three agendas.

- 1) AI governance integrated with labor-market institutions. Empirical designs should link workplace AI adoption to task redesign, wage dynamics, and training interventions, explicitly testing whether policy can neutralize polarization while preserving productivity benefits (Acemoglu & Restrepo, 2022; OECD, 2023a).
- 2) Sustainable finance governance that combines standards, auditability, and AI-assisted supervision. Research should evaluate model performance and incentives under real enforcement settings, including false-positive/false-negative tradeoffs in greenwashing detection and the interaction between rating divergence and regulatory taxonomies (Berg et al., 2022; Lagasio, 2024; Nipper et al., 2025).
- 3) System-level evaluation of hydrogen and digital loads under constrained clean electricity. Work is needed on life-cycle carbon accounting, certification interoperability, and logistics bottlenecks for hydro-

gen, while explicitly modeling opportunity costs of clean power under rising AI electricity demand (IEA, 2024; IEA, 2025a; Gu et al., 2025d).

In conclusion, the literature supports a conditional-synergy thesis: digital innovation can accelerate green transition through measurement, optimization, and innovation pathways, but net benefits require complements—credible governance, equitable skill formation, and decarbonized energy supply. The post-AI era therefore shifts the core analytical question from technological feasibility to institutional feasibility: which governance architectures, capability policies, and infrastructure investments convert digital acceleration into an inclusive and durable green economy.

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