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GREEN TECHNOLOGY INNOVATION IN YUNNAN'S PLATEAU AGRICULTURE: SOLUTIONS FOR HEAVY METAL POLLUTION CONTROL AND RURAL REVITALIZATION

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ABSTRACT

Agricultural practices on the Yunnan plateau are increasingly threatened by heavy metal contamination arising from mining activities and intensive farming, posing substantial risks to food safety and the sustainability of local agriculture. While green technologies offer environmentally sustainable solutions, their uptake has been limited due to fragmented regulatory frameworks, inadequate institutional support, and low levels of engagement among farmers. This research sought to examine the role of green technologies in alleviating heavy metal pollution, evaluate their impact on rural revitalization, and identify gaps in policy and innovation that hinder sustainable agricultural development within Yunnan's plateau regions. A qualitative Systematic Literature Review (SLR) was conducted, employing explicit inclusion and exclusion criteria to select peer-reviewed studies published between 2020 and 2025. The PRISMA protocol guided the screening and selection process, and thematic analysis was applied to categorise the results into three primary domains: pollution mitigation, rural revitalization, and policy and innovation gaps. The analysis indicates that approaches such as phytoremediation, biochar application, and microbial remediation are effective in substantially reducing heavy metal contamination. Additionally, initiatives involving digital technologies, green financing mechanisms, and cooperative models have demonstrated potential in supporting rural revitalization. Despite these advances, challenges including weak governance structures, regional inequalities, and barriers to technology adoption continue to limit the widespread integration of green technologies in Yunnan. Green technologies provide concurrent benefits for ecological restoration and the socioeconomic revitalization of rural communities in Yunnan. Nonetheless, achieving effective and equitable agricultural transformation requires comprehensive policy reforms and the development of innovation strategies tailored to local contexts.

KEYWORDS: Green Technology, Yunnan's Plateau, Agriculture, Heavy Metals, Pollution Control.

1. INTRODUCTION

Yunnan Province, a pivotal agricultural region in Southwest China, is characterised by its ecologically diverse plateau landscapes and abundant mineral resources. However, these geological advantages have simultaneously increased the region's vulnerability to heavy metal contamination, particularly in agricultural soils. Extensive mining activities, industrial expansion, and intensive farming have resulted in elevated concentrations of cadmium (Cd), lead (Pb), and arsenic (As) across numerous locations in Yunnan (Dong et al., 2022). This contamination presents a dual challenge: it threatens human health through bioaccumulation in the food chain and compromises both agricultural productivity and environmental sustainability.

Empirical studies have documented heavy metal accumulation in crops, with certain areas of Yunnan exceeding national food safety standards (Lai et al., 2022). For instance, research conducted in lead-zinc mining regions reported exceedingly high levels of Pb and Cd in soils and vegetables, posing serious health risks, particularly for children. Furthermore, different leafy vegetables, such as Malabar spinach, exhibit varying capacities to accumulate heavy metals, which has implications for food security and dietary exposure (Cui et al., 2023). The vertical migration of these compounds intensifies the problem; studies in tin ore mining sites indicate that pollutants penetrate deeper soil layers, limiting the efficacy of superficial remediation efforts (Liu et al., 2024). Additionally, floodplain soils impacted by mining demonstrate high metal enrichment in finer particulate fractions, adding complexity to potential remediation strategies (Zhang et al., 2021).

Green technologies offer promising solutions to this environmental challenge. Sustainable approaches such as phytoremediation, biochar application, and microbial bioremediation provide alternatives to conventional chemical treatments. However, these technologies remain underutilised in Yunnan's plateau regions due to incomplete policy frameworks, limited local innovation, and insufficient farmer training (Xu et al., 2023). With rural revitalization now a national priority in China, implementing green technologies in contaminated agricultural systems could simultaneously mitigate environmental hazards and enhance rural economic activity. Realising these benefits, however, requires locally adapted policy measures, innovation strategies, and an understanding of the socio-economic consequences of technology adoption.

Despite the recognised potential of green technologies for addressing heavy metal pollution and promoting ecological development in agricultural lands, their application in Yunnan's plateau agriculture remains limited. Constraints include insufficient policy support, weak coordination among stakeholders, and the high initial costs associated with implementation, all of which hinder widespread adoption in rural areas (Wang et al., 2020). Additional barriers include inadequate digital infrastructure, limited technical resources, and the need for further investment to operationalise innovations (Qi & You, 2024). These systemic challenges raise critical questions regarding the effective implementation, financing, and governance of green technologies to simultaneously address environmental degradation and socio-economic development in Yunnan's rural uplands.

1.1. Research Objectives

- To explore the role of green technologies in mitigating heavy metal pollution in Yunnan's Plateau agriculture.
- To assess the contribution of green technology to rural revitalization in Yunnan's Plateau agriculture.
- To identify policy and innovation gaps for implementing green technology solutions in Yunnan's Plateau agriculture.

Recent regional research underscores the significance of green agricultural development for the successful implementation of China's rural revitalization strategy. An assessment of agricultural green development in Northeast China by Hou and Wang (2022) revealed that competitive factors face substantial spatial disparities and structural limitations that impede sustainable progress, including inefficient land utilisation, underexploited technologies, and inadequate environmental governance. Prior literature described that, despite some advances in ecological conservation policies, persistent weaknesses—such as limited agricultural engagement and insufficient investment in green innovations continue to obstruct rural transformation. These findings emphasise the necessity of adopting region-specific strategies for green technology, which can simultaneously mitigate ecological degradation and enhance rural resilience. Within this context, examining plateau agriculture in Yunnan offers valuable insights into locally tailored and scalable approaches for integrated ecological and economic revitalization initiatives.

2. LITERATURE REVIEW

2.1. Green Technologies in Mitigating Heavy Metal Pollution in Yunnan's Plateau Agriculture

Dong et al. (2022) performed a systematic assessment of the soil–crop system across 11 cities in

Yunnan, revealing that agricultural soils have historically been contaminated with elevated levels of cadmium (Cd) and lead (Pb). The study underscores the urgent necessity of integrating pollution control measures into regional land management strategies. While recognising the multidimensional spatial heterogeneity of contamination, the authors advocate for the application of locally adapted green technologies rather than uniform interventions. Adjustments in plantation patterns represent a promising nature-based strategy. Cheng et al. (2024) examined different cultivation patterns of Dendrocalamus brandisii, a tropical bamboo species, in Yunnan and identified notable variation in heavy metal bioaccumulation across plantation types. Mixed forest systems demonstrated lower risk levels, indicating that afforestation design may serve as an effective green technology for capturing and mitigating heavy metals in polluted areas.

Qin et al. (2022) investigated heavy metal contamination in agricultural soils developed on karst landscapes in Southwest China, including Yunnan. Their findings indicate that the accumulation of metals such as zinc (Zn) and chromium (Cr) is influenced by landform characteristics interacting with anthropogenic activities. They emphasise that geomorphologically targeted interventions, including selective cultivation and soil amendments, can substantially reduce pollution levels. Jia et al. (2024) extended this line of research through spatial analysis to trace pollutant sources in areas affected by non-ferrous metal slag. Their study highlights source-specific remediation strategies and the integration of green technologies, such as phytostabilisation and microbial remediation, within policy frameworks to mitigate long-term environmental risks.

Other contamination pathways, particularly those independent of soil, also rely on green technologies to monitor heavy metals within the soil–feed–milk chain. Alarmingly high levels of metals have been detected in food products, with potential carcinogenic consequences for humans. These findings reinforce the importance of implementing comprehensive remediation measures that address all agricultural subsystems, including safe feed production practices and effective soil decontamination techniques. Finally, Wu et al. (2022) conducted a scoping review of national studies on phytoremediation, microbial remediation, and biochar application as cost-effective, environmentally sustainable alternatives. They emphasise that successful deployment of these technologies requires alignment with local soil chemistry, cropping systems, and pollution sources, a strategy particularly beneficial for the fragmented agroecological units of Yunnan.

2.2. Green Technology to Rural Revitalization in Yunnan's Plateau Agriculture

Deng et al. (2022) present micro-level evidence from Yunnan indicating that securing rural land rights can substantially enhance farmers' incomes through land transfer activities and the facilitation of scaled agricultural operations. While not a technology in itself, land tenure reform is critical for enabling the deployment of green technologies, as it permits investment in sustainable practices and necessary infrastructure. Their study emphasises that institutional reforms constitute a fundamental prerequisite for achieving both green development and income growth within the rural economy. Xie (2022) argues that policy frameworks must be compatible with rural revitalization goals and that innovation should emerge from grassroots levels to support green transformation in agriculture. The research identifies structural impediments—such as fragmented land use, low penetration of technological instruments, and inefficiencies within local governments—that restrict the regional feasibility of green technologies. Nevertheless, it highlights potential for scaling interventions like organic farming and clean irrigation when coupled with educational initiatives and financial incentives.

Sun et al. (2023) examine rural revitalization through the lens of green finance, demonstrating that environmentally oriented financial mechanisms can support green industries. Using panel data from across China, the study reveals that green finance produces significant spatial spillover effects, enhancing both innovation and agricultural output in rural localities. These findings are particularly relevant for Yunnan, where regional development remains uneven, suggesting that green financial instruments could serve to narrow interregional disparities. Zhao (2023) evaluates the role of the digital economy in catalysing rural revitalization via green technology adoption in Yunnan. The study finds that leveraging digital resources—including e-commerce platforms, innovative agricultural systems, and data-driven infrastructure planning—has substantially increased total factor productivity in rural industries between 2012 and 2021. This illustrates how technology-enabled green innovation can overcome the geographic and economic barriers inherent to plateau agriculture.

Shen (2024) provides an example of a successful ecological-economic revival model, resulting in integrated village–community green development in

Jiangsu Province. Although implemented outside Yunnan, its principles offer transferable lessons for plateau communities facing comparable socioeconomic fragmentation. Finally, Juanjuan and Wei (2024) advocate for system-level ecological revitalization through a comprehensive framework integrating natural resource management, support for green industries, and social infrastructure development. Their systems-oriented approach offers a strategic model for progressively enhancing Yunnan's rural capacity through the adoption of integrated green technologies.

2.3. Policy and Innovation Gaps for Implementing Green Technology Solutions in Yunnan's Plateau Agriculture

Li and Shangguan (2024) assessed the National Agricultural Green Development Pilot Zones policy, finding that while it enhanced eco-efficiency in regions of implementation, its effects were geographically uneven. The study indicated that areas where rural innovation was pivotal for policy success experienced delays, resulting in weaker institutional capacity and slower technological diffusion in less developed western provinces such as Yunnan. This highlights a key policy limitation in tailoring institutional structures to local socio-economic contexts. Case-specific research in Yunnan further illustrates these constraints. Yong et al. (2023) examined the Erhai Lake Basin, where strict ecological protection measures were enforced to minimise agricultural contamination. However, these measures inadvertently reduced farmers' income sources, revealing a persistent gap between ecological policy objectives and socio-economic realities. Addressing this discrepancy requires innovative approaches that are both socially acceptable to farming communities and capable of sustaining livelihoods alongside ecosystem health.

Economic disparities present additional barriers to the dissemination of innovation. Jiang et al. (2023) observed that widening urban–rural income gaps negatively impact agricultural green productivity, as resource-poor rural households are unable to adopt costly green technologies. This institutional imbalance reflects shortcomings in governance and policy planning, which fail to provide equitable access to innovation, particularly in lagging regions such as Yunnan. At the individual level, Xu et al. (2024) found that although a majority of farmers in Yunnan's multi-ethnic communities expressed willingness to engage in green agricultural practices, actual adoption was limited. The discrepancy between intention and practice was attributed to insufficient incentives, low awareness, and inadequate extension services, emphasising the need for targeted policy support, subsidies, and culturally sensitive training programmes.

Liu et al. (2023) analysed temporal and spatial variations in agricultural green development efficiency across China, concluding that western provinces consistently lag behind due to underdeveloped technological innovation systems. They emphasise that bridging these regional gaps requires locally tailored innovation systems and enhanced cross-provincial collaboration. Finally, Gan et al. (2023) investigated barriers to the development of green rural housing, identifying a self-reinforcing cycle of financial, infrastructural, and policy constraints. Their application of fuzzy cognitive mapping elucidated the interrelated structural barriers that impede effective policy formulation, providing a robust methodological framework for diagnosing systemic gaps in the green agricultural transformation of Yunnan.

2.4. Literature Gap

Although prior research underscores the promise of green technologies for mitigating heavy metal contamination, supporting rural revitalization, and informing policy reforms, several critical gaps persist. Firstly, studies in Yunnan have largely concentrated on quantifying contamination levels and assessing ecological risks (Cheng et al., 2024; Dong et al., 2022), with limited empirical investigation into the long-term efficacy of green remediation technologies within plateau-specific agroecosystems. Secondly, while instruments such as digital tools, green finance, and land tenure reforms have been identified as facilitators of rural revitalization (Deng et al., 2022; Sun et al., 2023; Zhao, 2023), their integration into pollution management frameworks in Yunnan remains insufficiently explored. Thirdly, policy assessments predominantly focus on pilot initiatives in eastern provinces (Li & Shangguan, 2024; Shen, 2024), often neglecting the unique institutional, cultural, and socio-economic characteristics of western highland regions. Finally, the discrepancy between farmers' willingness and actual adoption (Xu et al., 2024) emphasises the necessity for research that connects behavioural dynamics with policy innovation, enabling the design of inclusive and context-specific pathways for green technology deployment in Yunnan.

3. METHODOLOGY

3.1. Research Methods and Design

The study adopted a qualitative research design, employing a Systematic Literature Review (SLR) methodology to achieve its objectives. This approach

facilitated the comprehensive collection, analysis, and synthesis of peer-reviewed literature pertaining to green technologies, heavy metal contamination, rural revitalization, and policy gaps within Yunnan's plateau agriculture. The review process involved the establishment of explicit inclusion and exclusion criteria, alongside a rigorous assessment of the methodological quality and reliability of the selected studies. This procedure ensured that only the most pertinent and robust research was incorporated into the analysis.

3.2. Data Collection Methods

3.2.1. Searching Techniques

The relevant literature was systematically identified through a targeted search using keywords aligned with the study's objectives, including terms such as green technology, heavy metal contamination, rural revitalization, Yunnan plateau agriculture, and policy and innovation gaps.

3.2.2. Databases

The literature search focused on databases including JSTOR, Web of Science (WOS), Google Scholar, and ResearchGate, selected for their extensive collections of peer-reviewed publications pertinent to agricultural biotechnology, sustainability, and rural development.

3.2.3. Boolean Operators

Boolean operators, including AND, OR, and NOT, were employed to refine the search strategy. For instance, queries such as "Green Technology AND Heavy Metal Pollution AND Yunnan" and "Rural Revitalization OR Agricultural Innovation NOT Malaysia/Korea/Russia" were utilised to maintain a precise focus on the study context.

3.2.4. Inclusion and Exclusion Criteria

A structured framework was established to systematically screen and filter the selected studies, as presented in Table 1.

Table 1: Inclusion and Exclusion Criteria.

Criteria	Inclusion	Exclusion
Publications	Peer-reviewed journal articles published from 2020 to 2025	Non-peer-reviewed works or publications prior to 2020
Research Type	Empirical or theoretical investigations	Opinion pieces, commentaries, or non-scientific studies
Language	English-language publications	Non-English-language publications
Focus	Research examining green technology applications in agriculture within Yunnan or broader China	Studies not addressing agricultural contexts or unrelated to green technology

3.3. Selection of Papers through the PRISMA Framework

An initial pool of 100 articles was identified and subsequently screened according to the predefined inclusion and exclusion criteria. Abstracts and full texts were carefully reviewed multiple times to confirm their relevance to the research objectives. Following this rigorous evaluation, 12 studies were retained for the final analysis. This purposive selection process ensured that only research providing substantive insights into pollution mitigation, rural revitalization, and policy and innovation gaps was incorporated Figure 1.

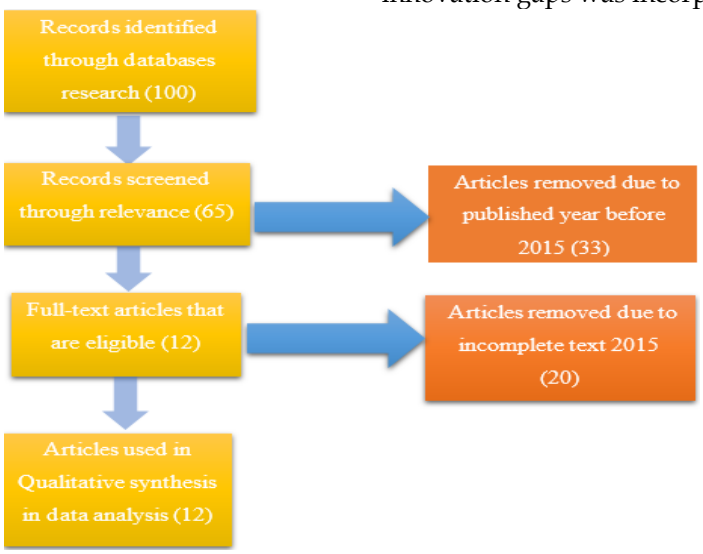

Figure 1: PRISMA Framework.

3.4. Data Analysis Methods

The findings were interpreted using a thematic analysis approach, with the overall process summarised in Table 2.

Table 2: Data Analysis Methods.

Step	Description
Familiarization	Engaging in multiple readings of the selected studies to discern central concepts
Coding	Allocating codes to salient themes, such as pollution, rural revitalization, and policy gaps
Theme Development	Organising codes into broader thematic clusters
Interpretation	Integrating and synthesising thematic findings to address the study's research objectives

3.5. Ethical Considerations

Ethical considerations were rigorously upheld throughout the study. Only publicly accessible, peer-reviewed sources were utilised, ensuring both transparency and adherence to academic integrity. Appropriate referencing and citation practices were employed to recognise all intellectual contributions. As the study did not involve human or animal participants, formal ethical approval was not required.

4. RESULTS

The study's results are presented through a thematic analysis of the selected literature, structured in alignment with the three research objectives. The findings illustrate the role of green technologies in mitigating heavy metal contamination in Yunnan's plateau agriculture, their impact on rural revitalization, and the policy and innovation gaps that limit their adoption. Collectively, these themes offer a comprehensive perspective on the opportunities and challenges associated with promoting sustainable agricultural transformation Table 3.

Table 3: Theme Extracted.

Theme	Sub-Themes	Focus of Analysis
Green Technologies for Pollution Mitigation	Phytoremediation (plants) Biochar and soil amendments Microbial remediation Plantation and land-use modification	Evaluation of the capacity of green technologies to diminish cadmium (Cd), lead (Pb), arsenic (As), and other heavy metal concentrations in soils and agricultural produce.
Green Technology and Rural Revitalization	Income growth and farmer livelihoods Digital and precision agriculture Green finance mechanisms Ecological agriculture models	Examination of the ways in which green technologies enhance rural socio-economic conditions and support the achievement of revitalization objectives.
Policy and Innovation Gaps	Weak institutional capacity Farmer adoption barriers Regional disparities Governance and regulatory limitations	Identification and analysis of systemic constraints that hinder the effective adoption and implementation of green technologies in Yunnan.

Theme 1: Green Technologies for Pollution Mitigation

Table 4 presents the green technologies employed to mitigate heavy metal contamination in agricultural soils, emphasising phytoremediation, biochar utilisation, and plant–microbe interactions.

Table 4: Green Technologies for Pollution Mitigation

Authors	Objectives	Methods	Findings	Conclusion
Harindintwali et al. (2020)	To investigate how interactions among biochar, bacteria, and plants can enhance the remediation of soils contaminated with heavy metals.	Review of literature on biochar applications, microbial partnerships, and plant-based remediation techniques.	Biochar functions as a carrier for beneficial microbes, improves soil nutrient retention, and supports plant growth under heavy metal stress. Microbial-assisted phytoremediation efficiency increased with biochar addition.	The integration of biochar, microbial inoculants, and plants offers a promising, environmentally sustainable approach to remediating heavy metal–contaminated agricultural soils.
Yang et al. (2022)	To identify global trends, research hotspots, and future directions in phytoremediation of heavy metal–polluted soils.	Bibliometric and scientometric analysis of 1,123 phytoremediation studies published between 2000 and 2020.	Cadmium (Cd) was the most frequently studied metal. Phytoremediation success was enhanced by microbial and chemical additives. Key research hotspots include plant diversity and mechanisms of heavy metal tolerance.	Future studies should focus on improving phytoremediation efficiency using biochemical aids and on identifying hyperaccumulator plants suitable for soils contaminated with multiple metals.
Khatoon et al. (2024)	To examine microbial contributions to heavy metal phytoremediation in agricultural soils.	Systematic review of plant–microbe interactions within agroecosystems.	Plant-associated microbes enhanced sequestration, stabilization, and detoxification of Cd, As, and Pb. Microbial activity promoted plant growth, improved soil fertility and biodiversity, and reduced contaminant levels.	Plant–microbe partnerships are critical for developing sustainable phytoremediation approaches, highlighting microbial-assisted remediation as a key pathway for future agricultural practices.
Jiang et al. (2024)	To evaluate the impact of biochar and phosphorus-based amendments on Amaranth's capacity to remediate Cd-contaminated soils.	Empirical experiments using soil treatments with biochar, phosphorus, and their combination under controlled conditions.	The combined application of biochar and phosphorus markedly decreased soil-available Cd, increased plant biomass, and enriched beneficial microbial communities. Soil enzyme activity and nutrient content also improved.	The synergistic use of biochar and phosphorus enhances plant-based phytoremediation effectiveness and fosters healthier microbial ecosystems in Cd-polluted soils.

The reviewed literature collectively indicates that the integration of green technologies, including biochar, microbial consortia, and plant-based interventions, substantially enhances the remediation of soils contaminated with heavy metals. Harindintwali et al. (2020) and Jiang et al. (2024) emphasise the role of biochar in promoting plant growth and supporting microbial activity, whereas Yang et al. (2022) and Khatoon et al. (2024) highlight the global applicability of phytoremediation and the contributions of microbial processes. These findings collectively underscore the necessity of employing synergistic, multi-technology approaches to achieve sustainable soil remediation in agricultural systems Table 4.

Theme 2: Green Technology and Rural Revitalization in Yunnan

Table 5 presents the green technologies that support rural revitalization in Yunnan, with a particular focus on financial mechanisms, digital innovations, renewable energy, and cooperative ecological models. The reviewed literature illustrates multiple pathways through which green technologies facilitate rural development. Li et al. (2023) highlighted the significance of green finance in promoting agricultural growth, while Jin et al. (2024) demonstrated the capacity of digital tools to enhance rural tourism and livelihoods. Harlan (2021) found that subsidised green infrastructure, such as small-scale hydropower, is necessary to ensure equitable benefits. Ye and Fan (2024) emphasised cooperative green economies as effective models for integrating ecological restoration with income generation, thereby reinforcing the contribution of technology to sustainable rural revitalization Table 5.

Table 5: Green Technology and Rural Revitalization in Yunnan.

Authors	Objectives	Methods	Findings	Conclusion
Li et al. (2023)	To investigate the influence of agricultural loans on rural revitalization in Yunnan Province.	Empirical analysis using provincial datasets, with indices constructed for rural revitalization and agriculture-related lending.	Agriculture-related loans were found to positively affect rural revitalization, particularly enhancing industrial prosperity and the efficiency of financial resource allocation.	Green finance, facilitated through agricultural loans, represents a significant driver of rural revitalization; however, improvements in efficiency and targeted lending strategies are necessary.
Jin et al. (2024)	To evaluate the role of digital technologies, including AI and machine learning, in enhancing rural bed-and-breakfast (B&B) management as part of rural revitalization in Yunnan.	Machine learning models (BERT, CNN, LSTM, GRU) were applied to online reviews, complemented by evolutionary game theory for stakeholder strategy analysis.	Key challenges in service quality and stakeholder coordination were identified. The application of digital technologies improved management efficiency and customer satisfaction.	Digital innovation strengthens rural tourism, enhances local livelihoods, and contributes substantially to sustainable rural revitalization.
Harlan (2021)	To assess whether small hydropower (SHP) projects in Yunnan deliver social and environmental benefits to rural communities.	Household survey of 122 households across 8 villages; comparative analysis between subsidized and unsubsidized SHP projects.	Subsidized SHP installations reduced reliance on fuelwood and improved energy access, whereas unsubsidized plants offered limited pro-poor benefits.	Only inclusive, subsidized green technologies can provide equitable advantages to rural populations, highlighting the importance of supportive policy frameworks.
Ye and Fan (2024)	To examine the role of green cooperative economies in promoting ecological restoration and rural development in Yunnan and neighbouring provinces.	Case studies of green cooperative industries, including fruit farming and photovoltaic initiatives, within rocky desertification regions.	Green cooperatives enhanced farmer incomes, strengthened ecological protection, and reinforced community resilience.	Cooperative green economic models can concurrently achieve environmental restoration and rural revitalization, offering replicable strategies for Yunnan.

Theme 3: Policy and Innovation Gaps

Table 6 outlines the policy and innovation gaps that impede the adoption of green technologies in Yunnan, focusing on institutional capacity, regional disparities, barriers to farmer uptake, and governance constraints. The reviewed literature indicates that persistent gaps in policy and innovation continue to limit the effective implementation of green technologies. Wang and Zhan (2024) demonstrate that while digital rural initiatives improve accessibility, their impact is constrained by weak institutional support. Similarly, Wang et al. (2024) highlight inconsistencies in adoption rates across different regions. Wang (2024) underscores the inadequate alignment of innovative practices with local agricultural requirements, and Feng et al. (2023) reveal governance shortcomings in the implementation of water-saving reforms. Collectively, these studies emphasise the necessity for context-specific, institutionally supported innovation policies to facilitate the widespread uptake of green technologies.

Table 6: Policy and Innovation Gaps.

Authors	Objectives	Methods	Findings	Conclusion
Wang and Zhan (2024)	To investigate how digital rural development initiatives address the urban–rural information gap in Yunnan.	Case study approach using data from rural development programmes in Yunnan.	Digital rural programmes improved access to information and essential services; however, progress was constrained by weak institutional capacity and limited infrastructure.	Bridging the digital divide in rural Yunnan requires strengthened governance support and the implementation of targeted innovation policies.
Wang et al. (2024)	To assess the role of rural digitization in promoting coordinated urban–rural development.	Quasi-natural experiment using panel datasets and econometric modelling.	Rural digitization reduced regional disparities and fostered integration, though adoption remained uneven, particularly in western provinces such as Yunnan.	Digitization strategies are effective but must be tailored to regional contexts to mitigate uneven adoption and structural inequalities.
Wang (2024)	To evaluate how scientific and technological innovation contributes to sustainable development in Yunnan's agricultural sector.	Theoretical and policy analysis using economic and innovation-related indicators.	Weak innovation systems and poor alignment of policies with local needs impeded agricultural modernisation and sustainability in Yunnan.	Enhancing local innovation capacity and aligning governance frameworks are critical for promoting sustainable agricultural development.
Feng et al. (2023)	To examine the effects of property rights reform on the maintenance of agricultural water facilities and farmer behaviour in Yunnan.	Empirical study using household survey data from 328 households and econometric models (Oprobit, IV-Oprobit).	Reforms improved irrigation facility maintenance and adoption of water-saving technologies, but institutional and governance limitations restricted overall effectiveness.	Property rights reform can facilitate the uptake of green technologies, contingent upon supportive policies and effective institutional coordination.

5. DISCUSSION

5.1. Interpretation of the Findings

This study is structured around three principal themes, through which the findings highlight both the opportunities and systemic challenges associated with promoting green technology in Yunnan's plateau agriculture. Regarding the first objective, the evidence demonstrates that phytoremediation, biochar, and microbial remediation effectively reduce cadmium (Cd), lead (Pb), and arsenic (As) concentrations in agricultural soils. Research by Harindintwali et al. (2020) and Jiang et al. (2024) indicates that the application of biochar and soil amendments not only enhances plant growth but also stabilises soil contaminants. Likewise, Yang et al. (2022) and Khatoon et al. (2024) emphasise that phytoremediation and microbial interventions possess global applicability while remaining adaptable to the fragmented agroecological zones of Yunnan.

For the second objective, findings suggest that green technologies contribute substantially to rural revitalization by increasing income, promoting digitalisation, facilitating access to financial tools, and supporting ecological cooperatives. Green finance plays a critical role in enhancing agricultural development, while Jin et al. (2024) highlight the beneficial impact of digital innovations on rural tourism and livelihoods. Harlan (2021) underscores the necessity of policy backing for renewable energy projects, whereas Ye and Fan (2024) demonstrate that cooperative ecological models function as multi-dimensional instruments capable of transforming both rural lifestyles and local environmental management practices. Concerning the third objective, the analysis reveals significant institutional and policy deficiencies that impede sustainable adoption of green technologies in Yunnan's plateau agriculture. Key barriers include limited governance capacity (Wang & Zhan, 2024), uneven regional adoption (Wang et al., 2024), inadequate alignment of innovations with local agricultural needs (Wang, 2024), and governance challenges associated with water-saving initiatives (Feng et al., 2023). These findings collectively underscore the pressing need for context-specific, institutionally supported interventions to facilitate the effective implementation of green technologies in the region.

5.2. Comparison with the Previous Studies

The findings of this study both corroborate and extend previous research while revealing distinctive patterns specific to Yunnan's plateau agriculture. Concerning heavy metal pollution control, prior studies, including Dong et al. (2022) and Qin et al. (2022), documented the severity of cadmium (Cd), lead (Pb), and zinc (Zn) contamination in Yunnan soils, emphasising spatial heterogeneity across karst landscapes. The present analysis reinforces these concerns by demonstrating that biochar, microbial inoculants, and phytoremediation approaches can effectively reduce the bioavailability of metals. This aligns with Wu et al. (2022), who identified nature-

based solutions as cost-effective alternatives to chemical remediation. However, unlike earlier research that predominantly considered remediation as a technical measure, the current study underscores the importance of integrated strategies combining biochar, plant systems, and microbial interventions. In contrast to studies analysing single-crop bioaccumulation, such as Cui et al. (2023), which highlighted isolated risks, the present research demonstrates the advantages of holistic, system-based approaches.

With respect to rural sustainability, prior research has highlighted the critical role of asset availability and financial resources in enabling sustainable livelihoods (Deng et al., 2022; Sun et al., 2023). This study builds on that perspective by demonstrating that digital technologies and cooperative green economies are equally pivotal enablers of rural development. Zhao (2023) illustrated that digital economies can generate transformative effects in plateau industries, and the current findings extend this by showing how artificial intelligence and information-driven platforms can shape tourism and service policy organisation. Unlike Zhao's broader economic focus, this study situates digital adoption within a green technology framework, highlighting its dual role as an economic driver and a mechanism for ecological restoration. Similarly, while Shen (2024) and Juanjuan and Wei (2024) emphasised system-level rural development frameworks, the present findings indicate that cooperative ecological models are particularly well-suited for fragmented plateau regions, demonstrating the scalability of community-based ecological interventions.

Regarding policy and innovation gaps, the results are consistent with prior research identifying regional and origin-related disparities as obstacles to green technology adoption. For example, Li and Shangguan (2024) observed that pilot programmes in western provinces frequently underperformed due to weaker governance systems. The current study builds upon these findings by emphasising the additional influence of barriers to farmer adoption and significant urban–rural income disparities. Yang et al. (2022) demonstrated that poverty alleviation initiatives only modestly reduced income inequalities in Yunnan without generating innovation-driven growth, supporting the current evidence that, in the absence of effective extension services and institutional incentives, farmers remain reluctant to adopt green agricultural practices. Likewise, Liu et al. (2023) mapped regional inefficiencies in agricultural green development, corroborating prior observations regarding the underdeveloped innovation ecosystem in western provinces.

A further conceptual advancement of this study is the framing of digital and cooperative models as both technological and institutional solutions. Whereas Wang et al. (2020) emphasised the role of stakeholder networks in overcoming diffusion barriers, the present research highlights rural digitalisation (Wang et al., 2024) and land tenure reforms (Feng et al., 2023) as mechanisms that simultaneously reduce governance inefficiencies and facilitate technology adoption. This conceptualisation suggests that institutional and technological reforms are not parallel processes but mutually reinforcing elements that should be integrated into coherent policy designs. Finally, whereas earlier studies such as Lai et al. (2022) and Liu et al. (2024) primarily focused on contamination risks and health implications, treating technological adoption as a secondary concern, the current study positions green technology adoption at the centre of analysis. Here, pollution mitigation, livelihood enhancement, and governance restructuring converge within a unified framework. This represents a conceptual shift from merely describing environmental hazards to prescribing actionable, sustainable interventions, synthesising bio-technical, socio-economic, and institutional insights that were previously examined largely in isolation.

5.3. Theoretical Implications

This study makes several theoretical contributions to the literature on sustainable agriculture and rural transformation. Firstly, it expands the scope of environmental governance theory by emphasising that both environmental conditions—including institutional structures and socio-economic contexts—and the effectiveness of ecological technologies influence the integration of new innovations, consistent with observed governance constraints in western provinces (Li & Shangguan, 2024). Secondly, the findings relate to rural development theory by linking ecological restoration processes with the outcomes of rural revitalization, offering insights that can be drawn from cooperative economic models (Ye & Fan, 2024). Thirdly, the study refines innovation diffusion theory by highlighting barriers specific to plateau agriculture, including weak institutional support and limitations in adoption. Finally, the research underscores the relevance of systems thinking, recognising governance and ecological systems as interdependent components and demonstrating that both environmental and rural transformations require cross-system, integrative approaches (Harlan, 2021).

6. CONCLUSION

This study demonstrates that phytoremediation, biochar application, and microbial remediation represent viable approaches for alleviating heavy metal

contamination in Yunnan's plateau agriculture, while simultaneously supporting rural revitalization. Evidence indicates that, when complemented by robust financial mechanisms, digital innovations, and cooperative frameworks, these technologies can enhance environmental quality, safeguard food security, and improve farmer livelihoods. Nonetheless, systemic challenges—such as limited institutional capacity, uneven regional availability, and barriers to farmer adoption—constrain the broad implementation of these solutions. Addressing these gaps requires context-specific interventions that integrate ecological, economic, and governance dimensions, thereby facilitating sustainable and transformative agricultural development in Yunnan's highland regions.

6.1. Limitations

The reliance on a systematic literature review constitutes a limitation of this study, as it restricted access to primary field data and depended predominantly on secondary sources. Additionally, the exclusive use of English-language, peer-reviewed journals may not have captured all locally produced research published in Chinese. While the thematic analysis provided a structured synthesis, it may also have oversimplified the complex socio-political dynamics that shape the adoption of technology in Yunnan's plateau agriculture.

6.2. Future Work

The effectiveness of green technologies under plateau-specific conditions, as observed in Yunnan, warrants validation through future field-based studies employing mixed-method approaches. Greater attention should be directed towards farmers' perceptions, behavioural adoption processes, and localised policy responses. Comparative analyses with other plateau regions in China or internationally would further enhance understanding and support the development of transferable, context-sensitive models for green agricultural advancement.

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