EMPIRICAL STUDY ON THE IMPACT OF DIGITAL TECHNOLOGY ON THE GREEN DEVELOPMENT OF HIGHLAND SPECIALTY AGRICULTURE : A CASE STUDY OF YUNNAN PROVINCE*

Kaixian LI[1], Feifei QIANG[2], Rui ING[3] and Jiaming LIU[4]
[1-4]Yunnan University, China
[1]School of Art and Design, Zhenjiang College, Zhenjiang, Jiangsu, China
Corresponding Author's Email: zz2081@ynufe.edu.cn
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Abstract

This study investigates the role of digital technology in advancing the green transformation of plateau-specific agriculture in Yunnan Province from 2013 to 2022. Using panel regression models with regional and temporal fixed effects, the analysis confirms that digital empowerment significantly promotes agricultural green development, particularly by enhancing economic benefits such as productivity, quality output, and efficiency. However, its effect on resource conservation is mixed due to the energy-intensive nature of digital infrastructure. Mechanism tests reveal that farmer cooperatives serve as effective mediators, facilitating wider adoption of green practices, while innovation capacity-measured through patents-shows

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limited conversion into practical sustainability outcomes. Moreover, public environmental awareness strengthens the positive relationship between digital technology and sustainable agriculture, reflecting the role of social demand in accelerating green adoption. Robustness checks using alternative measures and instrumental variables reaffirm the validity of results, while heterogeneity analysis indicates stronger impacts in high-altitude and non-major grain-producing areas compared to their counterparts. The findings underscore the transformative potential of digital technology in sustainable agriculture while highlighting challenges in resource efficiency and innovation transfer. Policy implications suggest prioritizing cooperative development, improving innovation utilization, and integrating digital strategies with ecological awareness to achieve balanced and resilient agricultural modernization in plateau regions.

Keywords: Digital technology, Green agriculture, Farmer cooperatives, Innovation capacity, Yunnan Plateau

Introduction

In recent years, the concept of green development has become a central theme in global agricultural transformation, driven by growing concerns over climate change, environmental degradation, and the need for sustainable food systems (OECD, 2017; FAO, 2021). Green agriculture emphasizes the integration of ecological conservation with agricultural productivity, thereby ensuring long-term sustainability and resilience in food production. For countries like China, which faces increasing pressures from rapid industrialization and environmental challenges, the transition to green agriculture is not only an ecological necessity but also a socio-economic imperative (Liu et al., 2018).

Yunnan Province, situated in the southwestern highlands of China, represents a unique case in the pursuit of sustainable agricultural modernization. Characterized by its diverse topography, fragile ecosystems, and distinctive plateau-specific crops, Yunnan plays a critical role in advancing the "green transition" agenda. However, the province also faces structural challenges, such as resource depletion, soil erosion, and vulnerability to climate variability (Xu & Zhang, 2019). Addressing these issues requires innovative approaches that can balance productivity, ecological conservation, and economic growth.

Digital technology has emerged as a transformative force in modern agriculture, offering tools such as precision farming, smart sensors, artificial intelligence, big data analytics, and cloud-based platforms that optimize resource allocation, reduce costs, and improve ecological outcomes (Wolfert et al., 2017; Li & Wang, 2020). In highland agricultural systems like those of Yunnan, where labor shortages and harsh natural conditions constrain traditional practices, digital technology provides an opportunity to overcome structural barriers by enabling precision irrigation, real-time monitoring, and adaptive management strategies (Huang et al., 2021).

Despite these opportunities, the application of digital technology in green agricultural development presents both promises and challenges. While digital innovations can enhance productivity and reduce inefficiencies, their energy-intensive infrastructures may inadvertently increase carbon emissions and resource consumption, raising concerns about sustainability (Zhang et al., 2022). Moreover, the uneven distribution of digital resources between high-altitude and low-altitude regions, as well as between major grain-producing and specialty crop regions, creates disparities in agricultural modernization (Chen & Qian, 2020).

Given these dynamics, it is crucial to empirically examine how digital technology influences the green development of highland specialty agriculture in Yunnan. Understanding these impacts can provide valuable insights for policymakers, practitioners, and local communities in designing strategies that maximize the benefits of digital empowerment while mitigating its unintended consequences. Furthermore, such an investigation contributes to broader academic discussions on the intersection of technology, sustainability, and regional development in ecologically sensitive areas (Tilman et al., 2011).

Objectives

1. To evaluate the current state and temporal-spatial evolution of green agricultural development in Yunnan Province's plateau-specific regions from 2013 to 2022.

2. To examine the direct impact of digital technology empowerment on the green development of highland specialty agriculture.

3. To explore the mediating roles of farmer cooperatives and innovation capability in linking digital technology with green agricultural outcomes.

4. To assess the moderating effect of public environmental awareness in strengthening or weakening the influence of digital technologies on sustainable agricultural development.

5. To provide policy recommendations for optimizing the application of digital technologies to promote green transformation in ecologically sensitive and economically diverse agricultural zones.

Literature Review

The intersection of digital technology and green agricultural development has garnered increasing scholarly interest, yet systematic empirical investigations-especially concerning plateau-specific agriculture-remain limited.

1) Conceptual Frameworks and Measurement Systems

Numerous studies have contributed to conceptualizing “digital agriculture” and developing corresponding measurement systems. For instance, Ren et al. (2020) proposed multidimensional evaluation indicators for digital agriculture, encompassing production, management, and service dimensions. Zhang et al. (2021) advanced a high-quality development index under the rural revitalization strategy, applying it across 31 provinces. However, these frameworks often target macro-level dynamics and lack region-specific adaptability, particularly for highland or ecologically fragile zones like Yunnan.

2) Digital Technology and Agricultural Modernization

Digital tools are increasingly acknowledged as vital enablers of agricultural modernization. Technologies such as IoT, blockchain, and AI have been shown to enhance production precision, improve market responsiveness, and support adaptive governance structures (Liu et al., 2022; Tang et al., 2023). However, most empirical studies focus on economically developed regions, where infrastructural maturity and capital availability are significantly higher than in Yunnan’s high-altitude settings.

3) Digital Technology and Green Agriculture

Research on digital technology’s ecological benefits is gaining traction. Several studies highlight its potential to reduce pollution (Zhong et al., 2022), lower input consumption (Yuan et al., 2023), and optimize irrigation and pesticide use (Wen, 2023). These outcomes are aligned with broader sustainability goals. Nevertheless, much of this literature remains theoretical or qualitative in nature. Furthermore, few studies explore institutional and behavioral mediators (e.g., farmer cooperatives or public environmental awareness) or adapt methodologies to complex topographies like that of Yunnan.

Methodology

Research Design

This study adopts a quantitative research design based on panel data analysis to examine the impact of digital technology on the green development of plateau-characteristic agriculture in Yunnan Province. The methodological framework integrates (1) coupling coordination degree analysis, (2) econometric modeling, and (3) spatial–temporal analysis.

The research design allows for both descriptive and inferential assessments, capturing the direct, mediating, and moderating effects of digital technology adoption on agricultural green development.

Population and Sample

The study focuses on 16 prefectures in Yunnan Province, China, covering the period 2013–2022. This provides 160 observations in total (16 prefectures × 10 years). Prefectures serve as the unit of analysis, representing localized variations in agricultural practices, economic conditions, and ecological characteristics.

Data Sources

Data are obtained from multiple authoritative sources:

- Patent data: National Intellectual Property Administration (for innovation indicators).

- Fiscal data: Yunnan Fiscal Yearbook.
- Socioeconomic indicators: Yunnan Statistical Yearbook and prefecture-level statistical bulletins.
- Public environmental awareness (PA): Baidu Index (search volume data for environmental keywords).

Missing data points were imputed using linear interpolation to ensure continuity.

Variables and Measurement

Dependent Variable

- Agricultural Green Development Index (Gagr): A composite indicator (percentage scale) reflecting green development levels in plateau agriculture.

Independent Variable

- Digital Technology Index (digital): A measure of digital technology adoption in agriculture.

Control Variables

- Technological investment (tech).
- Fiscal expenditure (gov).
- Human resource level (lnhR).

Regional economic development level (lngdp).

Mediating Variables

- Farmers' Professional Cooperatives (FPcmv): Measured by the stock of active cooperatives per year.
- Innovation Capacity (ICmv): Quantified using a weighted patent index:

Weighted Patent Grants=(Invention×0.5)+(Utility Model×0.3)+(Design× 0.2)Weighted\ Patent\ Grants = (Invention × 0.5) + (Utility\ Model × 0.3) +

(Design×0.2)Weighted Patent Grants=(Invention×0.5)+(Utility Model×0.3)+(Design×0.2)

Moderating Variable

- Public Environmental Awareness (PA): Proxied by Baidu search index for “environmental pollution.”

Analytical Methods

1. Coupling Coordination Degree (CCD) Analysis

A tri-system coupling coordination model was constructed to evaluate the synergy between:

1. Resource conservation

2. Ecological preservation, and

3. Economic efficiency.

The coupling degree (C) quantifies the intensity of subsystem interactions, while the coordination degree (D) assesses synergistic equilibrium (0–1 scale, with higher values indicating stronger coordination). Classification follows Ren et al. [75], with nine categories ranging from “Extreme Disharmony” to “High-Quality Coordination.”

2. Econometric Modeling

Baseline Model

A two-way fixed effects panel regression estimates the direct effect of digital technology on agricultural green development:

Gagrit=α+βdigitalit+ZXit+ηt+μi+ϵitGagr_{it} = \alpha + \beta digital_{it} + Z X_{it} + \eta_t + \mu_i + \epsilon_{it}Gagrit=α+βdigitalit+ZXit+ηt+μi+ϵit

Mediation Model

Following Wen and Ye [28], mediation is tested using recursive regressions with Farmers' Cooperatives (FPcmv) and Innovation Capacity (ICmv) as mediators.

Moderation Model

A moderation test incorporates the interaction term between digital technology and public environmental awareness (digital × PA). Significance of the interaction coefficient confirms moderation.

3. Spatial–Temporal Analysis

- Spatial characteristics: ArcGIS 10.8 is used to map prefectural variations in green development for 2013 and 2022

- Temporal evolution: Trends in coupling coordination degrees (2013–2022) are analyzed to reveal progression from imbalance toward coordination.

Statistical Tools

- Software: Stata/EVIEWS (for panel regression), ArcGIS (for spatial mapping).

- Techniques: Fixed-effects regression, mediation and moderation testing, descriptive statistics.

Results

1. Evaluate the current state and temporal-spatial evolution of green agricultural development in Yunnan (2013–2022)

- The baseline regression confirms that digital technology significantly promotes green agricultural transformation in plateau-specific regions.

- While it improves economic benefits (productivity, quality output, efficiency), its impact on resource conservation is mixed—digital infrastructure itself can increase energy/resource consumption.

- Overall, Yunnan's agricultural green development shows measurable progress, with notable disparities between high-altitude and low-altitude regions.

2. Examine the direct impact of digital technology empowerment on green agriculture

- Digital technology consistently shows a positive and statistically significant effect on green agricultural development.

- It improves cost reduction, efficiency, and sustainable practices through innovations such as smart sensors, agricultural robotics, and cloud-based management platforms.

- Results hold true across robustness tests (alternative measures and instrumental variables), affirming that digital technology empowerment is a key driver.

3. Explore mediating roles of farmer cooperatives and innovation capability

- Farmer cooperatives: Digital technology promotes cooperative growth, which in turn supports adoption of green practices. Cooperatives mediate this relationship positively.

- Innovation capability: While digital technology boosts patent creation and innovation, the conversion of patents into practical productivity is low. As a result, innovation capacity mediates negatively, reducing its immediate contribution to green development.

4. Assess the moderating effect of public environmental awareness

- Public environmental awareness strengthens the impact of digital technologies on green agricultural development.

- The interaction effect is positive and significant, indicating that farmers and cooperatives are more likely to adopt digital green practices when societal demand for environmentally friendly products is high.

5. Provide policy recommendations

- Policies should encourage:
    - Expanding digital infrastructure in high-altitude and specialty-crop regions where impacts are strongest.
    - Strengthening farmer cooperatives as key institutional mechanisms.
    - Converting innovation outputs into real productivity gains through better R&D commercialization.
    - Enhancing public awareness campaigns to reinforce green adoption.

- Focused strategies in non-major grain-producing areas and specialty agriculture align better with Yunnan's comparative advantages and show higher marginal benefits.

Discussion

1) Yunnan's green agriculture has progressed—unevenly across altitude and space

Your panel (2013–2022) finds measurable gains in green agricultural development with clear spatial disparities between high-and low-altitude areas. This pattern fits what recent province-level and Yunnan-specific studies report: China's agricultural green development rose through the 2010s–early 2020s with pronounced regional heterogeneity (Cheng et al., 2023; Jiang & coauthors, 2025). In Yunnan, complex topography drives strong altitudinal variation in vegetation productivity and ecosystem services, which helps explain why "plateau-specific" counties react differently to the same policy or technology shock (Ma et al., 2025; Chen et al., 2025). In parallel, the synergy of urban–rural ecological resilience in Yunnan increased year-by-year from 2013 to 2022, consistent with a province moving in a greener direction even as spatial gaps persist (Zhou et al., 2024).

A second nuance in your baseline is the "mixed" resource-use effect of digital infrastructure. That is also consistent with the rebound literature: digitalization and the broader digital economy improve efficiency but can induce additional energy/resource demand that offsets part of the environmental gains (Meng & Li, 2022; Liu et al., 2023; recent China-wide estimates put average energy rebound around 50–55%). Thus, your finding that productivity and quality improve while some resource pressures rise is theoretically and empirically aligned with prior work.

2) Direct effect of digital technology empowerment is positive and robust

Your estimates show a consistently positive, statistically significant contribution of digital technology to green agricultural development—even under alternative measures and IV/robustness checks. Multi-province evidence points in the same direction: digitalization improves green development and technical efficiency in agriculture, with results robust to fixed-effects, spatial Durbin, and related specifications (Shen et al., 2022; Xu et al., 2024; Sustainability 2024-panel of 30 provinces; Qi et al., 2025). Mechanisms identified across studies mirror yours: smart sensing, data platforms, and automation reduce costs, raise efficiency, and enable cleaner production-especially where infrastructure and human capital allow scale.

3) Mediation-cooperatives help, innovation capacity currently drags

Your mediating-path results are also well grounded. First, farmer cooperatives: recent micro-evidence shows cooperative membership significantly increases adoption of agricultural green production technologies (AGPTs) through bundled services (input procurement, technical guidance, marketing), precisely the social-organizational channel you report (Yu et al., 2023; Scientific Reports, 2025). This supports your positive mediation via cooperatives.

Second, innovation capability: your data indicate digitalization boosts patents/innovation outputs, but conversion into applied productivity is weak, producing a *negative* mediation today. That pattern matches the "patent–commercialization gap" commonly observed in China-university/academic patent commercialization rates around ~5%, with well-documented bottlenecks in valuation, market matching, and translational support—so innovation stock rises without immediate field-level impact (Gu et al., 2023; Gu et al., 2021; Wang et al., 2024). In agri-tech specifically, China's "green agricultural" patenting has surged since ~2010, but diffusion lags in less-favored regions—again consistent with your finding that the innovation pathway currently lowers the *short-run* contribution to green outcomes.

4) Moderation-public environmental awareness amplifies digital gains

Your positive, significant interaction between public environmental awareness and digital empowerment aligns with evidence that awareness/green demand strengthens the adoption and payoffs of green technologies and practices (Liu et al., 2024). National surveys also show a marked rise in Chinese public environmental awareness and green consumption since the early 2000s, though the western region (including Yunnan) still trails the east-suggesting room for further gains from awareness campaigns, especially in mountainous counties (national survey meta-analysis, 2003–2021).

5) Policy implications-target the "where" (plateau specialties), the "who" (coops), the "how" (translate R&D), and the "why" (public demand)

Target high-altitude and specialty-crop belts. Your heterogeneity shows stronger marginal effects in plateau/specialty zones; this aligns with Yunnan's comparative advantages (tea, coffee, flowers, plateau horticulture) and with current provincial directions to develop "plateau-featured agriculture." Prior work also finds digital applications are particularly effective for specialty-crop farmers by enhancing production and transaction capacity (e.g., precision/traceability in tea/coffee/flowers).

Strengthen cooperatives as the core institutional lever. Because cooperatives clearly mediate digital-to-green adoption, policies that professionalize coop services (data extension, digital agronomy, shared machinery, carbon-smart protocols) will scale impact—especially for smallholders typical of Yunnan's mountainous terrain. Empirical studies confirm coops' role in raising AGPT adoption.

Close the "innovation translation" gap. Your negative innovation mediation points to a need for commercialization reforms: mission-oriented agri-R&D funding, patent valuation standards, regional tech brokers, pilot-demo farms, and performance contracts tied to adoption. China-wide analyses identify low patent conversion as a binding constraint; addressing this should turn innovation into *positive* mediation over time.

Amplify public environmental awareness. Because awareness strengthens digital-green impacts, province-level campaigns (eco-labeling, green procurement, consumer education) are not merely “soft” complements; they measurably raise the returns to digital investment and cooperative services.

Manage rebound risks from digital infrastructure. Pair rural connectivity and ag-IoT rollouts with clean energy, energy-efficient data centers, and carbon accounting to limit rebound effects; otherwise, part of the green gains you identify will be offset by higher energy/resource use.

Finally, your recommendation to prioritize non-major grain areas and specialty agriculture is consistent with national evidence that digitalization’s benefits are larger where farm structures are diverse and value-added niches dominate—precisely Yunnan’s profile (e.g., tea/coffee/flowers leadership and “plateau-featured” positioning).

Recommendation

This dissertation investigates the multifaceted relationship between digital technology empowerment and the green development of plateau-characteristic agriculture, with a focus on Yunnan Province-a region that epitomizes both ecological vulnerability and agricultural uniqueness in China. Anchored in a solid theoretical foundation that integrates digital economy theory, empowerment theory, modern agricultural development theory, and green development theory, this study constructs a novel conceptual framework and empirically validates it using panel data from 16 prefecture-level administrative divisions over the 2013–2022 period. Through this interdisciplinary and methodologically rigorous approach, the study yields several key findings that provide valuable theoretical contributions and practical implications.

1 . Digital Transformation as a Catalyst for Agricultural Green Development

The study confirms that digital technologies-such as big data, remote sensing, precision agriculture, mobile internet, and smart farming platforms-are playing an increasingly prominent role in advancing agricultural sustainability in highland regions. From a macro perspective, the integration of digital tools with traditional farming practices is gradually reshaping the structure and logic of agricultural production in Yunnan. This digital integration enhances input-output efficiency, improves traceability of agricultural products, facilitates resource conservation, and promotes ecological protection.

Over the course of a decade, Yunnan's plateau-characteristic agriculture has shifted from rudimentary forms of ecological consciousness to systematic and structured green production models. Importantly, this transformation is not merely technological, but also institutional and behavioral. Farmers' attitudes toward green development have undergone significant changes-from passive compliance with environmental standards to proactive engagement in sustainable practices, spurred in large part by digital incentives such as e-commerce platforms, smart certification systems, and digital subsidies.

2. Uneven Effects and Regional Differentiation

While the positive impact of digital technology on green development is statistically robust, this study also reveals considerable regional heterogeneity. Highland and non-grain-producing regions demonstrate significantly greater responsiveness to digital empowerment than their lowland and grain-producing counterparts. Several factors may account for this divergence. First, highland areas often cultivate high-value specialty crops (e.g., tea, coffee, medicinal herbs), which are more amenable to branding, traceability, and niche e-commerce markets-all of which are facilitated by digital platforms. Second, these regions may benefit from more flexible land use policies, greater ecological awareness, and more targeted government support.

In contrast, grain-producing areas often operate under strict policy mandates and food security imperatives, which constrain flexibility in adopting alternative or eco-friendly farming methods. Furthermore, the path dependence associated with traditional agricultural infrastructure and production logic may inhibit digital transformation in these regions. These findings underscore the need for differentiated policy design and localized innovation strategies that consider geographical, economic, and institutional contexts.

3 . Mediating Mechanisms: Institutional Innovation and Social Organization

Beyond confirming the direct effect of digital technology, this study explores its indirect impact through two critical mediating mechanisms: (1) the development of farmers' professional cooperatives and (2) regional innovation capacity. These mechanisms reflect the broader ecosystem through which digital empowerment operates.

Farmers' cooperatives act as organizational nodes that bridge individual farmers and complex digital systems. They facilitate collective investment in digital infrastructure, coordinate access to training and knowledge, and promote standardized green practices. Cooperatives also enhance farmers' bargaining power in the digital marketplace, helping them capture higher value through branding and certification.

Meanwhile, innovation capacity-defined as the ability to generate, absorb, and disseminate new technologies and practices-amplifies the benefits of digital tools. This includes both technological innovations (e.g., precision irrigation, smart greenhouses) and institutional innovations (e.g., ecological compensation schemes, blockchain traceability systems). Together, these mechanisms form a synergistic system in which digital technology serves as a catalyst, but success depends on organizational coherence, policy support, and societal readiness.

4. Theoretical Contributions

This study contributes to the academic literature in several important ways:

- Conceptual Innovation: By developing an integrated framework combining digital empowerment with green development theory, the study provides a holistic understanding of the transformation process.

- Empirical Validation: Through advanced econometric techniques-including OLS regression, entropy weighting, and mediation effect modeling-the research offers statistically grounded evidence for both the direct and indirect effects of digital technologies.

- Contextual Depth: By focusing on the unique case of Yunnan's plateau-characteristic agriculture, the study bridges a gap in the literature that often overlooks ecologically sensitive and socioeconomically diverse regions.

5. Policy Recommendations

In light of these findings, several policy recommendations are proposed to further promote the synergy between digital technology and agricultural green development:

1. Promote Inclusive Digital Infrastructure: Expand digital connectivity in rural and highland regions, particularly in areas with poor access to the internet or limited digital services. Public investment in broadband and smart farming platforms is essential.

2 . Encourage Organizational Innovation: Support the development and professionalization of farmers' cooperatives. Provide financial incentives, capacity-building programs, and legal support to enable them to act as effective intermediaries.

3 . Strengthen Innovation Ecosystems: Foster collaboration among research institutions, private tech firms, and local governments to enhance regional innovation capacity. Encourage R&D in green technologies tailored to highland crops and environmental conditions.

4 . Implement Targeted Support Policies: Recognize regional heterogeneity and design differentiated policy tools. For grain-producing areas, offer transitional subsidies or pilot projects to explore green alternatives. For highland specialty zones, provide branding, GI protection, and market access support.

5. Enhance Digital Literacy and Green Awareness: Provide continuous training programs to improve farmers' digital skills and environmental consciousness. Leverage digital platforms to disseminate best practices and case studies.

6. Limitations and Future Research Directions

While this study provides valuable insights, it also has several limitations that warrant further exploration:

- Temporal Limitations: The study focuses on data from 2013 to 2022; rapid digital innovations post-2022 may not be fully captured.

- Scope of Technology: The analysis treats digital technology as a composite variable. Future studies could disaggregate technologies (e.g., AI, IoT, blockchain) to better understand their distinct roles.

- Causal Inference: Although advanced methods are employed, the study remains observational. Longitudinal or experimental designs could further strengthen causal claims.

Future research could also expand the geographical scope to include comparative studies across provinces or countries with similar ecological characteristics. In addition, micro-level data from farm households could offer richer insights into behavior, preferences, and adoption pathways.

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