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Cover Story

Minning Town is situated in the Gobi Desert region at the eastern foot of the Helan Mountains in Ningxia. The town is also an empirical model of East－West coordinated poverty alleviation—a Chinese development strategy that pairs affluent eastern provinces with less developed western regions for targeted support. Once declared "one of the least suitable areas for human settlement" by the United Nations, the town has undergone a remarkable transformation since Fujian and Ningxia launched their collaborative mechanism in 1997. Established as a demonstration project for ecological migration and institutional poverty alleviation, the town has resettled over 66,000 residents and established a sustainable development model centered on ecological restoration and industrial cultivation. Fujian province, a relatively developed coastal region which is more than 2,000 kilometers away, gave full support for funds, investment, job opportunities and human resources to the town to improve the harsh living environment and reduce poverty.

The "Minning Model" is built on a Four-Dimensional Synergy Framework, integrating ecological-industrial development, skill training, market connectivity, and collaborative governance. A multi-level training system enhanced farmers' capabilities, while Fujian's business networks helped the town access national markets. An innovative credit-based governance model encouraged residents to shift from aid recipients to active agents of development. After 28 years, per capita income rose 38-fold to ¥19,000, poverty was eliminated, and vegetation coverage reached 35%.

The "Minning Model" illustrates three core mechanisms: interregional institutional coordination to overcome resource bottlenecks; place-based industrial adaptation for sustainable self-development; and the cultivation of local agency to ignite endogenous motivation, enabling a transition from poverty eradication to shared prosperity. This integrated system—combining institutional design, sectoral support, and human capacity building—offers a policy solution with both Chinese characteristics and broader relevance for global poverty reduction efforts.

(Xiaoyun Ma, Associate Professor, Jiyang College of Zhejiang A&F University).

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About the Journal

Agricultural & Rural Studies (**A&R**, **ISSN 2959-9784**) is an exclusively digital, open-access journal dedicated to advancing interdisciplinary scholarship at the critical nexus of agricultural sustainability, rural revitalization, and farmer well-being. Published quarterly, **A&R** features a range of content types—including original research, reviews, perspectives, and commentaries—serving as a professional and innovative platform for rigorous academic dialogue and global knowledge dissemination.

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(1) **Interdisciplinary Scope:** A&R centers on interdisciplinary and multidisciplinary inquiry, integrating insights from economics, sociology, human geography, and cognate disciplines to address pressing contemporary issues in agriculture, rural development, and farmer-related policies—bridging theoretical frameworks to advance holistic understandings of these dynamic systems.

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(3) **Culture-Driven Operations:** Rooted in our mission, vision, and values, cultural stewardship lies at the core of A&R's identity. Our unwavering commitment to ethical principles, community engagement, and purposeful impact permeates every facet of the journal's operations.

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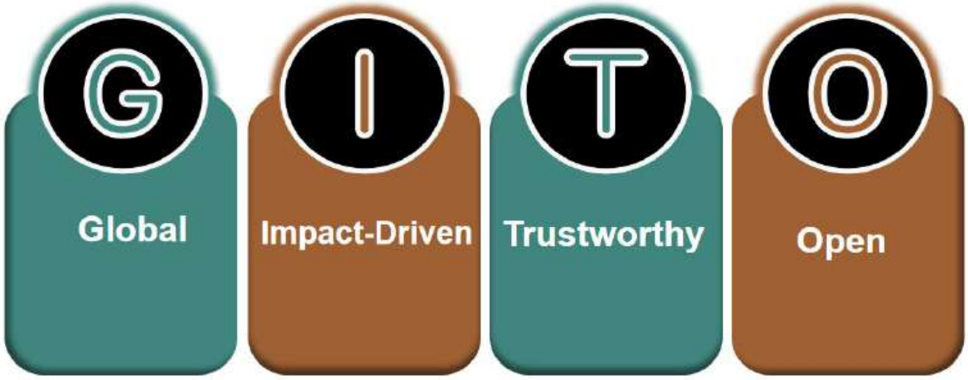

Agricultural & Rural Studies

Article

Rice, Rules, and Rural Roads: Evolutionary Dynamics of China's Milled Rice Industry

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Abstract: China's milled rice imports present both opportunities and challenges for the transformation of its rural agricultural supply chain. However, the mechanisms through which international rice trade co-evolves with domestic supply chain upgrading remain underexplored. By isolating trade volumes, price effects, or food security concerns, previous approaches risk oversimplifying policy design, as they fail to account for how shifts in government incentives, market procurement preferences, and smallholder upgrading decisions dynamically reinforce or undermine one another over time. This study addresses that gap by integrating SWOT analysis into a tripartite evolutionary system to model the strategic co-adaptation of the stakeholder groups. Simulation results demonstrate that aligning incentives across the three stakeholder groups leads to stable and mutually beneficial equilibria, which the SOAR framework reframes as dynamic levers in a complex adaptive system. By revealing how positive feedback loops are generated, the results offer actionable guidance for improving market inclusivity, enhancing rural incomes, and ensuring long-term food system stability in the face of global trade pressures. In conclusion, this study provides a strategic framework for fostering a cooperative, resilient, and high-performing rice supply chain through the coordinated evolution of government, market enterprises, and smallholder strategies. The insights can inform targeted interventions that simultaneously advance rural prosperity. Future research could enrich the model by incorporating climate risks, international market shocks, and digital supply chain innovations to capture emerging challenges and opportunities in the global agri-food landscape.

Keywords: food security; rural economy; supply chain upgrading

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1. Introduction

Rice holds a central place in China's food security strategy and rural economy. Beyond its role as a staple food, rice cultivation in China generates a variety of valuable by-products that underscore its broader economic and ecological importance. Rice husks, bran, and straw, though often seen as agricultural residues, are increasingly utilized in bioenergy production, organic fertilizers, construction materials, and even animal feed, contributing to circular agricultural practices and rural industrial diversification. For instance, rice husks can be converted into biomass energy, supporting low-carbon transitions in rural areas, while rice straw is being repurposed into biodegradable packaging and soil enhancers. Building on recent advancements in green remediation, the study (Irshad et al., 2022) offers exemplary and valuable insights for sustainable rice cultivation in contaminated regions. In the context of rice biomass utilization, Sriariyanun et al. (2022) showcase a promising one-pot approach using IL-tolerant cellulases for efficient lignocellulose breakdown, offering novel opportunities to valorize rice straw and by-products in biorefinery applications. These outputs not only reduce waste but also enhance the value chain of the milled rice industry, reinforcing rice as a strategic crop that drives innovation, environmental sustainability, and rural resilience in China's agricultural landscape.

As a country with vast consumption demand and complex regional production patterns, China has traditionally depended on domestic rice cultivation to stabilize supply. However, over recent years, increasing openness to international grain markets and supply chain modernization have transformed China's rice landscape. Particularly, the milled rice import has grown as a complementary supply channel, meeting diversified consumer demands and supporting price stability amidst periodic fluctuations in domestic production, which present both opportunities and challenges for the transformation of its rural agricultural supply chain. While international rice trade can stimulate rural economic upgrading, the underlying mechanisms through which trade interacts with domestic supply chain evolution remain underexplored. Existing research often isolates variables such as trade volume, price effects, or food security concerns, resulting in fragmented insights that oversimplify policy design. This reductionist approach neglects the dynamic interplay between government incentives, market procurement strategies, and smallholder upgrading behaviours. These interactions can either reinforce or undermine long-term supply chain resilience. Between 2020 and 2022, China's milled rice imports remained relatively stable and regionally concentrated, sourced predominantly from ASEAN countries and South Asian exporters such as India and Pakistan. Since 2023, a noticeable shift has emerged that imports from traditional suppliers have declined, while India has significantly expanded its presence in the Chinese market. In contrast, non-Asian exporters have seen their share shrink, reflecting a broader trend toward regionalization and a preference for cost-efficient, high-quality supply channels. In examining China's imports, the USD/RMB exchange rate is often used as a proxy for external price sensitivity and import purchasing power, while the CSI Agricultural Theme Index reflects broader trends in agricultural sector performance and market sentiment. These indicators are commonly employed to interpret fluctuations in trade volumes through financial and macroeconomic lenses. Figure 1 presents the milled rice import structure from 2020 to May 2025, with the data obtained from Customs Statistics, General Administration of Customs of the People's Republic of China (http://stats.customs.gov.cn/). However, as illustrated in Figure 2, the expected directional correspondence between these variables and China's milled rice import trends does not prominently emerge.

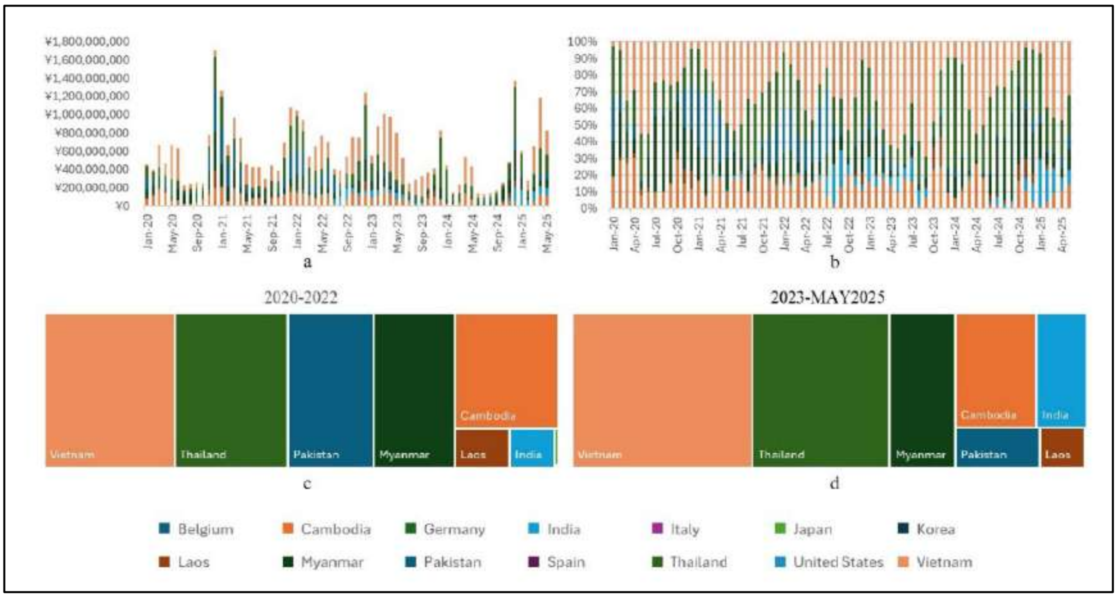

Figure 1. China's Milled Rice Import Structure from 2020 to May 2025: (a) Monthly Import Value (RMB); (b) Country-wise Monthly Percentage Share; (c) Country-wise Proportion (2020–2022); (d) Country-wise Proportion (2023-May 2025); Data Source: China Customs.

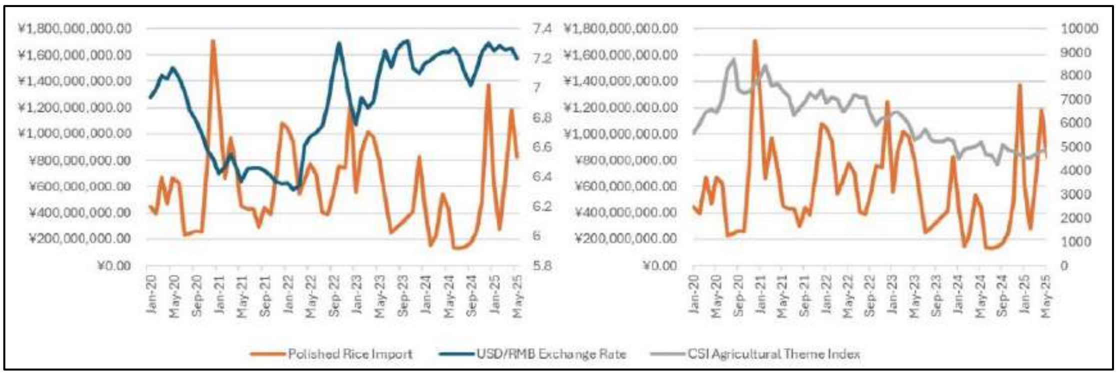

Figure 2. Comparison of China's Milled Rice Import Value and Financial Index from 2020 to May 2025.

Figure 1 and Figure 2 are pivotal to the manuscript because they provide empirical grounding for the argument that China's milled rice import patterns are undergoing a structural transformation that cannot be fully explained by conventional macroeconomic or financial indicators alone. Figure 1 is included to visualize the evolving structure and source composition of China's milled rice imports from 2020 to May 2025. By depicting both the monthly import values and country-wise proportions, the figure highlights two key trends. Trend 1 is the regional concentration and relative stability of imports prior to 2023. Trend 2 is the subsequent rise in India's market share and a decline in non-Asian exporters post-2023. This supports the paper's thesis that China's rice import dynamics are increasingly shaped by structural, regional, and demand-side forces, rather than purely by trade liberalization or short-term price signals. Figure 2, in contrast, serves to challenge a common assumption in trade analysis that variables like the USD/RMB exchange rate or the agricultural sector index (as represented by the CSI) are reliable predictors of import behavior. By showing the lack of strong correlation between these indicators and milled rice import volumes, Figure 2 justifies the study's shift in focus toward institutional, supply chain, and consumption-driven explanations. It reinforces the idea of a structural decoupling between financial signals and trade behavior in this sector. Together, both figures establish the empirical necessity for an evolutionary game-theoretic approach that captures the strategic interactions among government regulators (G), milled rice enterprises (B), and domestic smallholder producers (P), which is a framework that traditional linear or econometric models may fail to capture. Thus, the inclusion of these figures is not merely descriptive, but integral to motivating and legitimizing the model-based analysis that follows. Given this absence of strong alignment, the present study focuses instead on more direct structural and demand-side factors driving import behavior. Similarly, the underutilization of domestic rice futures markets reflects a broader structural dynamic. While japonica and indica rice contracts are listed on the Dalian Commodity Exchange (DCE) and Zhengzhou Commodity Exchange (ZCE), their relatively stable pricing shows limited responsiveness to changes in milled rice import volumes. This decoupling is perhaps unsurprising, given China's position as a major rice-producing nation with a high degree of self-sufficiency. Consequently, external price cues appear to play a more muted role in shaping import behavior. Instead, fluctuations in milled rice imports seem to stem primarily from evolving domestic consumption patterns, such as rising quality expectations in urban areas, regional taste variations, and broader nutritional transitions. Within this context, imports function less as price-responsive substitutes and more as targeted supplements to meet differentiated domestic demand, reinforcing the structural, demand-led nature of China's milled rice trade. Chinese importers still tend to rely on market signals rather than domestic futures for decision-making. This structural decoupling becomes even more significant in light of a striking new trend: from January to May 2025, the value of imported milled rice rose sharply compared to the same period in 2024, with year-on-year increases of 37.50%, 87.80%, 179.10%, 120.80%, and 88.97%, respectively. These unprecedented surges point to a growing preference for international sources at a time when China is also prioritizing rural revitalization, food security, and supply chain upgrading. This study focuses exclusively on the market-oriented operations of China's milled rice industry and does not address policy-based procurement mechanisms. The combination of regionalized sourcing, weak futures market integration, and accelerating import dependence underscores the urgency of re-evaluating how policy, market strategies, and supply chain structures evolve together. Although milled rice imports have become an increasingly important complement to China's grain supply, the mechanisms by which international trade co-evolves with domestic agricultural upgrading remain poorly understood. Much of the existing literature addresses trade volumes, price fluctuations, or food security outcomes in isolation, often overlooking the dynamic interactions among government policy incentives, market procurement strategies, and the upgrading behaviors of smallholder producers. Since 2023, a notable shift has emerged in China's rice import pattern, characterized by regional consolidation of sourcing and a significant rise in import value, particularly between January and May 2025. These developments point to a strategic realignment among the key stakeholders in China's rice economy, yet this transformation has not been systematically analyzed using an integrated, evolutionary framework.

Rice, as the staple food for more than half of the world's population (Mohidem et al., 2022), holds a pivotal position in the global food system. The United Nations'(2015) Sustainable Development Goal 2 emphasizes the need to end hunger and promote sustainable agriculture in "Transforming Our World: The 2030 Agenda for Sustainable Development," highlighting the importance of reliable international trade in securing food access. However, while the Food and Agriculture Organization (FAO) recognizes that trade liberalization and reduced barriers can improve food availability and stability, some researchers caution that international price volatility can undermine supply chain security (Saravia-Matus et al., 2012). Within this complex context, rice has been the subject of sustained attention, particularly regarding its sensitivity to trade liberalization and national food security concerns (Calingacion et al., 2014; Dorosh, 2001; Mobarok et al., 2021). Yet, the specific mechanisms through which government policy incentives, importer strategies, and domestic supply chain upgrading behaviors evolve together remain largely unexplored. Policy and academic discussions have increasingly focused on rural development goals using tools such as procurement reforms and smallholder training programmes (Geng et al., 2024; Sarfo et al., 2024; Zhang & Li, 2025). While these measures have produced some positive results, they are typically implemented in isolation and assessed through static or linear frameworks. Existing models rarely capture the iterative feedback loops among key stakeholders, nor do they provide a systemic lens for understanding how cooperative strategies evolve over time. As a result, there remains a gap in identifying and sustaining the conditions that lead to stable, mutually beneficial outcomes for all actors in the rice supply chain. Beyond food security, the environmental and structural implications of rice trade warrant critical examination. It is argued that international trade intensifies production pressures on key commodities, necessitating supply chain redesign to mitigate sustainability risks. Economies of scale may improve efficiency, but without system-wide changes, agricultural intensification may exacerbate environmental degradation (Pretty et al., 2018). Evidences of significant cross-country variation also emerge in the environmental efficiency of rice production, suggesting that trade can contribute positively by reallocating production to more efficient regions (Halpern et al., 2022). Furthermore, well-managed globally integrated sourcing can impose fewer environmental burdens than localized but inefficient systems (Roux et al., 2021). Conversely, poorly regulated trade may lead to unsustainable resource exploitation (Erhardt & Weder, 2020), while localization itself does not guarantee environmental benefits (Enthoven & Van den Broeck, 2021). Therefore, social-ecological resilience is important as it enables supply chains to be adaptive systems that are able to persist, transform, and evolve in response to external shocks (Wieland & Durach, 2021). The societal importance of this study lies in its potential to strengthen national food security, narrow rural–urban income gaps, and preserve smallholder livelihoods in the face of global competition. By identifying coordination mechanisms that balance efficiency with inclusivity, the framework supports rural revitalization strategies and fosters equitable participation in value-added segments of the rice supply chain. The industry relevance is equally significant. For agribusinesses, cooperatives, and processing enterprises, the model offers a roadmap for optimizing procurement strategies, reducing transaction costs, and enhancing supply chain resilience. By clarifying how policy incentives interact with market behavior and production decisions, the findings equip industry actors to better navigate volatile trade environments, leverage collaborative innovations, and secure long-term competitive advantages in both domestic and international markets. These insights collectively point to the critical role of governance and policy guidance in shaping sustainable trade patterns and domestic supply chain responses, which directly inform how collaborative strategies can be designed to strengthen rural supply chain resilience and high-quality development in China. The core of these evolving dynamics is the governance structure. It connects international trade, supply chain modernization, and rural development. Institutional design and policy coordination are central to balancing conservation and production goals in agricultural systems (Baylis et al., 2021). However, most existing studies address these components in isolation, lacking a unified framework that captures the co-evolutionary behaviors of governments, importers, and producers within a shared, policy-driven environment.

This study addresses the gap by integrating SWOT analysis into a tripartite evolutionary game model that simulates the co-adaptation of government regulators, market-based procurement agents, and smallholder producers. The model incorporates data-informed parameters to reflect realistic decision-making processes, enabling the capture of strategic adjustments and emergent equilibria over time. By framing stakeholder interactions as part of a complex adaptive system, the approach reveals how aligning incentives can generate self-reinforcing positive feedback loops. These loops, in turn, promote cooperative behaviours that enhance supply chain stability, inclusivity, and resilience against both domestic and global market pressures, reframed by the SOAR framework as dynamic levers in a complex adaptive system. The model captures how decisions made by each stakeholder interact over time to influence broader supply chain trajectories. Its structure is aligned with China's rural development goals. Therefore, the study offers a coherent and dynamic lens through which to assess the mutual influence of trade, governance, and agricultural modernization, guided by two primary questions: RQ1: How do government incentives, market procurement strategies, and domestic upgrading behaviors evolve together within China's rice import ecosystem? RQ2: How can collaborative strategies among these stakeholders promote resilience and high-quality development in China's rural agricultural supply chain?

The novelty of this study lies in its dynamic modelling of multi-stakeholder co-evolution within the context of China's milled rice imports. It is moving beyond static trade or policy analyses to capture the real-time interdependence of governance, market, and smallholder strategies. By aligning the game structure with China's rural modernization agenda, the study reframes milled rice as a policy-sensitive lever that links global sourcing with local capacity building, bypassing zero-sum trade logic. The primary objective is to reveal how collaborative, incentive-aligned strategies among government, market actors, and smallholders can generate stable and mutually beneficial equilibria, thereby improving market inclusivity, boosting rural incomes, and enhancing food system resilience, while simultaneously advancing multiple SDGs. Therefore, Research Objective 1 is to analyze the dynamic feedback mechanisms through which government incentives influence market procurement patterns, how these procurement patterns shape smallholder upgrading pathways, and how, in turn, the upgrading behaviors of smallholders feed back into policy adjustments and market strategies, which together determine the adaptive trajectory of China's rice import–domestic supply chain system. Research Objective 2 is to identify and evaluate strategic configurations in which incentives are aligned across all three stakeholder groups, ensuring that government policies support market inclusivity, market actors enable equitable participation, and smallholders sustain innovation and productivity gains. Thereby, they foster cooperative behavior that underpins a resilient, inclusive, and innovation-driven rural agricultural supply chain capable of sustaining high-quality growth under global trade pressures. By unpacking the evolving interplay among governance incentives, market behavior, and smallholder responses, this study reframes milled rice as a conduit for institutional alignment and rural modernization. As so, milled rice becomes a policy-sensitive lever through which procurement practices and grassroots innovation co-evolve. This dynamic system bypasses zero-sum trade logic. It forges productive linkages between global sourcing and local capacity-building. Such a co-evolutionary approach reinforces China's overarching development agenda and aligns with multiple Sustainable Development Goals. It advances SDG 2 by strengthening food security through sustainable agricultural practices; supports SDG 9 by driving innovation and infrastructure upgrades across agro-industrial systems; promotes SDG 12 via more efficient and responsible resource use; and contributes to both SDG 1 and SDG 10 by facilitating inclusive growth and reducing rural inequality. It weaves together trade, governance, and rural resilience within a unified developmental trajectory. Despite growing scholarly attention to China's rice trade and rural supply chain modernization, existing research tends to examine domestic agricultural upgrading in isolation. Studies focus predominantly on technological adoption (S. Zhang et al., 2025), distribution volatility and macro-level food security (Pu & Xiang, 2025; Xie et al., 2025; J. Zhang et al., 2025), while few research centers on institutional reforms within domestic markets. This compartmentalized approach overlooks the interdependent and adaptive nature of stakeholder strategies, where government incentive design, enterprise procurement behavior, and smallholder upgrading decisions co-evolve in response to both domestic policy shifts and global trade dynamics. As a result, there is limited understanding of how these strategic interactions generate reinforcing or counteracting feedback loops that shape long-term supply chain resilience, competitiveness, and inclusivity. Addressing this gap requires a dynamic systems perspective capable of integrating policy, market, and producer behaviors into a unified analytical framework, precisely the contribution this study aims to make.

2. Materials and Methods

This study employs a multi-method approach to investigate the dynamic interplay between milled rice industry strategies and rural transformation in China. It combines strategic diagnostic tools, including SWOT analysis, with a tripartite evolutionary system to capture the co-evolutionary behaviours of key stakeholders. It provides a dynamic lens through which to model the strategic interactions among heterogeneous agents. This system differs from the classical game framework by assuming bounded rationality and learning over time, allowing strategies to adapt based on relative payoffs rather than instant optimization. The model in this study draws upon the replicator dynamics system to capture how strategies evolve across iterations, depending on their performance relative to population averages. Each player's payoff is influenced by both external incentives and internal trade-offs, formalized into differential equations. The stability conditions are derived by analyzing the Jacobian matrix at key fixed points, representing different equilibrium configurations. This framework also incorporates notions from institutional economics and policy feedback theory, recognizing that strategic shifts are not merely economic calculations, but also shaped by historical policy signals, trust in institutions, and perceived legitimacy. Thus, the stability is not positioned as a terminal equilibrium, but as a reflection of adaptive coordination, incentives alignment, and feedback responsiveness.

The model operates through a replicator dynamics framework within a bounded rationality setting. Each of the three stakeholders including government regulators (G), milled rice enterprises (B), and domestic smallholder producers (P). Each of them can adopt one of two strategies. G can adopt one of two strategies including $G0$ and $G1$. $G0$ is implementing market-led milled rice optimization without extra cost while $G1$ is implementing milled rice collaborating optimization. B can adopt one of two strategies including $B0$ and $B1$. $B0$ is importing milled rice independently while $B1$ is importing in coordination with milled rice collaborating optimization. P can adopt one of two strategies including $P0$ and $P1$. $P0$ is independently operating milled rice optimization while $P1$ is participating in milled rice collaborating optimization. Their choices affect not only their own payoffs but also the payoffs of other stakeholders through interactive payoffs influenced by policy alignment and strategic signalling.

The system improves itself through adaptive learning over time. *G*, *B*, and *P* do not make globally optimal decisions; instead, they incrementally update their strategies based on observed relative payoffs. That is to say, the binary strategic set assigned to each stakeholder by the model's structural architecture is enriched with costs and gains that evolve over time. As higher-payoff strategies proliferate, the system gradually aligns towards dynamically stable strategy configurations. The model is non-zero-sum and can evolve towards Pareto-improving equilibria, allowing coordinated rural upgrading and regulatory innovation. Replicator dynamics drive this strategy evolution in the way that stakeholders adjust strategies based on relative payoffs compared to group averages. For example, if *G1* yield higher payoffs for *B* and *P*, when the adoption rates increase, collaboration is reinforcing. The Jacobian matrix evaluates equilibrium stability, identifying conditions where strategies become dominant or coexist. Importantly, the model can self-improve through parameter recalibration as real-world data accumulates. This adaptive capability allows the model to function not as a static policy assessment tool but as an evolving decision-support system.

Specifically, the three stakeholder groups modelled are: government regulators, who shape incentive environments and coordinate supply chain integration; milled rice business, who respond to trade patterns and price signals to source quality imports; and domestic smallholder producers, who make decisions on whether to upgrade production standards and integrate into collaborative supply chains, presented in Table 1 where "Latent gain" refers to unrealized but potential benefits that may accrue to stakeholders under certain policy conditions, used to explain why actors may choose strategy even before direct rewards are visible; "symbolic authority" denotes the perceived legitimacy or credibility government regulatory commands, even in the absence of formal enforcement penalty. This can shape strategic behavior by altering expectations of compliance or reward. "Institutional ignition points" are critical junctures or triggers, such as a sharp import surge or a policy announcement, that catalyze a shift in stakeholder strategies, setting off new evolutionary dynamics in governance or market adaptation.

Table 1. Parameters and Definitions

Parameter	Definition
B	Enterprises in milled rice industry also operating in milled rice import
$B0$	B imports milled rice independently
$B1$	B imports in coordination with milled rice collaborative optimization
BC_0	B's cost of choosing $B0$
BC_1	B's cost of choosing $B1$
BI_1	B's incentives from G received when choosing $B1$ under $G1$
BR_0	B's revenue from $B0$
BR_1	B's revenue from $B1$
G	Government regulators
$G0$	G implements market-led milled rice optimization without extra cost
$G1$	G implements milled rice collaborative optimization
GC_1	G's extra cost of implementing the $G1$ policy
GL_1	G's latent gain by regulatory pressure when B choose $B0$ under $G1$
GR_0	G's benefit from implementing $G0$
GR_1	G's benefit from implementing $G1$
P	Domestic smallholder producers in milled rice industry
$P0$	P independently operates milled rice optimization
$P1$	P participates in milled rice collaborative optimization
PC_0	P's cost for adopting $P0$
PC_1	P's cost for adopting $P1$
PI_1	P's extra incentives from G as adopting $P1$ under $G1$
PR_0	P's revenue from B adopting $P0$
PR_1	P's revenue from B adopting $P1$

By embedding the game model within a broader strategic and empirical framework, this methodology enables a nuanced understanding of how collaborative governance, market preferences, and rural upgrading behaviours can co-evolve. In contrast to static or zero-sum trade models, this approach emphasizes the possibility of mutually reinforcing strategies and positive-sum outcomes, aligning with China's policy aspirations for rural revitalization and sustainable food security. The integrated methodology thus not only offers analytical rigor but also generates actionable insights for policymakers seeking to foster systemic transformation across the agricultural value chain.

As an extra cost of implementing $G1$, GC_1 measures fiscal burden. If $GC_1 > GR_1 - GR_0$, G may prefer $G0$. GL_1 is latent gain that captures intangible benefits such as regulatory credibility, even without enforcement. GR_0 is the baseline payoff if no intervention is made. GR_1 represents long-term gains benefit from $G1$, and it should outweigh $G0 + GC_1$. GC_1 influences whether G adopts interventionist policies. So, GL_1 is unique because it models soft power. GR_1 vs. GR_0 determines if policy shifts are worthwhile. BC_0 determines the baseline expense for enterprises that opt out of collaboration. Higher BC_0 discourages $B0$. BC_1 reflects expenses like compliance or coordination. If $BC_1 < BC_0 + BI_1$, $B1$ becomes attractive. BI_1 represents subsidies or policy support. Critical for encouraging B to shift from $B0$ to $B1$. If $BR_0 > BR_1$, B resists collaboration unless BI_1 compensates. Higher BR_1 makes collaboration economically viable. So, BC_0 vs. BC_1 define cost trade-offs. BI_1 acts as a policy lever to incentivize collaboration. BR_0 vs. BR_1 determine profitability under different strategies.

Similarly, either high PC_0 or low PR_0 pushes P toward $P1$. For PC_1 includes compliance and upgrading costs, if $PC_1 - PI_1 < PC_0$, P prefers $P1$. In practice, PI_1 can reflect the subsidies or training programs that reduce P's adoption barriers. PR_1 reflects premium prices or stable demand under collaboration. So, PC_0 vs. PC_1 define the cost-effectiveness of upgrading. PI_1 is a policy tool to incentivize $P1$ adoption. $PR_1 > PR_0$ ensures economic viability for smallholders.

In sum, each parameter reflects a real trade-off in either economic or institutional terms and contributes directly to the shape of the fitness landscape in replicator dynamics. Incentive parameters are policy-driven levers that can steer stakeholders toward collaboration. Cost parameters determine adoption barriers, since if they are too high, collaboration fails. Revenue parameters should outweigh alternatives to make strategies sustainable. Latent gains introduce behavioral economics into policy design, such as through regulatory reputation.

These parameters quantify trade-offs between costs vs. benefits for each stakeholder, capture policy impacts, and determine equilibrium stability. Without these parameters, the model would lack real-world applicability in analyzing how policies influence stakeholder behavior.

The model is founded on several key assumptions as follows.

Assumption 1: All stakeholders, including G, B, and P, are assumed to exhibit bounded rationality in this positive-sum setting model. They adjust their strategies incrementally over time based on observed relative payoffs rather than make optimally rational decisions. Each can choose between two strategies.

Assumption 1 is mainly about bounded rationality.

Assumption 1 is introduced to reflect the behavioral and institutional realities of the milled rice industry in transitional economies like China, where decisions are rarely made with full information, infinite foresight, or perfect optimization. Instead, actors adapt incrementally through trial and error, policy learning, and market feedback, particularly in contexts involving rural transformation and regulatory experimentation. Bounded rationality is embedded into the replicator dynamics framework, where players adjust their strategy shares over time based on the relative payoff differential between available strategies. The use of differential equations reflects this dynamic adjustment without requiring agents to solve for equilibrium directly.

Assumption 1 reflects real-world behavior. In rural and developing regions, decisions are made under uncertainty, time constraints, and with limited information. Perfect rationality would be an unrealistic modeling assumption. This assumption enables dynamic adaptation. Bounded rationality allows strategies to evolve over time based on experience and feedback, which is crucial for modeling long-term systemic change. This assumption supports positive-sum interaction. In a bounded rationality setting, cooperative behavior may emerge gradually as actors learn to recognize mutual benefits, not merely as a static outcome of rational calculation. This assumption is grounded in behavioral economics. It is strongly supported by the work of Herbert Simon, Daniel Kahneman, and others in showing that agents typically satisfice rather than optimize. In essence, this assumption makes the model more empirically plausible and structurally resilient by introducing cognitive realism and institutional inertia into the interaction logic.

Assumption 1 is justified and supported in multiple ways as follows. This assumption is supported by canonical behavioral economics and institutional literature (Bischi et al., 2024; Campitelli & Gobet, 2010; Mirowski, 1994; Sent, 2018), which argue that decision-makers often rely on heuristics and adaptive learning rather than perfect optimization. This assumption aligns with contextual validity in transitional governance systems like China's rural economy, where policy experimentation, learning-by-doing, and adaptive feedback loops dominate decision-making under regulatory complexity. This assumption is empirically justified by observed behaviors in China's rural economy, such as the gradual adoption of sustainable farming practices, iterative adjustments to subsidy schemes, and informal policy experimentation. This assumption enables the model to realistically simulate observed phenomena such as slow diffusion of cooperative strategies and path-dependent transitions, whereas perfect rationality fails to capture these dynamics.

Assumption 2: All payoffs for *G*, *B*, and *P* are assumed to be measurable and quantifiable, enabling direct empirical calibration based on trade data and policy costs.

Assumption 2 is mainly about quantifiable payoffs.

Assumption 2 is included to operationalize the game-theoretic model in a way that allows for real-world data integration and empirical validation. By assuming that each stakeholder's cost-benefit outcomes can be represented numerically, the model becomes estimable, testable, and policy-relevant. Specifically, this assumption enables this study to parameterize the payoff matrix using observable indicators, simulate replicator dynamics based on actual stakeholder incentives, and allow scenario analysis under different policy shocks or market conditions. Without this assumption, the model would be confined to a purely theoretical realm, lacking the capacity for real-world inference.

Assumption 2 ensures empirical calibratability by allowing abstract payoffs to be mapped directly to measurable economic variables, which is essential for policy relevance and model validation. This assumption enables comparative strategy evaluation by simulating how stakeholder strategies evolve over time in response to observed differences in payoffs. This assumption supports both ex-ante and ex-post policy evaluation, facilitating the assessment of interventions. This assumption permits sensitivity analysis, making it possible to test how fluctuations in real-world parameters affect equilibrium outcomes. This assumption also supports the positive-sum setting of the model by enabling an explicit accounting of collective welfare gains from cooperation and coordination.

Assumption 2 is justified and supported in multiple ways as follows. This assumption aligns with evolutionary game theory models in economics, as supported by the literature (Eshoa & Zomorrodi, 2024; Fischer et al., 2024), which commonly adopt quantifiable payoffs to analyze strategic interactions among bounded rational agents. This assumption is also empirically grounded, as government reports, official regulations, institutional studies, and media sources provide verifiable data on compliance costs, subsidies, fines, and incentive schemes that enable payoff quantification.
Assumption 3: The decision-making process for *G*, *B*, and *P* is governed by replicator dynamics, where each group is assumed to adjust its strategy frequency based on the comparative performance of current behaviours. Since each group is assumed to observe previous strategy outcomes, *G*, *B*, and *P* can update their strategies with full inter-round information, though not with perfect foresight.

Assumption 3 is mainly about the dynamic behavioral mechanism.

Assumption 3 is included to provide a dynamic behavioral mechanism for the evolution of strategies among *G*, *B*, and *P*. The use of replicator dynamics enables modeling how each group adjusts its strategy proportion over time based on relative payoffs, reflecting a learning and adaptation process. It is included to capture realistic iterative decision-making in complex policy and market environments, where actors continuously observe, evaluate, and adapt their behavior.

Assumption 3 grounds the model in evolutionary game theory, which is particularly suited for modeling adaptive behavior under bounded rationality. Unlike static optimization, replicator dynamics reflect gradual adjustment and real-world inertia, making the model more empirically plausible and policy-relevant. It also captures the interdependence of stakeholders' decisions, highlighting how the success of one strategy influences its replication or abandonment across the population.

Assumption 3 can be supported by empirical and theoretical precedent in evolutionary game theory and policy modeling literature (Jiang & Luo, 2025; Musthofa & Engwerda, 2025). Evidence of adaptive strategy adjustment in real-world policy and business environments—including but not limited to firms reacting to regulatory changes and farmers adjusting to subsidy schemes—validates the core mechanism. Additionally, the use of replicator equations calibrated with real payoff data and tested for convergence behavior provides simulation-based validation of the dynamic assumption.

Assumption 4: The total number of *G*, *B*, and *P* is assumed to remain constant throughout the simulation, and no external actors are introduced. No exogenous shocks intervene in the short-run evolution of strategies. No strategy mutation is allowed.

Assumption 4 is mainly about a closed system.

Assumption 4 is included to ensure model tractability and focus, allowing the simulation to isolate the endogenous strategic dynamics among *G*, *B*, and *P*. By holding the population size fixed and excluding external actors, exogenous shocks, or random strategy mutations, the model focuses purely on the strategic feedback mechanisms within the system. This controlled environment helps to identify equilibrium conditions and evolutionary pathways without noise or confounding variables.

Assumption 4 creates a closed-system setting necessary for deriving clear, interpretable results from replicator dynamics. Constant size avoids complications from flux, and the absence of external shocks ensures that equilibrium shifts arise from endogenous interaction, not random disturbances. Likewise, excluding mutation maintains the model's deterministic structure, which is key for stability analysis, bifurcation patterns, and comparative statics. Assumption 4 can be justified by clarifying the temporal scope of the model—typically short- to medium-term policy cycles— where demographic shifts, major shocks, or the entry of new actors are unlikely to dominate behavior. Moreover, the exclusion of shocks and mutations is a standard modeling choice in many foundational and applied evolutionary game studies (Gomoyunov & Lukoyanov, 2024; Ushakov & Ershov, 2024) when the focus is on deterministic strategic evolution rather than stochastic innovation or disruption. Importantly, the payoff term GL_1 is introduced to represent the latent gain allows for a more nuanced reflection of modern governance, where value is accrued through credibility and symbolic authority rather than just punitive mechanisms. *G* may have issued public statements, signaled potential penalties in the future, or introduced surveillance without executing sanctions. From the perspective of *G*, GL_1 is a policy gain for it strengthens its regulatory image even without punishing *B*. From the perspective of *B*, GL_1 is not a realized cost, since no fines, fees, or reputational damage have yet materialized. Therefore, GL_1 is not a realized cost of *B*, since no fines, fees, or reputational damage have yet materialized.

3. Results

The three stakeholders' strategic positioning and potential responses to policy shifts are first evaluated using the SWOT framework, which offers a qualitative basis for assessing strengths, weaknesses, opportunities, and threats (see Figure 3).

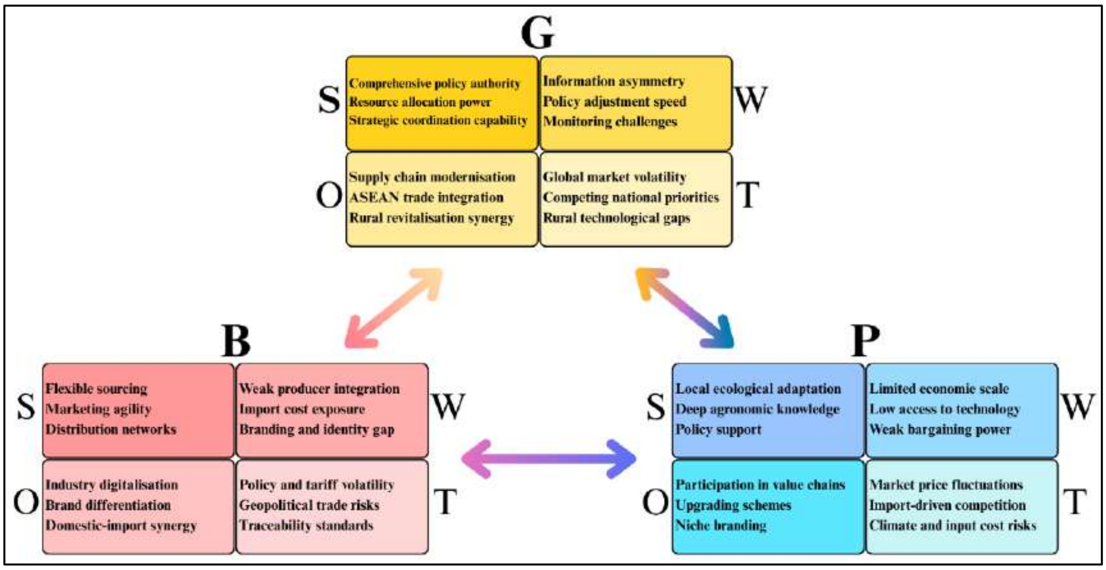

Figure 3. SWOT of All Stakeholders in China's Milled Rice Industry.

Building upon this foundation, the expected payoffs for each stakeholder based on all possible strategy combinations and the corresponding probabilities are computed to determine how strategies evolve over time. This framework allows for the simulation of different governance pathways, helping to visualize how policy intensity, coordination, and institutional trust can shape long-term patterns of cooperation or resistance. It is especially relevant in contexts like China, where subsidy types, standards, and local policy implementation vary widely, affecting both strategic logic and behavioural inertia among stakeholders. Table 2 presents the complete payoff matrix for the tripartite evolutionary game in the milled rice industry.

Table 2. Payoff Matrix of Strategy Profiles

G	B	P	G's Payoff	B's Payoff	P's Payoff
0	0	0	GR_0	$BR_0 - BC_0$	$PR_0 - PC_0$
0	0	1	GR_0	$BR_0 - BC_0$	$PR_0 - PC_1$
0	1	0	GR_0	$BR_1 - BC_1$	$PR_1 - PC_0$
0	1	1	GR_0	$BR_1 - BC_1$	$PR_1 - PC_1$
1	0	0	$GR_1 - GC_1 + GL_1$	$BR_0 - BC_0$	$PR_0 - PC_0$
1	0	1	$GR_1 - GC_1 + GL_1 - PI_1$	$BR_0 - BC_0$	$PR_0 - PC_1 + PI_1$
1	1	0	$GR_1 - GC_1 - BI_1$	$BR_1 - BC_1 + BI_1$	$PR_1 - PC_0$
1	1	1	$GR_1 - GC_1 - BI_1 - PI_1$	$BR_1 - BC_1 + BI_1$	$PR_1 - PC_1 + PI_1$

The mixed strategy probabilities are denoted by y_1 as G enforces $G1$, y_2 as B opts for $B1$, and y_3 as P chooses $P1$. The following section outlines the expected payoffs and strategic dynamics for G, B, and P.

$$E_G = (1 - y_1)GR_0 + y_1[GR_1 - GC_1 + GL_1 - y_2(BI_1 + GL_1) - y_3(PI_1 + GL_1) + y_2 y_3(BI_1 + PI_1 + GL_1)] , \quad (1)$$

$$E_B = (1 - y_2)(BR_0 - BC_0) + y_2[BR_1 - BC_1 + y_1 \cdot BI_1], \quad (2)$$

$$E_P = (1 - y_3)(PR_0 - PC_0 + y_1 y_2(PR_1 - PR_0)) + y_3[PR_0 - PC_1 + y_1 PI_1 + y_1 y_2(PR_1 - PR_0)] , \quad (3)$$

The corresponding replicator dynamic equations are derived as:

$$\frac{dy_1}{dt} = y_1(1 - y_1)\left[GR_1 - GC_1 + GL_1 - GR_0 - y_2 BI_1 - y_3 PI_1 + y_2 y_3(BI_1 + PI_1)\right], \quad (4)$$

$$\frac{dy_2}{dt} = y_2(1 - y_2)\left[BR_1 - BC_1 - BR_0 + BC_0 + y_1 BI_1\right], \quad (5)$$

$$\frac{dy_3}{dt} = y_3(1 - y_3)\left[-PC_1 + PC_0 + y_1 PI_1 + y_1 y_2(PR_1 - PR_0)\right], \quad (6)$$

To analyze the local stability of the evolutionary equilibria of G, B, and P, the Jacobian matrix is constructed. It is derived from the system of simplified replicator dynamics. The Jacobian matrix captures the sensitivity of each strategy's growth rate. The eigenvalues indicate whether small perturbations will decay or amplify over time. Specifically, an equilibrium is deemed locally stable if all eigenvalues of the Jacobian matrix at that point have negative real parts. This implies that the strategy profile resists deviations, and the system tends to return to that state. Conversely, if any eigenvalue possesses a positive real part, the equilibrium is unstable. Where eigenvalues have mixed signs, there is a saddle point, which indicates directional instability—meaning some perturbations grow while others decay. Thus, by explicitly evaluating the Jacobian elements at each equilibrium, one can systematically identify which strategic configurations G, B, and P are capable of sustaining themselves dynamically under small shocks or fluctuations in behavior.

$$J = \begin{bmatrix} \frac{\partial \dot{y}_1}{\partial y_1} & \frac{\partial \dot{y}_1}{\partial y_2} & \frac{\partial \dot{y}_1}{\partial y_3} \\ \frac{\partial \dot{y}_2}{\partial y_1} & \frac{\partial \dot{y}_2}{\partial y_2} & \frac{\partial \dot{y}_2}{\partial y_3} \\ \frac{\partial \dot{y}_3}{\partial y_1} & \frac{\partial \dot{y}_3}{\partial y_2} & \frac{\partial \dot{y}_3}{\partial y_3} \end{bmatrix}, \quad (7)$$

$$\frac{\partial \dot{y}_1}{\partial y_1} = (1 - 2y_1)[(GR_1 - GR_0 - GC_1) + GL_1(1 - y_2) - BI_1 y_2 - PI_1 y_3], \quad (8)$$

$$\frac{\partial \dot{y}_1}{\partial y_2} = y_1(1-y_1)(-GL_1-BI_1), \quad (9)$$

$$\frac{\partial \dot{y}_1}{\partial y_3} = -y_1(1-y_1)PI_1, \quad (10)$$

$$\frac{\partial \dot{y}_2}{\partial y_1} = y_2(1-y_2)[BI_1-y_3(PR_0-PC_1-BR_0+BC_0)], \quad (11)$$

$$\frac{\partial \dot{y}_2}{\partial y_2} = (1-2y_2)[(1-y_1)y_3(PR_0-PC_1-BR_0+BC_0)+y_1BI_1], \quad (12)$$

$$\frac{\partial \dot{y}_2}{\partial y_3} = y_2(1-y_2)(1-y_1)(PR_0-PC_1-BR_0+BC_0), \quad (13)$$

$$\frac{\partial \dot{y}_3}{\partial y_1} = y_3(1-y_3)PI_1, \quad (14)$$

$$\frac{\partial \dot{y}_3}{\partial y_2} = y_3(1-y_3)(PR_1-PR_0-PC_0+PC_1), \quad (15)$$

$$\frac{\partial \dot{y}_3}{\partial y_3} = (1-2y_3)[PC_0-PC_1+y_1PI_1+y_2(PR_1-PR_0-PC_0+PC_1)], \quad (16)$$

The interactions among G, B, and P are not fixed but dynamically evolve depending on the cost-benefit structures and policy environments. It reflects the institutional, market, and social entanglements in China's agricultural governance landscape. These interactions are not abstract, for they mirror the real-world coordination challenges that arise in balancing food security, rural livelihoods, and environmental governance in the rice sector. These interactions define the strategic interdependence that drives the replicator dynamics when each stakeholder's payoff is not determined in isolation but evolves in response to the strategies adopted by the other two.

$G \leftrightarrow B$: The government sets regulatory frameworks, subsidies, and standards that directly influence the operational costs and strategic compliance decisions of rice enterprises. Enterprises, in turn, respond by either complying or evading, which affects the government's symbolic regulatory payoff and enforcement cost. This interaction captures top-down policy effectiveness and its feedback on institutional legitimacy. This modelled interaction is crucial because it allows simulation of regulatory slack or effective enforcement scenarios. This can also guide policymakers to fine-tune adaptive regulatory designs that are both cost-effective and institutionally credible.

$B \leftrightarrow P$: Milled rice enterprises' domestic business depends on smallholder producers for raw inputs. Their decision whether to engage fairly influences producers' loyalty and productivity. Producers, depending on perceived benefits, choose whether to collaborate—thereby shaping business payoffs and long-term supply chain stability. The dyad captures market-based coordination and trust-building mechanisms, reflecting real-world scenarios such as the success or failure of contract farming initiatives. This component helps predict supply chain stability, identify conditions for mutual trust formation, and evaluate the long-term viability of inclusive business models.

$P \leftrightarrow G$: Producers rely on the government for access to infrastructure, extension services, and protection against market risks. The government, in return, gains or loses grassroots support depending on how well it addresses rural concerns. Compliance or resistance from producers feeds back into the political and economic costs of policy implementation, modeling the state-society interaction. The model captures how producers respond to state interventions. It is not with perfect rationality, but based on bounded learning from past outcomes. In this way, the model reflects actual dynamics of policy uptake, grassroots resistance, or informal circumvention, often observed in rural development programs. This facilitates a better understanding of institutional responsiveness and the political economy of rural support systems.

These triadic relationships are embedded in the payoff matrix and encoded in parameters such as $B0$, $B1$, BC_0, BC_1, BI_1, BR_0, BR_1, $G0$, $G1$, GC_1, GL_1, GR_0, GR_1, $P0$, $P1$, PC_0, PC_1, PI_1, PR_0, and PR_1. These parameters determine the direction and stability of strategy evolution over time. Their calibration ensures that the model captures the co-evolutionary logic of real-world stakeholder dynamics in China's milled rice industry. Thus, these interactions and parameters are not just structural components, as they are the engines of the model, allowing it to simulate adaptive governance, regulatory resilience, and market inclusivity in a grounded and policy-relevant way.

This analytical approach enables a deeper interpretation of the eigenvalues themselves, where specific strategy profiles reveal the underlying structural stability of the system. In the eigenvalues of the Jacobian matrix, the strategy profiles (0,0,1) and (0,1,0) represent partial market-based activation without government intervention. These configurations are inherently unstable and can hardly withstand even minor perturbations.

(0,0,1) means smallholder producer collaboration alone. This producer collaboration may support resource pooling, standardized processing practices, and shared infrastructure use. Yet, the absence of business engagement restricts market integration, while limited regulatory support may constrain the scale and credibility of the collaboration. Consequently, gains in grassroots-level efficiency may not translate into broader system improvements. Similarly, (0,1,0) means business collaboration alone. Businesses acting in concert can strengthen bargaining positions, stabilize procurement, and enhance downstream coordination. Nonetheless, without producer alignment, upstream supply variability may undermine contract enforcement and logistical planning. Governmental absence may also lead to weak oversight, insufficient support for smallholders, and barriers to traceability or sustainability certification efforts.

Meanwhile, (1,1,0) and (0,1,1) reveal an economic contradiction: the producer would rationally abandon its original strategy, rendering these combinations unsustainable in equilibrium. At (1,1,0), since $\lambda_3 = PR_1 - PR_0 + PI_1$, if $\lambda_3 > 0$, P would switch to $P1$, violating $P0$. In the equilibrium conditions of point (0,1,1) with $\lambda_2 = -(PR_0 - PC_1 - BR_0 + BC_0 + BI_1)$ and $\lambda_3 = -(PR_1 - PR_0 - PC_0 + PC_1 + PI_1)$, for $G0$, $BI_1 = 0$ and $PI_1 = 0$, and the stable status must meet the following requirements at the same time as $PR_1 \geq PR_0 + PC_0 - PC_1$ and $PR_0 - PC_1 \geq BR_0 - BC_0$. Thus, P faces an awkward situation like the prisoner's dilemma of high cost and almost no premium. If P reverts to $P0$ as a solution, the equilibrium is destroyed.

(1,1,0) enables regulatory enforcement and coordinated procurement strategies, potentially standardizing quality and promoting traceability. However, exclusion of producers from decision-making can lead to policy misalignment, implementation challenges, and erosion of producer autonomy. Top-down approaches may fail to reflect the realities and constraints of smallholder farming, ultimately compromising policy effectiveness and equity. (0,1,1) suggests the middle-ground configuration. There is some level of horizontal coordination within the value chain, potentially improving efficiency and communication between supply and demand. However, lacking state involvement may inhibit long-term infrastructure investment, consistent quality controls, and dispute resolution mechanisms. Over time, asymmetries between powerful businesses and vulnerable producers could widen, which would reduce inclusivity and stability.

Moreover, (1,0,0) and (1,0,1) are mathematically stable when $BI_1 < 0$, violating the logic of reality. Therefore, although these saddle points may appear mathematically stable, they lack real-world viability due to stringent constraints or inherent contradictions with economic logic, making long-term stability unlikely in practice.

(0,0,0) and (1,1,1) demonstrate both theoretical stability and practical feasibility. For (0,0,0), local stability is achieved when $GR_1 - GC_1 + GL_1 < GR_0$ and $PC\_0 < PC\_1$, revealing the lower cost of $G0$ and $P0$. For (1,1,1), stability could be reached with positive incentive effects in $GR_1 - GC_1 - BI_1 - PI_1 > GR_0$, $BR_1 - BC_1 + BI_1 > BR_0 - BC_0$ and $PI_1 > 0$. The equilibrium proves particularly robust as it satisfies all three conditions simultaneously, representing a stable state where all parties are optimally incentivized.

(0,0,0) represents a scenario of independent strategies across G, B, and P. This configuration reflects a decentralised and market-led arrangement. Its advantages lie in maintaining flexibility and allowing actors to tailor decisions to local conditions. However, the lack of strategic coordination may result in fragmented supply chains, inconsistent quality standards, and missed opportunities for structural improvement. This autonomy can limit resilience against collective shocks or long-term environmental and economic pressures. The (0,0,0) equilibrium represents a stable but low-engagement state within the milled rice collaboration system. While this configuration maintains systemic balance, it offers minimal collective benefits and reflects widespread stakeholder disengagement. Transitioning toward a more participatory and mutually beneficial state, such as the (1,1,1) equilibrium, requires timely and well-calibrated interventions. These early efforts can disrupt entrenched patterns, shift stakeholder expectations, and establish the foundations for voluntary coordination. Importantly, such a transition is not automatic; in the absence of strategic action, the system may persist at (0,0,0), remaining stable yet underperforming in terms of long-term developmental gains. In contrast, (1,1,1) involves full collaboration among *G*, *B*, and *P*. This ideal-type scenario reflects an integrated governance model with joint decision-making and resource sharing. It offers the potential for high levels of system efficiency, equitable value distribution, and policy responsiveness. Nonetheless, it requires significant institutional coordination, trust, and administrative capacity.

Beyond the pure strategy points, there is a possibility of a feasible mixed-strategy equilibrium $(y_1^*, y_2^*, y_3^*) \in (0,1)^3$. Such an interior equilibrium reflects a dynamic balance where none of the strategies dominate, and all stakeholders maintain adaptive behaviors based on expected payoffs. It is rigorously characterized by the following conditions, as $PI_1 > max(\frac{PC_1 - PC_0}{1-\kappa}, GR_1 + GC_1 - GR_0 - GL_1\kappa)$, $\kappa = \frac{BR_0 - BC_0 + PR_0 - PC_1}{BI_1}$, where $BI_1 > max(BR_0 - BC_0, \frac{PR_0 - PC_1}{1 - \frac{GL_1}{PI_1}})$, and $PC_1 - PC_0 \in (\frac{PI_1(GL_1 - GR_1 + GR_0)}{GC_1}, PI_1)$. As such, there are also critical thresholds for stability, which focus on the minimum incentive threshold as follows:

$$PI_1^{min} = \frac{(PC_1 - PC_0)(GR_0 + GC_1 - GR_1)}{GL_1 - (BR_0 - BC_0)}, \tag{17}$$

If $PI_1 < PI_1^{min}$, the system inevitably converges to one of the pure-strategy equilibria. When PI_1 approaches but remains marginally below the minimum threshold, the system exhibits metastable characteristics, with slow convergence and heightened sensitivity to parameter fluctuations. The specific equilibrium attained is determined by the relative magnitudes of the remaining parameters. It may go for (0,0,0) if $PC_0 < PC_1$ or (0,0,1) if $PC_0 > PC_1$.

Compared to static optimization or linear equilibrium models often used in agri-policy analysis, the evolutionary game approach presented here offers greater flexibility in capturing dynamic behavioral shifts, bounded rationality, and stakeholder learning over time. Unlike general equilibrium models that assume full information and instant adjustment, this framework allows for path dependency, delayed responses, and institutional feedback, providing a more realistic depiction of rural governance under uncertainty.

However, while this enhances explanatory power, the model's accuracy remains contingent on how well the parameters reflect real-world dynamics, particularly in assigning costs, incentives, and behavioral thresholds. Hassini et al. (2025) provided an insightful analysis of the transformative potential of IoT technologies within food supply chains, rigorously elucidating how digital integration enhances coordination, mitigates food waste, and influences pricing dynamics—thereby setting a valuable precedent for modeling technological impacts on supply chain resilience and sustainability. Li and Liu (2025) also presented a mathematically rigorous framework wherein the construction of Lyapunov functionals is adeptly employed to establish global stability and convergence toward coexistence equilibria, offering a high standard of analytical precision that is instructive for complex system modeling. Mutuku et al. (2025) offered valuable methodological inspiration by a nuanced computational modeling approach, particularly in its integration of spatial dynamics and real-world exposure scenarios to inform effective interventions. In sum, the mixed-strategy equilibrium captures a dynamic balance in which no single pure strategy dominates absolutely, where each stakeholder adopts their strategies with certain probabilities. This state reflects real-world complexity. It embodies adaptive behavior under uncertainty, bounded rationality, and evolving payoffs. Stakeholders continuously adjust, learn, and respond to each other, preventing lock-in to rigid patterns. The mixed equilibrium offers a robust but fluid stability, different from the fixed-point stability of a pure evolutionarily stable strategy. It acknowledges that perfect coordination is rare, yet cooperation can persist in a probabilistic or contingent form. Thus, future improvements of this study could involve incorporating agent-based extensions to simulate heterogeneous actors, calibrating the model using longitudinal data, and integrating spatial layers or ecological feedback to better reflect the complexity of cross-regional supply chain networks. Such enhancements would improve both predictive validity and policy relevance.

4. Discussion

To illustrate the three-dimensional evolutionary trajectories of strategy choices, this study incorporates a conceptual parameter simulation grounded in the complex and heterogeneous reality of rice subsidy schemes in China.

The country exhibits a high diversity in subsidy types, fluctuating subsidy amounts, and region-specific implementation practices. By incorporating real-world incentive structures and institutional mechanisms, the framework captures both the theoretical dynamics of strategic interaction and the practical realities shaping decision-making in China's rice economy. The Hunan case exemplifies this approach, where comprehensive policy measures, including targeted subsidies, institutional innovations, and market stabilization tools, have produced measurable impacts on agricultural productivity and stakeholder behavior. These empirical observations directly inform the model's parameterization, ensuring its outputs reflect the complex interplay of economic incentives and policy interventions characteristic of China's agricultural modernization process.

Hunan's policy trajectory offers a precise and data-rich foundation for this calibration (sourced from Department of Agriculture and Rural Affairs of Hunan Province [https://agri.hunan.gov.cn/]; Official website of the Hunan Provincial Government [www.hunan.gov.cn]; Hunan Daily [https://epaper.voc.com.cn/]; and China.com.cn & China.org.cn [http://agri.china.com.cn]). The province's 2019 Hunan Agricultural Subsidy and Fee Policy and the 2020 CPC Hunan Provincial Committee No. 1 Document underscored a steadfast commitment to securing grain production, integrating acreage and yield stability into the provincial governor's food security responsibility system. These policies pressed municipal and county governments to maintain local grain output, enforced strict arable land protection targets, and guarded the "red line" for farmland preservation by prioritizing early rice cultivation, scaling specialized seedling nurseries, expanding high-grade rice planting, promoting drought-tolerant coarse grains, and preventing farmland abandonment. Measures also included strict pest and disease control, reforms to grain reserve systems, implementation of minimum purchase price schemes, and targeted land allocation for leading grain-producing counties. In 2024, Hunan achieved a historic grain output of 61.56 billion jin (30.78 million tonnes), accounting for 4.4% of national production on just 2.8% of China's arable land, a testament to its efficiency as one of only two provinces to continuously supply commercial grain since 1949. This success stems from targeted policies directly mirrored in the model as follows.

In subsidy mechanisms, the province mobilized 95 billion yuan for farmland protection and seedling infrastructure, with an additional 9 billion yuan for mechanized planting support, reflected in the model's incentive parameters (BI_1, PI_1). Farmers received 500 yuan/mu (0.0667 ha) in direct subsidies and insurance payouts, aligning with the payoff structures (PR_1, PC_1) for adopting collaborative practices. However, there were per-mu payments of 109.1 yuan for single-season rice and 182.91 yuan for double-season rice, comprising 13.5 yuan/mu in direct grain subsidies, 80.6 yuan/mu in comprehensive agricultural input subsidies, 15 yuan/mu in quality seed subsidies for early, middle, and late rice (for each type), and an additional 58.81 yuan/mu for double cropping.

In institutional innovations, Hunan's 42.5 million mu of high-efficiency farmland (yielding 200 yuan/mu in cost savings and productivity gains) informs the model's cost-benefit trade-offs (BR_1, BC_1) for enterprises (*B*). The more than 95% adoption rate of high-yield hybrid rice seeds for a legacy of Hunan's leadership in seed innovation validates the evolutionary dynamics of strategy diffusion in the simulation. The previous complementary programs included returning-farmland-to-forest living allowances of 20 yuan/mu, grain support payments of 210 yuan/mu, and forest ecological compensation of 10.5 yuan/mu to incentivize sustainable land use and production stability.

In market stabilization tools, the guidance pricing for fertilizers via Hunan's supply cooperatives and minimum grain purchase guarantees by provincial reserves are captured in the model's latent regulatory gains (GL_1) and risk-reduction payoffs ($PR_0 \rightarrow PR_1$). For example, by 2024, the agricultural department had been providing seeds free of charge, while agricultural machinery operation teams had offered free mechanized plowing and planting services under certain circumstances. Among other support measures, machinery purchase subsidies covered up to 30% of costs in 2019.

By calibrating the model to these real-world levers—subsidies, institutional trust, and market safeguards—the adaptive coordination, such as the sequence of *G*'s policy shifts → *B*'s import strategies → *P*'s production upgrades, emerges in transitional economies. This bridges theoretical rigor with actionable policy insights, demonstrating how positive-sum outcomes arise from aligned incentives.

Based on this context, the simulation explores the evolutionary pathways under specified payoff conditions. So, this study employs EG-Moderate and EG-Optimized as two conceptual configurations to simulate the evolutionary dynamics within China's rice subsidy governance system.

This framework is constructed in three integrated stages.

In Stage 1 Conceptual Design, the framework is built on institutional economics, rural policy frameworks, and strategic interaction logics of government regulators (*G*), milled rice enterprises (*B*), and domestic smallholder producers (*P*).

In Stage 2 Mathematical Formulation, differential equations are developed for *G*, *B*, and *P* using replicator dynamics, with payoff matrices dependent on cost-benefit calculations under each strategy configuration.

In Stage 3 Numerical Simulation, simulations are conducted to visualize system trajectories and equilibrium stability under different parameter conditions. The software MATLAB R2016b is used in Stage 3.

The numerical simulations are performed by MATLAB R2016b's built-in ordinary differential equation (ODE) solver ode45 that implements an adaptive Runge-Kutta method. This solver was selected for the following principal reasons, including algorithmic robustness and field-standard validation, which ensure the reliability of the evolutionary game dynamics analysis.

In algorithmic robustness, the method employed by ode45 provides automatic step-size control, dynamically adjusting the temporal resolution during integration. This adaptive approach maintains optimizing computational efficiency, particularly crucial for the system where strategy proportions may exhibit both rapid transitions near bifurcation points and prolonged quasi-equilibrium periods. In field-standard validation, as the default ODE solver in MATLAB for non-stiff systems, ode45 has undergone extensive numerical validation through decades of application across ecological systems, evolutionary game theory, and engineering control systems. All numerical simulations were conducted with absolute tolerance of 1×10^{-8} and relative tolerance of 1×10^{-6}. The parameters ensure solution accuracy while preventing artificial stabilization that could occur with overly lax tolerances.

The implementation explicitly avoids using MATLAB version-specific features since MATLAB R2016b was chosen as a long-term support release with proven numerical stability for solving ODEs.

In EG-Moderate, the parameter values are defined as follows: $BC_0 = 1$; $BC_1 = 3$; $BI_1 = 0.5$; $BR_0 = 4$; $BR_1 = 5$; $GC_1 = 2$; $GL_1 = 0.5$; $GR_0 = 6$; $GR_1 = 5$; $PC_0 = 1$; $PC_1 = 2$; $PI_1 = 0.5$; $PR_0 = 3$; $PR_1 = 4$. For EG-Optimized, the configuration is adjusted to reflect a scenario of stronger governmental and market incentives aiming at milled rice collaborative optimization: $BC_0 = 1$; $BC_1 = 3$; $BI_1 = 2$; $BR_0 = 4$; $BR_1 = 7$; $GC_1 = 2$; $GL_1 = 0.5$; $GR_0 = 3$ $GR_1 = 9$; $PC_0 = 1$; $PC_1 = 2$; $PI_1 = 1$; $PR_0 = 3$; $PR_1 = 5$. It is important to note that they are grounded in conceptual realism. These configurations serve to illustrate how different cost-benefit structures might shape stakeholder strategies, which are rooted in observed trends and regulatory frameworks that influence strategic evolution. The models highlight how slight adjustments in subsidy incentives, regulatory costs, or perceived payoffs may collectively reshape governance equilibrium in the milled rice sector. The simulation horizon is set to t = 100, which enhances the visibility of dynamic stability and allows for a clearer interpretation of long-run strategy convergence across the triadic interactions of *G*, *B*, and *P*, as visualized in Figure 4.

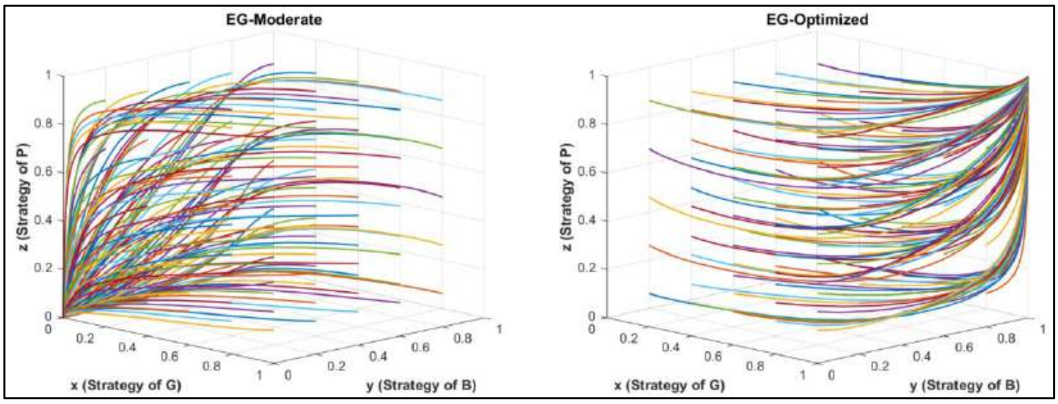

Figure 4. Simulated Evolutionary Trajectories of Tripartite Strategies in China's Milled Rice Industry.

Figure 4 depicts the evolutionary dynamics of stakeholder strategies under two distinct parameter settings: EG-Moderate and EG-Optimized. EG-Moderate denotes a scenario characterized by moderate governmental and market incentives coupled with a balanced cost-benefit environment, where stakeholder strategies tend to stabilize near the status quo. In contrast, EG-Optimized captures a setting with intensified policy incentives and differentiated payoffs that drive dynamic convergence toward proactive coordination among *G*, *B* and *P*.

In EG-Moderate, the evolutionary path tends to stabilize near (0,0,0), indicating that under moderate incentive structures and relatively balanced cost-benefit profiles, *G*, *B* and *P* are more inclined to retain the status quo, preferring minimal policy intervention, conservative behaviour from enterprises, and passive public engagement. In contrast, EG-Optimized, which incorporates stronger governmental incentives and a more pronounced benefit differential, displays a dynamic convergence toward (1,1,1).

Figure 4 offers a comparative visualization of the strategic trajectories among G, B, and P across two distinct governance scenarios, including EG-Moderate and EG-Optimized over a simulation horizon of t = 100. The figure captures how variations in parameterized incentives and costs influence the long-run evolutionary stability of each stakeholder's strategy.

The eight strategy vectors, ranging from (0,0,0) to (1,1,1), represent all possible combinations of strategic choices by the three stakeholders within the evolutionary game framework. Here, 0 indicates a passive, conservative, or non-cooperative strategy, while 1 signifies an active, reform-oriented, or cooperative stance.

For instance, (0,0,0) reflects a full-status quo scenario where no actor engages in proactive change, often leading to stagnation or policy inertia. In contrast, (1,1,1) captures a fully engaged and synergistic configuration.

Intermediate vectors illustrate partial alignments or mismatched behaviors, offering insights into transitional or unstable phases in the governance landscape as follows.

(0,0,1) reflects only the domestic smallholder producers (P) adopt an active strategy; government regulators (G) and milled rice enterprises (B) remain passive. (0,1,0) reflects only the milled rice enterprises (B) adopt an active strategy; government regulators (G) and domestic smallholder producers (P) remain passive. (1,0,0) reflects that only the government regulators (G) adopt an active strategy; milled rice enterprises (B) and producers remain passive.

(0,1,1) reflects milled rice enterprises (B) and domestic smallholder producers (P) adopt active strategies; government regulators (G) remain passive. (1,0,1) reflects government regulators (G) and domestic smallholder producers (P) adopt active strategies; milled rice enterprises (B) remain passive. (1,1,0) reflects government regulators (G) and milled rice enterprises (B) adopt active strategies; domestic smallholder producers (P) remain passive.

Each intermediate vector reflects real-world governance asymmetries where only subsets of actors respond to policy shifts or market changes.

In the EG-Moderate configuration, the dynamics reveal a gradual convergence toward the strategy vector (0,0,0). This outcome signifies a systemic reluctance to engage in proactive behaviors: the government refrains from implementing stringent regulatory or incentive-based policies; enterprises do not perceive sufficient marginal benefits from collaborative behaviors; and smallholder producers maintain low engagement due to minimal institutional and economic support. The convergence toward this inactive equilibrium highlights how moderate incentive structures and low differential returns fail to disrupt the status quo, reinforcing conservative governance logic and fragmented stakeholder coordination.

Conversely, the EG-Optimized configuration exhibits a sharply contrasting dynamic. Here, the figure shows a clear upward trajectory toward the strategy vector (1,1,1), reflecting high levels of strategic engagement from all three actors. The strengthened incentives, particularly the increase in regulatory rewards, enterprise benefits, and public incentives, alter the payoff landscape enough to shift the population dynamics toward cooperation and alignment. Over time, this leads to the emergence of a self-reinforcing virtuous cycle in which active governance, enterprise compliance, and public responsiveness mutually validate and stabilize one another. This equilibrium is not only evolutionarily stable but also socially desirable, as it embodies the systemic conditions under which rice subsidy policies can become both efficient and inclusive.

Thus, Figure 4 serves as a dynamic diagnostic tool, enabling stakeholders and policymakers to visualize the non-linear feedbacks and thresholds embedded in governance structures. It illustrates how even marginal adjustments in policy levers can lead to qualitatively different governance equilibria. Importantly, the model demonstrates that fostering a high-engagement equilibrium (as in EG-Optimized) is not merely a function of increasing all incentives indiscriminately but of strategically realigning incentives to generate cross-actor complementarities, as a finding with direct implications for real-world policy design and institutional reform in China's rice subsidy system.

The emergence of EG-Moderate and EG-Optimized as stable yet fragile equilibria reflects not a deficiency in institutional design, but an inherent feature of rural governance systems marked by uneven infrastructural access and varying incentive responsiveness. These outcomes suggest that regulatory coherence alone is insufficient; rather, strategic stability hinges on calibrated reciprocity across government, enterprises, and producers. When policies offer moderate but credible incentives, and when infrastructure enables timely participation, even partial alignment can stabilize cooperation. This interpretation is consistent with studies emphasizing that in complex value chains, adaptive coordination and relational trust often matter more than rigid compliance frameworks (Li, 2025; Waqas et al., 2025; Yu et al., 2025).

This suggests that under intensified incentive mechanisms and more compelling returns for proactive strategies, G, B, and P are more likely to coordinate around active government regulation, enterprise compliance, and public responsiveness.

By embedding these complex interdependencies into a formal evolutionary game framework, the model becomes a decision-support tool for adaptive governance. It offers several key benefits to society as follows.

In evidence-based policy design, the model allows policymakers to simulate how changes in subsidies or transaction costs ripple through the system, offering insights into which policy levers lead to cooperative equilibrium across the three actors.

In early warning for systemic risk, the model helps identify unstable equilibria or strategy collapses, such as a scenario where producers collectively withdraw or enterprises disengage due to high compliance costs. Recognizing these inflection points can inform preemptive interventions, ensuring food security and rural economic stability.

In inclusive rural development, by highlighting conditions that promote trust-based cooperation, the model contributes to more equitable participation of smallholder farmers in value chains. It supports initiatives that build resilience, not dependency, among vulnerable rural actors.

In stakeholder dialogue and negotiation, the model provides a transparent platform for dialogue among stakeholders. By making strategic feedback loops explicit, it can be used in policy sandbox environments to test alternative rules, incentivize experimentation, and build consensus.

In sum, the interactions among G, B, and P in the model are not only analytically significant but also deeply reflective of China's institutional realities and policy challenges. The model offers a structured way to navigate these complexities, yielding actionable insights that can enhance governance capacity, promote inclusive growth, and foster ecological sustainability in the milled rice industry and beyond.

The proposed evolutionary game model benefits society by serving as a strategic decision-support tool that bridges theoretical modeling with real-world agricultural governance challenges. First, it enables evidence-based policy formulation by simulating how changes in subsidies or transaction costs influence the strategic behavior of government regulators, enterprises, and smallholder producers. This empowers policymakers to design more targeted, efficient, and equitable interventions that reduce regulatory failure, rent-seeking, and producer marginalization.

Second, the model facilitates inclusive rural development by identifying conditions under which cooperative strategies become evolutionarily stable, thus supporting long-term trust and fair value distribution across the supply chain. This is particularly beneficial in empowering smallholders to move from subsistence participation to meaningful integration within the rice economy.

Finally, the model enhances institutional learning and stakeholder dialogue. By making feedback loops and behavioral thresholds explicit, it enables scenario testing in policy sandbox settings and encourages cross-sector coordination. As a result, it strengthens governance capacity, minimizes unintended policy consequences, and improves the resilience and adaptability of the agricultural system—benefiting both rural communities and society at large.

The divergence among these models highlights how slight shifts in regulatory pressure and incentive allocation can fundamentally alter the strategic trajectory of all players involved. It underscores the sensitivity of system outcomes to policy design, not only in quantitative terms but in shaping collective behavior over time.

These findings reframe stability not as a static endpoint but as a launchpad for strategic transformation. What the game model identifies in formal terms can be reinterpreted as practical tensions and leverage points for systemic change. This transition from diagnostic insight to transformative strategy is where technical modeling meets developmental vision. Rather than treating system attributes as fixed descriptors, the SOAR (Strengths, Opportunities, Aspirations, Results) framework reimagines them as dynamic levers within a complex adaptive system. Within this framework, strengths and opportunities are not simply assets to catalogue. They act as institutional ignition points that shape the landscape on which aspirations such as inclusivity, resilience, and global competitiveness can gain operational momentum. The game model warns that in the absence of coordinated action, the system may remain locked in suboptimal equilibria. These may be stable in a mathematical sense, but socially stagnant or economically inefficient. Saddle points in particular reveal the fragility of isolated efforts. They expose scenarios where promising initiatives fail to scale, or where innovation occurs without structural reinforcement.

Applied strategically, SOAR transforms these analytical insights into a forward-looking governance architecture. It shifts the emphasis from planning as prediction to planning as active calibration. Results are no longer seen as final outputs but as emergent patterns, sustained through iterative adaptation and multi-actor alignment. In this light, SOAR is not merely a reflective tool but a directional compass that helps navigate long-term transitions. It connects equilibrium analysis with meaningful change, ensuring that China's milled rice industry does not just stabilize around favorable configurations but evolves through intelligent coordination, institutional synergy, and alignment with both national goals and global sustainability imperatives, visualized in Figure 5.

Figure 5. Simulated Evolutionary Trajectories of Tripartite Strategies in China's Milled Rice Industry.

Anchored in this strategic foundation, the ensuing analysis advances a deeper inquiry into the research questions, translating theoretical insights into empirically grounded explanations.

The SWOT analysis of all stakeholders in China's milled rice industry serves as a critical empirical and conceptual foundation for the construction of the three-party evolutionary game model. Each component of the SWOT—including strengths, weaknesses, opportunities, and threats—captures the strategic environment and bounded rationality of the actors, aligning closely with the model's assumptions about adaptive behavior and payoff sensitivity.

In particular, the strengths and weaknesses of each stakeholder group define their initial strategic advantages and constraints, shaping the relative payoff structures in the model. For instance, the government's institutional leverage is a strength, while enforcement asymmetry may be a weakness while both of which directly affect its cost-benefit matrix when choosing between regulatory strategies. Similarly, milled rice enterprises' market access or technological efficiency can be modeled as strengths, whereas dependence on subsidies may constitute a vulnerability. These empirical realities inform the parameterization of the replicator dynamics, allowing the model to simulate realistic adaptation processes.

Meanwhile, opportunities and threats reflect dynamic external factors, such as evolving policies, standards, or pressures, which, although held constant in the short run within the model, still shape stakeholder expectations and potential shifts in payoff landscapes. This ensures that while the model remains structurally closed for analytical clarity, it still resonates with broader real-world policy contexts and sectoral developments.

Therefore, the SWOT analysis does not merely support the model, for it anchors it in context-sensitive realism, enabling it to capture how the strategic interactions among stakeholders unfold within China's actual rice governance ecosystem. It strengthens the model's credibility, policy relevance, and applicability by ensuring that simulated dynamics are not abstract or arbitrary, but reflective of the real-world capacities, incentives, and vulnerabilities of the actors involved. In response to RQ1, the results illuminate how government-led incentives, market-driven procurement strategies, and behavioural adjustments by domestic producers form a co-evolutionary triad. These interactions unfold through nonlinear feedback mechanisms within a complex adaptive system. Government regulators act as institutional architects, shaping the strategic landscape through policy instruments and regulatory signals. Market businesses, particularly those engaged in milled rice procurement, respond to or resist these signals, amplifying or muting the intended policy effects through selective sourcing behaviours. Domestic producers, positioned at the supply chain base, dynamically adjust their practices in response to these shifting signals. This interdependency reinforces systemic responsiveness and strategic coupling across actors, thereby contributing to SDG 2 (Zero Hunger) via food security enhancement and sustainable agriculture, and to SDG 12 (Responsible Consumption and Production) through improved quality control and resource efficiency.

Concerning RQ2, the results confirm that tripartite collaboration is anchored in joint engagement among stakeholders. It is not only desirable but essential to the structural stability of China's rural milled rice supply chain. Stability analysis via Jacobian eigenvalues reveals that fragmented or binary coalitions tend to exhibit saddle-point characteristics as mathematically stable in one direction but vulnerable to perturbations in another. In contrast, full coordination, particularly strategy profile (1,1,1), emerges as the most resilient configuration under dynamic perturbations. This strategic synergy directly supports SDG 8 (Decent Work and Economic Growth) by reinforcing inclusive rural employment and entrepreneurship, while also advancing SDG 9 (Industry, Innovation and Infrastructure) through value chain digitization, infrastructure enhancement, and traceability technologies.

5. Conclusions

This study unpacks the milled rice industry not merely as an agricultural subsector but as a strategic theatre where institutional incentives, infrastructural asymmetries, and behavioral responses converge into evolving patterns of cooperation and divergence. It finds that structural stability within China's milled rice supply chain is not a given but an emergent outcome of synchronized expectations and strategic alignment among government regulators, enterprises, and smallholder producers. Through the evolutionary game framework, it identifies that effective rural governance does not require perfect consensus; rather, it depends on credible expectations and robust feedback loops. The model shows that stability is not a static endpoint but a dynamic process. It is the process shaped by the mutual calibration of institutional rules, infrastructural capacity, and stakeholder behaviour. Milled rice, in this context, becomes more than a staple crop—it transforms into a strategic signal that reflects the underlying strength of trust, responsiveness, and infrastructural integration across the rural economy.

The structural instability and coordination failures that often characterize China's milled rice industry, where fragmented incentives and uneven infrastructure hinder coherent cooperation between government regulators, enterprises, and smallholder producers. The model was designed to investigate whether institutional incentives and behavioural dynamics can be strategically aligned to stabilize rural value chains. Through an evolutionary game framework, the study successfully demonstrates that such alignment is possible by shaping credible expectations and fostering synchronized feedback mechanisms among stakeholders.

Through an evolutionary game lens, it reveals that structural stability within China's rural supply chains is not an automatic outcome, but an emergent property shaped by the alignment or misalignment of three interdependent forces: rules that guide engagement, roads that enable participation, and rice as the value-laden commodity that binds them. The model identifies not just endpoints of equilibrium, but the conditions under which these equilibria become socially meaningful and resilient. The discovery suggests that rural governance does not require perfect consensus to function effectively; what matters more is the credibility of expectations and the strength of feedback loops. In sum, the findings reimagine stability as a process of iterative synchronization. This process transforms milled rice from a staple crop into a strategic mirror reflecting the depth of institutional trust, policy responsiveness, and infrastructural integration.

While rooted in the structural contours of China's milled rice industry, the model's architecture holds interpretive resonance far beyond its immediate context. The tripartite interaction among state, market, and producers echoes across rural value chains where trust, timing, and institutional asymmetries shape collective outcomes. It is governed not by command but by calibrated reciprocity. The identified equilibria capture the kind of strategic ambiguity familiar to other agri-food systems navigating reform, decentralization, and globalization. Though embedded in China's unique policy terrain, the relational patterns illuminated here are translatable that they invite comparative applications in similarly transitional contexts, where infrastructure, incentives, and identities remain in flux.

In practice, the analysis reorients the policymaking lens from control to coordination, from compliance to coherence. The discovery of fragile yet recurrent saddle points reveals that fragility is not a deviation from policy but often its unintended product. Fragility arises when one stakeholder moves ahead without the responsive participation of others. Stability, therefore, emerges not from the mere existence of formal rules but from the rhythm of mutual anticipation and alignment. In such a system, governance becomes less about issuing directives and more about composing conditions, where rules and relational trust converge to nurture adaptive capacity. Policies that embed such logic are not only more resilient but more humane, recognizing the lived uncertainty of those who plant, trade, and consume.

While the current model offers a compelling analytical lens, it operates under a set of necessary abstractions. The binary strategy vectors, though analytically tractable, simplify the more complex and nuanced spectrum of real-world stakeholder behaviour. In addition, the exclusion of ecological disruptions, climate-related risks, and international trade spillovers, though intentional to preserve model clarity, limits the explanatory scope of the model in increasingly globalized agri-food systems. Future research could enrich the model through dynamic parameterization, empirical calibration using real-time datasets, and the integration of digital agricultural platforms and climate adaptation mechanisms. Such extensions would deepen its policy relevance, especially in an era where food security is increasingly shaped by climate volatility and cross-border interdependence. Recognizing these limits invites future interdisciplinary engagement and empirical grounding. As with any model, abstraction brings both clarity and constraint. The binary strategy set simplifies a spectrum of behaviors, and feedback loops shaped by ecological disruptions or cross-border trade spillovers remain outside the present scope. Future iterations would benefit from dynamic parameterization, real-time data calibration, and the inclusion of digital supply chain innovations and climate risk scenarios. Yet these simplifications offer a conceptual skeleton upon which future layers of empirical richness may be added. The exclusion of ecological disruptions, climate-related risks, and international trade spillovers, though intentional to preserve model clarity, limits the explanatory scope of the model in increasingly globalized agri-food systems. Future research could enrich the model through dynamic parameterization, empirical calibration using real-time datasets, and the integration of digital agricultural platforms and climate adaptation mechanisms. Such extensions would deepen its policy relevance, especially in an era where food security is increasingly shaped by climate volatility and cross-border interdependence. Recognizing these limits invites future interdisciplinary engagement and empirical grounding.

This study composes a narrative of evolving interdependence, where milled rice becomes a signal. It reframes stability as a pattern of synchronized expectations, forged not through mandates but through mutual foresight. The framework developed here bridges game theory with developmental realism, grounding equilibrium concepts in the granular realities of rural governance. It opens new analytical pathways for integrating institutional design, behavioral strategy, and infrastructural planning into a unified logic of transformation. In doing so, it contributes to the growing corpus of scholarship that sees agriculture as a frontier of strategic innovation.

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Abbreviations

The following abbreviations are used in this manuscript:

IL	Ionic Liquid
ASEAN	Association of Southeast Asian Nations
USD	United States Dollar
RMB	Renminbi Yuan
CSI	China Securities Index Co.,Ltd
DCE	Dalian Commodity Exchange
ZCE	Zhengzhou Commodity Exchange
SDG	Sustainable Development Goal
FAO	Food and Agriculture Organization
SWOT	Strengths, Weaknesses, Opportunities and Threats
SOAR	Strengths, Opportunities, Aspirations, Result
RQ	Research Question
CPC	Communist Party of China
EG	Evolutionary Game
ODE	Ordinary Differential Equation

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Article

Structural Vector Autoregressive Modeling for Carbon Dioxide Emissions—Evidence from India

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Abstract: India, one of the world's fastest-growing economies, faces the pressing challenge of reconciling rapid economic expansion with the imperative to reduce CO_2 emissions. This study examines the dynamic interrelationships among Gross Fixed Capital Formation (GFCF), Gross National Product (GNP), Population (POP), and Forest Cover (FC) in influencing CO_2 emissions using a Structural Vector Autoregression (SVAR) framework. The model captures both short- and long-run dynamics to uncover the persistence and transmission of shocks across variables. Short-run results reveal a positive and significant self-impact of CO_2 emissions, indicating emission inertia. While economic activity (GFCF and GNP) and population growth exert positive short-term effects on emissions, forest cover demonstrates a negative immediate impact, highlighting its short-run mitigating role. In the long run, CO_2 emissions remain sustained, reflecting structural dependence on carbon-intensive growth. Forest expansion contributes to gradual emission reduction, whereas economic and population growth persist as dominant emission drivers. Impulse Response Functions illustrate the nuanced short-term interplay between environmental and economic variables, while Structural Variance Decomposition indicates that economic and demographic shocks increasingly explain CO_2 variations over time. Diagnostic tests confirm model robustness, with residuals satisfying normality assumptions. Evidence of long-run bidirectional causality among key variables underscores the interdependence of growth and environmental sustainability. The findings emphasize the need for targeted policy interventions promoting low-carbon capital formation, technological innovation, and strengthened forest management to align India's development goals with its environmental commitments.

Keywords: carbon dioxide emissions; gross fixed capital formation; gross national product; population; forest cover; impulse response function; variance decomposition

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1. Introduction

In the intricate landscape of the contemporary global scenario, the challenge of harmonizing economic development with environmental sustainability stands as a defining imperative for nations worldwide. This challenge is further compounded by the urgent need to address the profound consequences of climate change, a global phenomenon that traverses geographical and political boundaries indiscriminately. Climate change, primarily driven by the relentless accumulation of greenhouse gases, poses an imminent and existential threat to our planet, marked by rising global temperatures, unpredictable extreme weather events, and disruptions to delicate ecosystems (Krishnan et al., 2020; Mohanty & Wadhawan, 2021). The current scientific consensus resounds unequivocally, emphasizing the imperative for immediate and concerted measures to constrain global warming's trajectory and mitigate the multifaceted repercussions of climate change (Nathaniel et al., 2021). The crux of this global conundrum lies in the pursuit of a harmonious equilibrium—sustaining robust economic development while concurrently curbing the ominous specter of Carbon Dioxide (CO_2) emissions. Achieving this equilibrium demands a radical shift in the paradigms that underpin the conceptualization and execution of economic policies, environmental stewardship, and societal progress.

India's per capita CO_2 emissions in 2022 stand at 1.91 t.CO_2, placing it 15th among the countries listed, ranking among the lowest on a per-person basis despite being the third-largest emitter in absolute terms globally, contributing 6.99% of total world emissions (Table 1). This contrast highlights that while individual carbon footprints in India are relatively low, the country's sheer population size means that its total emissions remain significant on the global scale. Positioned at the forefront of the world's fastest-growing economies, India faces a critical juncture in balancing rapid economic growth with environmental sustainability. The low per capita emissions mask the underlying challenge: a burgeoning population, rising industrialization, and expanding energy demand collectively exert pressure on carbon emissions trajectories. Amidst ambitious development goals and rising socio-economic expectations, India must navigate a complex interplay between sustaining economic growth and meeting climate commitments. The situation is further compounded by transformative shifts in climate patterns, including the increasing frequency of extreme weather events and the global rise in temperatures, underscoring the urgency of effective mitigation strategies. Consequently, understanding per capita CO_2 trends is pivotal for designing innovative policies and technological solutions that can simultaneously support economic growth, enhance energy efficiency, and reduce carbon intensity.

Table 1. Trends in country-wise CO_2 emissions.

Country	Fossil CO_2 emissions (m.tonnes of CO_2/year)					Per capita (t.CO2)	Rank	% of world
	1970	**1990**	**2005**	**2017**	**2022**	**2022**	**2022**	**2022**
United States	4595.41	4984.07	5888.50	4959.63	4853.78	14.44	4	12.60
China	910.08	2406.18	6258.41	11026.11	12667.43	8.85	7	32.88
Russia	1413.94	2353.97	1719.01	1730.52	1909.04	13.31	5	4.96
Japan	848.59	1165.38	1282.14	1205.92	1082.65	8.61	8	2.81
Germany	1074.75	1008.14	835.26	769.11	673.60	8.16	9	1.75
India	213.95	600.68	1216.51	2434.12	2693.03	1.91	15	6.99
Canada	356.15	440.41	576.47	595.06	582.07	15.22	2	1.51
South Africa	185.56	313.36	434.31	468.96	404.97	6.75	11	1.05
Mexico	120.91	289.98	446.87	498.90	487.77	3.56	14	1.27
Australia	160.38	277.20	383.82	415.46	393.16	15.12	3	1.02
South Korea	62.02	272.12	515.40	668.14	635.50	12.26	6	1.65
Iran	79.50	204.79	467.59	664.90	686.42	8.08	10	1.78
Saudi Arabia	46.92	173.60	345.93	602.84	607.91	16.98	1	1.58
Indonesia	30.98	160.85	359.83	542.05	692.24	2.5	13	1.80
Turkey	45.13	155.02	245.65	434.08	481.25	5.66	12	1.25

Source: Crippa et al., 2023.

CO_2 emissions, primarily propelled by the nation's rapid economic development, have witnessed notable trends that underscore the intricate interplay between growth and environmental sustainability. Table 1 shows that the United States, with a slightly declining yet consistent emission pattern, constitutes 12.60% of the global total in 2022. In contrast, China emerges as the predominant global emitter, accounting for a substantial 32.88% share, indicative of its rapid industrialization. Russia's emissions display fluctuations, contributing 4.96% globally. Japan and Germany showcase relatively stable or decreasing emission levels, representing 2.81% and 1.75% of global emissions, respectively. Notably, India exhibits a noteworthy increase in emissions, although it maintains a comparatively lower per capita footprint. Contributing 6.99% to global emissions in 2022, India's trajectory reflects the complexities of balancing economic growth and environmental concerns. This rise in emissions, while lower on a per capita basis, is indicative of the intricate challenges faced in balancing economic growth and environmental considerations. Factors like growing population, intensified industrial activities, and heightened energy demands play a role in shaping India's emissions trajectory, emphasizing the imperative for the formulation and implementation of sustainable development strategies.

As one of the world's fastest-growing economies, India faces the dual challenge of sustaining economic growth while addressing the rise in CO_2 emissions, an inherent aspect of its developmental trajectory. The increasing frequency of extreme weather events and rising global temperatures further emphasize the urgency of mitigating the environmental impacts of this growth. India's contribution to the global carbon footprint, although shaped by its unique local dynamics, resonates on an international scale, underlining the need for innovative approaches that transcend traditional economic metrics and recognize the deep interconnections between ecological sustainability and long-term economic resilience. Achieving this delicate balance is crucial, not only for India's future but for global efforts to secure a sustainable and resilient future for all nations.

The existing literature on India's CO_2 emissions highlights the tension between rapid economic expansion and its environmental consequences, yet there remain significant research gaps, particularly regarding sector-specific emissions. Key industries such as energy, transportation, and agriculture, which form the backbone of India's economy, contribute disproportionately to its carbon footprint, but their distinct roles in shaping emission trends are often overlooked. Additionally, the effects of India's policy shifts—such as its increasing focus on renewable energy, technological innovation, and environmental regulations—on emission trajectories have not been fully explored. A nuanced understanding of how these factors interact with macroeconomic variables over time is vital for the development of effective and targeted policy interventions. Furthermore, the complex relationship between India's demographic dynamics—urbanization, population growth, and industrialization—and CO_2 emissions demands more granular analysis. These demographic shifts play a critical role in shaping energy demand and carbon output, yet their full implications are not adequately addressed in current studies. The interaction of these variables, alongside environmental factors such as forest cover, offers a rich area for further research to better understand the drivers of emissions and the strategies needed to mitigate them.

To address these gaps, the present study employs Structural Vector Autoregressive (SVAR) modeling, a sophisticated analytical tool that allows for the identification of dynamic cause-and-effect relationships between key variables influencing CO_2 emissions. By incorporating variables such as Gross Fixed Capital Formation (GFCF), Gross National Product (GNP), Population (POP), and Forest Cover (FC), the SVAR model captures the complex interdependencies driving emissions in India. GFCF, as a measure of investment in infrastructure and industrial processes, directly influences energy consumption, a major source of CO_2 emissions. GNP, representing the total economic output, often correlates with higher emissions as growth intensifies industrial activities. Population size, with its impact on energy demand, urbanization, and consumption patterns, is another critical factor, while forest cover, which acts as a carbon sink, plays a crucial role in balancing emissions. By applying the SVAR model to these variables, the study offers valuable insights into the long-term effects of policy interventions, such as the National Action Plan on Climate Change (NAPCC), renewable energy adoption, and industrial reforms, on India's emission trajectory. The model also accounts for external shocks—such as fluctuations in global oil prices or climate-related disasters—that can influence CO_2 emissions, thus providing a more comprehensive understanding of the forces at play. India's experience serves as a compelling case study with far-reaching global implications. As the world grapples with the challenge of harmonizing economic growth and environmental sustainability, India's struggle reflects the broader global effort to reconcile these competing priorities. This study, by delving into the intricacies of India's emissions dynamics, not only addresses the country's unique challenges but also offers a valuable blueprint for other nations facing similar dilemmas. The findings from this research contribute to the global discourse on sustainable development, providing actionable insights that can help shape the future path toward a resilient and ecologically balanced global economy.

2. Background

Review of relationships between economic growth, fixed capital investments, population growth, and CO_2 emissions has garnered researchers' attention since the 1990s because of increasing recognition of the interconnectedness between economic development and environmental sustainability. The most relevant studies are illustrated in Table 2.

Table 2. Categorization of Empirical Studies on CO_2 Emissions.

Research Theme	Authors (Year)	Country / Region	Methodology	Period	Key Findings on CO_2 Emissions
1. Economic Growth and CO_2 Emissions	(Ayobamiji & Kalmaz, 2020)	Nigeria	Fully modified ordinary least squares (FMOLS) and Dynamic ordinary least squares (DOLS)	1971–2015	Economic growth positively impacts CO_2 emissions in both short and long run.
	(Sbia et al., 2014)	UAE	ARDL	1975–2012	Bi-directional causality between CO_2 emissions and GDP.
	(Bozkurt & Akan, 2014)	Turkey	Johansen Cointegration	1960–2010	Negative relationship between CO_2 emissions and economic growth.
	(Antonakakis et al., 2017)	106 Countries	Panel Vector Autoregression (Panel VAR)	1976–2011	Bi-directional causality between economic growth and energy; renewable energy segments are not individually linked to growth.
	(Aqeel & Butt, 2001; Bowden & Payne, 2009; Cheng & Andrews, 1998; Erbaycal, 2008; Ferreira et al., 2005; Halicioglu, 2009; Jalil & Mahmud, 2009; Narayan & Prasad, 2007; Narayan et al., 2008; Ozturk, 2010; Payne, 2010; Ramos-Martín & Ortega-Cerdà, 2003; Stern, 1993)	Various	VAR, ARDL, Cointegration	Various	Mixed evidence on direction and causality between growth, energy use, and emissions.
2. Energy Consumption and Structural Determinants	(Li, 2023)	Heilongjiang Province, China	VAR	2000–2019	Industrial and energy structures suppress CO_2 emissions, while growth in scale and energy intensity increases them.
3. Renewable Energy and Emission Reduction	(Silva et al., 2012)	USA, Denmark, Portugal, Spain	SVAR	1960–2004	Increase in RES-E share reduces CO_2 emissions but may initially harm growth (except the USA).
	(Oryani et al., 2020; Tiwari, 2011)	India	SVAR	1960–2009	Positive shock on renewable energy consumption decreases CO_2 emissions.
4. Capital Investment and Industrial Transformation	Implied in multiple studies, such as Li (2023) and Antonakakis et al. (2017)	Various	VAR, Panel VAR	Various	Industrial structure, energy intensity, and capital accumulation indirectly influence CO_2 levels through the energy mix and production

The reviewed literature reveals several key research gaps and inconsistencies. First, the relationship between economic growth and CO_2 emissions remains inconclusive, with some studies (Ayobamiji & Kalmaz, 2020; Sbia et al., 2014) reporting a positive association, while others (Bozkurt & Akan, 2014) find a negative one—indicating that the Environmental Kuznets Curve (EKC) hypothesis may not be universally applicable. Furthermore, many existing studies (e.g., Ozturk, 2010; Payne, 2010) rely on traditional VAR or cointegration approaches that do not account for structural shocks, limiting their causal interpretability and policy relevance. Another gap is the limited use of the Structural VAR (SVAR) model in the Indian context—despite the country's rapid economic growth and evolving energy landscape, only Tiwari (2011) has applied this framework. In addition, factors such as gross fixed capital formation, industrial restructuring, and energy intensity remain underexplored, though they critically influence emission patterns. The role of renewable energy also appears ambiguous, as Silva et al. (2012) identified short-term economic trade-offs, whereas Tiwari (2011) observed clear emission-reducing effects, underscoring the need for context-specific dynamic modeling.

Against this background, the present study contributes to the literature by employing an SVAR model to capture structural shocks and dynamic interactions among economic growth, energy use, and CO_2 emissions in India. By imposing identification restrictions, the study enhances the interpretability of causal mechanisms and provides a more accurate understanding of policy transmission effects. This structural approach not only fills a methodological gap in the Indian context but also yields policy-relevant insights into how targeted interventions in the energy and industrial sectors can influence carbon emissions, thereby offering a more robust framework for sustainable economic and environmental planning.

3. Materials and Methods

In this paper, the SVAR model incorporates GNP, GFCF, POP, and FC to capture the key drivers of CO_2 emissions in India through three channels—scale, composition, and technique. GNP reflects the scale of economic activity; GFCF represents investment and industrial structure; POP measures demographic pressure; and FC serves as a proxy for natural carbon sequestration. Together, these variables mirror the main policy levers influencing emissions. The SVAR framework is used because it allows identification of structural shocks—such as investment, growth, or land-use changes—and traces their dynamic impacts on CO_2 through impulse responses and variance decomposition. This approach offers policy-relevant insights by distinguishing short-run and long-run causal effects that conventional VAR models cannot capture. It is important to acknowledge the limitations in the selection of determinants, particularly the risk of omitted-variable bias. Key factors such as total energy consumption, energy mix (coal, gas, renewables), energy intensity, technological progress, trade openness, urbanization, and explicit policy instruments (e.g., taxes, subsidies, regulations) are not included and could potentially confound the estimated structural responses. Additionally, measurement challenges—including differing data frequencies, revisions in forest cover and CO_2 series, and uncertainties in land-use emission accounting—along with sample-size constraints, may reduce the precision and reliability of the inferences drawn from the analysis (Buckle et al., 2002).

3.1. Data Sources

For the analysis, we used CO_2 emissions (m. tonnes), real GNP (million US$), GFCF (million US$), POP (million), and FC (million ha). The secondary data are collected from multiple sources, viz., World Bank Indicators (CO_2 emissions); FAOSTAT and Agricultural Statistics at a Glance, Government of India, for other selected variables during 1990 to 2022. For the purpose of analysis, all variables are transformed into logarithms as it minimizes the fluctuations in the data series (Apergis & Payne, 2010; Tiwari, 2010).

3.2. Structural Vector-Autoregression

In this study, the Ng-Perron unit root test, recently developed by Ng and Perron (2001), was chosen to assess the stationarity of time series. Ng and Perron sought to address the limitations of ADF and PP tests by introducing a set of four test statistics (Yıldırım et al., 2015). These tests include the MZa (Modified Zivot-Andrews); MZt (Modified Zivot-Andrews with a structural break at an unknown time); MSB (test which is the modified version of the Bhargava test); and MPT (Modified versions of Augmented Dickey-Fuller-Generalized Least Squares [ADF-GLS] test). For the Ng and Perron (2001) test, the fundamental hypothesis sets a unit root for the MZa and MZt tests, and stationarity for the MSB and MPT tests. The determination of the lag length to be incorporated in our analysis is based on the Akaike Information Criteria (AIC) due to its superior performance in small sample sizes (Liew, 2004).

The SVAR methodology meticulously examines the intricate interactions among all variables, and its constraints are grounded in economic theory or disclose information regarding the dynamic properties of the investigated economy (Narayan et al., 2008). Consequently, this model proves invaluable for predicting the ramifications of precise policy interventions or significant transformations in the economy, as exemplified in scenarios involving alterations in CO_2 emissions (Buckle et al., 2002; Narayan et al., 2008). The following SVAR is formulated:

$$RY_t = \alpha_0 + \alpha_1 Y_{t-1} + u_t \quad (1)$$

The generalized form can be represented as:

$$RY_t=\sum_{j=1}^{n}\alpha_1 Y_{t-1}+u_t,\ u_t\sim N(0,K) \tag{2}$$

In the above generalized form, $Y_t(=Y_{1t}, Y_{2t}, Y_{3t}, \ldots Y_{kt})$ is a $k\times 1$ vector of endogenous variables, $\alpha_1 \ldots \alpha_k$ is a $k\times k$ matrix of lag coefficients to be estimated on j^{th} lag, u_t is a $k\times 1$ vector of white noise innovation processes representing the structural shocks. R is a matrix that reflects the contemporaneous relationship among endogenous variables.

Now considering the study, here vector Y_t includes five variables: CO_2 emissions, FC, GFCF, GNP, and POP. The system is represented as shown below:

$$\begin{gathered} a_{11}lnCO_{2t} + a_{12}lnFC_t + a_{13}lnGFCF_t + a_{14}lnGNP_t + a_{15}lnPOP_t \\ =\alpha_{10} + \alpha_{11}lnCO_{2t-1} + \alpha_{12}lnFC_{t-1} + \alpha_{13}lnGFCF_{t-1} + \alpha_{14}lnGNP_{t-1} + \alpha_{15}lnPOP_{t-1} + u_{lnCO_t} \end{gathered} \tag{3}$$

$$\begin{gathered} a_{21}lnCO_{2t} + a_{22}lnFC_t + a_{23}lnGFCF_t + a_{24}lnGNP_t + a_{25}lnPOP_t \\ =\alpha_{20} + \alpha_{21}lnCO_{2t-1} + \alpha_{22}lnFC_{t-1} + \alpha_{23}lnGFCF_{t-1} + \alpha_{24}lnGNP_{t-1} + \alpha_{25}lnPOP_{t-1} + u_{lnFC_t} \end{gathered} \tag{4}$$

$$\begin{gathered} a_{31}lnCO_{2t} + a_{32}lnFC_t + a_{33}lnGFCF_t + a_{34}lnGNP_t + a_{35}lnPOP_t \\ =\alpha_{30} + a_{31}lnCO_{2t-1} + a_{32}InFC_{t-1} + a_{33}lnGFCF_{t-1} + a_{34}lnGNP_{t-1} + a_{35}lnPOP_{t-1} + u_{lnGFCF_t} \end{gathered} \tag{5}$$

$$\begin{gathered} a_{41}lnCO_{2t} + a_{42}lnFC_t + a_{43}lnGFCF_t + a_{44}lnGNP_t + a_{45}lnPOP_t \\ =\alpha_{40} + \alpha_{41}lnCO_{2t-1} + \alpha_{42}lnFC_{t-1} + \alpha_{43}lnGFCF_{-1} + a_{44}lnGNP_{t-1} + \alpha_{45}lnPOP_{t-1}+u_{lnGNP_t} \end{gathered} \tag{6}$$

$$\begin{gathered} a_{51}lnCO_{2t} + a_{52}lnFC_t + a_{53}lnGFCF_t + a_{54}lnGNP_t + a_{55}lnPOP_t \\ =\alpha_{50} + \alpha_{51}lnCO_{2t-1} + a_{52}lnFC_{t-1} + \alpha_{53}lnGFCF_{t-1} + a_{54}lnGNP_{t-1} + \alpha_{55}lnPOP_{t-1} + u_{lnPOP_t} \end{gathered} \tag{7}$$

The matrix form of the above system is given as:

$$\begin{gathered} \begin{bmatrix} a_{11} & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 & 0 \\ a_{31} & a_{32} & a_{33} & 0 & 0 \\ a_{41} & a_{42} & a_{43} & a_{44} & 0 \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{bmatrix} \begin{bmatrix} CO_{2t} \\ FC_t \\ GFCF_t \\ GNP_t \\ POP_t \end{bmatrix} = \\ \begin{bmatrix} \alpha_{10} \\ \alpha_{20} \\ \alpha_{30} \\ \alpha_{40} \\ \alpha_{50} \end{bmatrix} \begin{bmatrix} \alpha_{11}(C(11)) & 0 & 0 & 0 & 0 \\ \alpha_{21}(C(21)) & \alpha_{22}(C(22)) & 0 & 0 & 0 \\ \alpha_{31}(C(31)) & \alpha_{32}(C(32)) & \alpha_{33}(C(33)) & 0 & 0 \\ \alpha_{41}(C(41)) & \alpha_{42}(C(42)) & \alpha_{43}(C(43)) & \alpha_{44}(C(44)) & 0 \\ \alpha_{51}(C(51)) & \alpha_{52}(C(52)) & \alpha_{53}(C(53)) & \alpha_{54}(C(54)) & \alpha_{55}(C(55)) \end{bmatrix} + \begin{bmatrix} CO_{2t-1} \\ FC_{t-1} \\ GFCF_{t-1} \\ GNP_{t-1} \\ POP_{t-1} \end{bmatrix} + \begin{bmatrix} u_{CO_{2t}} \\ u_{FC_t} \\ u_{GFCF_t} \\ u_{GNP_t} \\ u_{POP_t} \end{bmatrix} \end{gathered} \tag{8}$$

To derive the reduced form VAR, multiply both sides of Equation (1) by R^{-1}; we get:

$$R^{-1}RY_t = R^{-1}\alpha_0 + R^{-1}\alpha_1 Y_{t-1} + R^{-1}u_t \tag{9}$$

Multiplying a matrix with its inverse gives an identity matrix, i.e., $R^{-1}R = I$, where I is the identity matrix. Thus, the above equation can be written as:

$$Y_t = Z_0 + Z_1 Y_{t-1} + e_t \tag{10}$$

where vector Y_t depends on lag of itself and the forecast error e_t. The matrix R here also indicates the forecast errors of VAR, e_t and the structural shocks u_t i.e., $e_t = R^{-1}u_t$. In reduced form VAR, e_t is the linear makeup of u_t.

Structural VAR is basically a conceptually constructed framework and is non-observable (Jena et al., 2023). Thus, it cannot be computed directly. As we have time series or a history of variables, we use these to estimate the VAR. Following that, the regression of each variable is run against its lag and the lag of other variables included in the VAR. Hence, we get the coefficient Z and the forecast error e_t. Starting from the reduced form VAR estimation, our goal is to get the structural model that isolates the purely exogenous shocks and responds to the variables of interest. To do this, we would need to get matrix R, or more precisely, we need to restrict matrix R. Get R

and multiply the reduced form VAR by R to get the structural model, shocks, and contemporaneous channelization among the variables (Auclert et al., 2021; Cravino et al., 2020).

$$RY_t = RZ_0 + RZ_1 Y_{t-1} + Re_t$$
$$RY_t = \alpha_0 + \alpha_1 Y_{t-1} + u_t \left(\because RR^{-1}\alpha_0 = \alpha_0\right) \tag{11}$$

After getting the structural model, we impose restrictions on contemporaneous relationships among endogenous variables of the structural model. This is what identification entails. Identification means imposing restrictions on matrix R based on economic intuition. From the calculated coefficients, the SVAR with both short-run restriction is presented as follows:

$$R = \begin{bmatrix} C(1) & 0 & 0 & 0 & 0 \\ C(2) & C(6) & 0 & 0 & 0 \\ C(3) & C(7) & C(10) & 0 & 0 \\ C(4) & C(8) & C(11) & C(13) & 0 \\ C(5) & C(9) & C(12) & C(14) & C(15) \end{bmatrix} \tag{12}$$

Similarly, SVAR with imposing long-run restriction is given as:

$$R' = \begin{bmatrix} L(1) & 0 & 0 & 0 & 0 \\ L(2) & L(6) & 0 & 0 & 0 \\ L(3) & L(7) & L(10) & 0 & 0 \\ L(4) & L(8) & L(11) & L(13) & 0 \\ L(5) & L(9) & L(12) & L(14) & L(15) \end{bmatrix} \tag{13}$$

In the computation of SVAR, we must impose restrictions on the parameter matrices (Garratt et al., 1998). These restrictions can take the form of either contemporaneous restrictions on the parameter matrices of A_0 and B, where A_0 and B are the (K × K) matrices indicating instantaneous relationship relations of variables in X_t and ε_t, respectively, or long-run restrictions on the total effects of structural shocks to identify the structural parameters. In this paper, we employ both short-run and long-run restrictions methods (Blanchard & Quah, 1989). For example, in the long-run restrictions model, A_0 is set as an identity matrix, i.e., $A_0 = I_K$. These restrictions are based on long-run restrictions imposed on the cumulative impulse response function. In total, $K(K - 1)/2$ restrictions are imposed on the lower triangular matrix, where some of the structural shocks do not have contemporaneous impacts on the other variables. The variables are ordered as follows: CO_2 emissions, FC, GFCF, GNP, and POP. For the Recursive Short-Run Impulse Response (S triangular) and Recursive Long-Run Impulse Response (F triangular) models, the same principles are applied, but with variations in the imposition of restrictions based on specific characteristics of each model (Blanchard & Quah, 1989; Love & Zicchino, 2006; Sims, 1980). The conceptual framework of SVAR is illustrated in Figure 1.

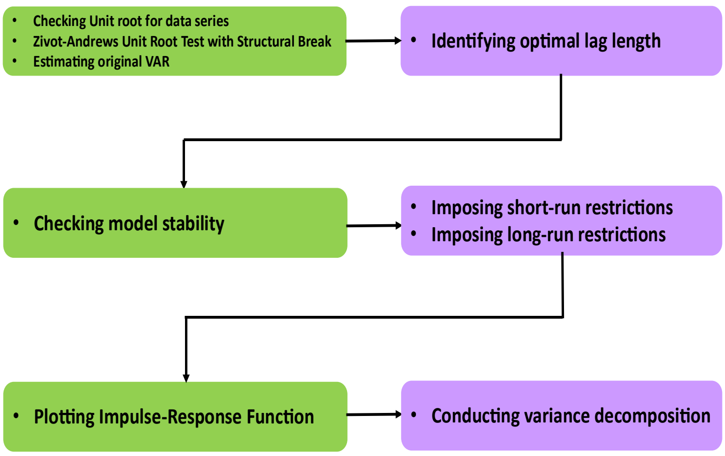

Figure 1. Conceptual framework of SVAR.

4. Results

4.1. Unit Root Tests and Structural Break

The unit root tests (Table 3), employing both Ng and Perron (2001) and Zivot and Andrew methodologies (Adewole et al., 2020), contribute valuable insights into the stationarity and structural properties of the variables (Mollick, 2009). In their level form, CO_2 emissions, FC, GFCF, GNP, and POP exhibit non-stationary behavior, as evidenced by consistently smaller calculated statistical values for the MZa and MZt tests compared to critical values. Conversely, the MSB and MPT tests show statistical values surpassing critical values, further affirming non-stationarity. However, the transformation through differencing renders the variables stationary, with first differences demonstrating the absence of a unit root at both 1 and 5% significance levels. The Zivot and Andrew test reveals unit roots in the levels of all variables, but structural breaks (Table 4), identified as A (Intercept), B (Trend), and C (Trend and Intercept), signify shifts in their properties at specific years. These findings collectively provide a robust foundation for justifying the application of a Structural VAR model, as it accommodates the stationary nature post-differencing and captures the dynamic relationships amidst structural shifts in the economic system.

Table 3. Ng- Perron Unit Root Test Results.

Variable	MZa	MZt	MSB	MPT
Level form				
CO_2 emissions	−2.2801	−0.8010	0.3523	9.0793
Critical Value	−5.7078	−1.6206	0.2753	4.4521
FC	−1.1402	−0.3530	0.3099	10.0861
Critical Value	−5.7026	−1.6213	0.2751	4.4566
GFCF	0.3669	0.6210	1.6930	161.8241
Critical Value	−5.7026	−1.6222	0.2753	4.4524
GNP	−5.0039	−1.4327	0.2864	5.2639
Critical Value	−5.7018	−1.6225	0.2754	4.4536
POP	−1.6475	−0.6890	0.4189	37.9777
Critical Value	−14.2045	−2.6207	0.1853	6.6771
First difference form				
CO_2 emissions	−31.2232**	−24.5354**	0.0242**	0.0514**
Critical Value	−13.8432	−2.5991	0.1746	1.7927
FC	−34.4600**	−14.7234**	0.1043**	0.7341**
Critical Value	−13.8337	−2.5898	0.1748	1.7968
GFCF	−16.7291**	−3.8958*	0.1736*	1.5224*
Critical Value	−13.8762	−2.6044	0.1748	1.7966
GNP	−11.8807*	−3.1095*	0.2151*	2.9499*
Critical Value	−8.1374	−1.9924	0.2345	3.1915
POP	−7.0997*	−2.7722*	0.2509*	3.8971*
Critical Value	−5.7228	−1.6269	0.2758	4.4828

Note: ** & * - shows the absence of unit roots at 1% and 5% significance levels, respectively.

Table 4. Results of Zivot and Andrew unit root test.

Variables	t_{cal}	Structural break down	Structural break year	Order of Integration
CO_2 emissions	−7.9371**	A	2009	I(1)
FC	−3.5391**	A	2001	I(1)
GFCF	−4.0714**	A	2004	I(1)
	−4.1409*	B	2011	
	−3.9354**	C	2004	
GNP	−3.5352*	A	2005	I(1)
	−2.5050*	B	2012	
POP	−0.4519*	B	2017	I(1)

Note: Break location: A = Intercept, B = Trend, C = Trend and Intercept;
** & * - shows the absence of unit roots at 1% and 5% significance levels, respectively.

4.2. Lag Selection Criteria

Table 5 shows the outcome of the lag selection criteria. The result indicates that the majority of lag selection criteria—such as FPE, AIC, SC, and HQ—suggest an optimal lag length of 4 (Liew, 2004). This convergence across multiple criteria enhances confidence in the selection of lag 4, affirming its suitability for the cointegration test as well as estimating the SVAR.

Table 5. VAR lag length criteria.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	368.0973	NA	$3.75e^{-18}$	−25.93552	−25.69763	−25.86280
1	643.9278	433.4480	$6.42e^{-26}$	−43.85199	−42.42463	−43.41563
2	692.8481	59.40312*	$1.41e^{-26}$	−45.56058	−42.94375	−44.76058
3	731.3286	32.98331	$9.38e^{-27}$	−46.52347	−42.71717	−45.35985
4	798.6051	33.63826	$1.95e^{-27}$*	−49.54322*	−44.54746*	−48.01597*

Note: *indicates lag order selected by the criterion; LR - sequential modified LR test statistic (each test at 5% level; FPE: Final prediction error; AIC: Akaike information criterion; SC: Schwarz information criterion; HQ: Hannan-Quinn information criterion.

4.3. Johansen Cointegration Test

Findings from Table 6 highlight both trace and maximum eigenvalue tests to ascertain the presence of a long-run relationship among the analyzed variables. The trace test assesses various hypotheses concerning the number of cointegrating equations, providing compelling evidence in favor of cointegration. At the 0.05 significance level, the trace statistic exceeds the critical values for all scenarios considered, strongly indicating the existence of a cointegrating relationship. Similarly, the maximum eigenvalue test supports these findings, displaying statistical significance for the same scenarios. Consistently, both tests suggest the presence of four cointegrating equations, bolstering the robustness of this conclusion. These results establish a fundamental groundwork for subsequent SVAR analysis, confirming the interconnectedness of variables in the long run.

Table 6. Results of Johansen Cointegration test.

Unrestricted Cointegration Rank Test (Trace)				
Hypothesized No. of CE(s)	**Eigenvalue**	**Trace Statistic**	**0.05 Critical Value**	**Prob.****
None *	0.974171	217.2628	69.81889	0.0000
At most 1 *	0.840717	114.8873	47.85613	0.0000
At most 2 *	0.699031	63.44932	29.79707	0.0000
At most 3 *	0.654845	29.82838	15.49471	0.0002
At most 4	0.001536	0.043037	3.841465	0.8356
Unrestricted Cointegration Rank Test (Maximum Eigenvalue)				
Hypothesized No. of CE(s)	**Eigenvalue**	**Max-Eigen Statistic**	**0.05 Critical Value**	**Prob.****
None *	0.974171	102.3755	33.87687	0.0000
At most 1 *	0.840717	51.43798	27.58434	0.0000
At most 2 *	0.699031	33.62094	21.13162	0.0006
At most 3 *	0.654845	29.78534	14.26460	0.0001
At most 4	0.001536	0.043037	3.841465	0.8356

Note: Trace test indicates 4 cointegrating eqn(s) at the 0.05 level.
Max-eigenvalue test indicates 4 cointegrating eqn(s) at the 0.05 level.

4.4. Stability Test

We conducted a stability test, assessing the stationary properties of variables using the AR root table (Table 7) and the corresponding graph (Figure 2). The findings showed that all the roots of the characteristic polynomial exhibit moduli less than one. The accompanying graph illustrates that all the unit circles lie inside the circle, indicative of the VAR model's variance and covariance stationarity, meeting the necessary stationary conditions. This observation underscores the stability of the model, affirming its suitability for analyzing the dynamic relationships among variables over time. The consistent moduli below one signify that the system is not prone to explosive or divergent behavior, enhancing the reliability of the SVAR results derived from this model.

Table 7. Results of the AR root table.

Root	Modulus
−0.242359 + 0.781007i	0.814177
−0.168252 – 0.821575i	0.802511
0.808526	0.808526
0.992080	0.992080
0.954869 − 0.265886i	0.991196
0.954869 + 0.265886i	0.991196
0.594543 − 0.728428i	0.940260
0.594543 + 0.728428i	0.940260
0.331748 + 0.844647i	0.907461
0.331748 − 0.844647i	0.907461
−0.779670 − 0.449947i	0.900187
−0.779670 + 0.449947i	0.900187
−0.525968 − 0.712170i	0.885341
−0.525968 + 0.712170i	0.885341
0.592544 + 0.464048i	0.752629
0.592544 − 0.464048i	0.752629
−0.647900	0.647900
−0.070119 + 0.622368i	0.626306
−0.070119 − 0.622368i	0.626306
0.073044	0.073044

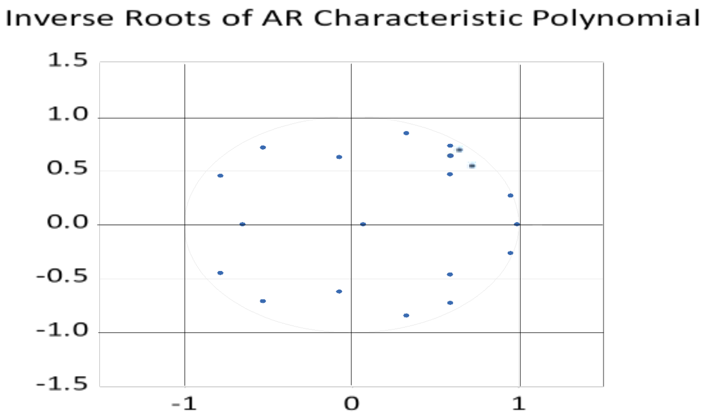

Figure 2. AR Root Graphic.

4.5. Test for Normality of Residuals

The analysis of VAR residuals (Table 8) for normality reveals encouraging results, with skewness values for all components near zero and non-significant chi-square tests, indicating a lack of substantial skewness in the data. Similarly, kurtosis results across all components exhibit non-significance, and the joint test does not reach significance either, suggesting that the tails of the distribution do not deviate significantly from normality. The Jarque-Bera test, considering both skewness and kurtosis, further supports these findings, indicating no individual or joint significance. Collectively, these tests provide robust evidence that the VAR residuals adhere well to multivariate normality.

Table 8. Skewness, Kurtosis, and Jarque-Bera Test for Normality of VAR residuals.

Component	Skewness	Chi-sq	df	Prob.*
1	0.0039	0.0001	1	0.9921
2	0.3667	0.8457	1	0.3578
3	0.5609	1.8988	1	0.1682
4	0.1057	0.0724	1	0.7879
5	0.1135	0.0835	1	0.7727
Joint		2.9004	5	0.7153
Component	**Kurtosis**	**Chi-sq**	**df**	**Prob.**
1	3.1919	1.6642	1	0.1970
2	2.3801	0.3551	1	0.5512
3	3.0921	0.0467	1	0.8289
4	3.0223	0.9967	1	0.3172
5	3.0252	0.9907	1	0.3196
Joint		8.7315	5	0.1203
Component	**Jarque-Bera**	**df**	**Prob.**	
1	1.6643	2	0.4351	
2	1.2008	2	0.5486	
3	1.9455	2	0.3781	
4	5.7472	2	0.0565	
5	1.0741	2	0.5845	
Joint	11.6320	10	0.3104	

Note: *Approximate p-values do not account for coefficient estimation.

4.6. Test for Autocorrelation of Residuals

The VAR Residual Serial Correlation LM Test assesses whether the residuals from the estimated VAR model are serially correlated across different time lags (Table 9). The first part of the test examines serial correlation at individual lags, while the second part evaluates the joint absence of correlation across multiple lags. In this study, the adjusted test results indicate that all probability values exceed the 5% significance level, leading to the acceptance of the null hypothesis of no serial correlation. This confirms that the residuals are independently distributed, implying that the VAR model is correctly specified and the dynamic relationships among the variables are appropriately captured without systematic errors in the error structure. These independently distributed residuals are crucial for generating valid Impulse Response Functions (IRFs) in a VAR model. They ensure that each shock represents a unique, exogenous disturbance, free from overlap with past errors. This independence allows the IRF to accurately trace the pure dynamic response of one variable to another over time. Consequently, it enhances the credibility of causal interpretations and the reliability of policy inferences derived from the model.

Table 9. VAR Residual Serial Correlation LM Tests.

Null hypothesis: No serial correlation at lag h						
Lag	**LRE* stat**	**df**	**Prob.**	**Rao F-stat**	**df**	**Prob.**
1	18.642	25	0.812	NA	(25, NA)	NA
2	22.754	25	0.644	NA	(25, NA)	NA
3	20.389	25	0.727	NA	(25, NA)	NA
4	24.117	25	0.508	NA	(25, NA)	NA
Null hypothesis: No serial correlation at lags 1 to h						
Lag	**LRE* stat**	**df**	**Prob.**	**Rao F-stat**	**df**	**Prob.**
1	18.642	25	0.812	NA	(25, NA)	NA
2	38.416	50	0.875	NA	(50, NA)	NA
3	54.229	75	0.929	NA	(75, NA)	NA
4	69.357	100	0.943	NA	(100, NA)	NA

4.7. SVAR for Short-Run and Long-Run Restrictions

The short-term SVAR estimations (Buckle et al., 2002) reveal the immediate dynamics among CO_2 emissions, FC, GFCF, GNP, and POP (Table 10). A positive and statistically significant self-impact of CO_2 emissions (0.0108**) indicates that current emission levels influence future emissions even in the short term, reflecting the persistence of carbon-intensive practices. Economically, this suggests that emission reductions cannot occur instantaneously; short-term policy interventions must be complemented by sustained structural changes to industrial processes and energy use (Bernanke, 1986; Blanchard & Watson, 1986; Sims, 1986).

Table 10. Results of Structural VAR Estimate on Short-run pattern.

Variables		Coefficient	Std. Error	z-Statistic	Prob.
α_{11}	C(1)	0.0108**	0.0014	7.4833	0.0000
α_{21}	C(2)	−0.0841**	0.0277	−3.0399	0.0024
α_{31}	C(3)	0.0131*	0.0059	2.1976	0.0280
α_{41}	C(4)	0.0126**	0.0035	3.5960	0.0003
α_{51}	C(5)	0.0311*	0.0142	2.1929	0.0283
α_{22}	C(6)	0.0001**	0.0000	7.4833	0.0000
α_{32}	C(7)	−0.0115*	0.0055	−2.1121	0.0347
α_{42}	C(8)	−0.0072*	0.0029	−2.4693	0.0135
α_{52}	C(9)	0.00002	0.00001	1.6578	0.0974
α_{33}	C(10)	0.0277**	0.0037	7.4833	0.0000
α_{43}	C(11)	0.0135**	0.0021	6.4669	0.0000
α_{53}	C(12)	0.0024*	0.0011	2.2964	0.0217
α_{44}	C(13)	0.0056**	0.0007	7.4833	0.0000
α_{54}	C(14)	−0.0013**	0.0004	−3.3387	0.0008
α_{55}	C(15)	0.00005**	0.00001	7.4833	0.0000
R^2 = 0.79**; Adj R^2 = 0.72**					
Akaike Information Criterion (AIC): –4.87					
Bayesian Information Criterion (BIC): –4.11					

Note: ** and * - Significance at 1 and 5% levels respectively.

The negative immediate effect of FC (−0.0841**) demonstrates that short-term increases in forested area can reduce CO_2 emissions. Although the magnitude may appear moderate numerically, at the national scale even small increments in forest cover translate into substantial carbon sequestration, emphasizing the short-term mitigation potential of afforestation, reforestation, and forest conservation programs.

GFCF (0.0131*) shows a positive immediate effect on CO_2 emissions, indicating that short-term expansions in capital investment, especially in industrial and infrastructure sectors, quickly translate into higher emissions. This underscores the environmental cost of rapid capital deployment unless investments are directed toward low-carbon or energy-efficient technologies. Similarly, GNP (0.0126**) positively affects CO_2 emissions, reflecting the short-term responsiveness of emissions to economic output. The magnitude suggests that even modest increases in economic activity can immediately elevate carbon output, highlighting the challenge of balancing short-term growth with environmental sustainability.

Finally, POP growth (0.0311*) contributes positively to short-term CO_2 emissions. The relatively larger magnitude compared to GFCF and GNP indicates that demographic pressures quickly amplify energy demand, consumption, and industrial activities, thus increasing emissions. This finding aligns with classical economic interpretations that population expansion drives short-run energy consumption patterns and environmental stress (Bernanke, 1986; Blanchard & Watson, 1986; Sims, 1986).

These short-run coefficients quantify the relative influence of each determinant on immediate emissions. Forest cover acts as a mitigating factor, while population, economic output, and investment accelerate emissions even in the short term. These results highlight the need for targeted short-term policies—such as afforestation incentives, energy-efficient investment programs, and demand-side management—to moderate emissions while structural and technological transitions take effect. The Adjusted R^2 confirms that the SVAR model is statistically sound, with a high explanatory power and efficient specification. Further, the low AIC and BIC values indicate optimal lag selection and model parsimony, supporting the credibility of the structural dynamics and impulse response analysis derived from the estimated coefficients.

$$\begin{bmatrix} . & \boldsymbol{CO_2\text{-}emi} & \boldsymbol{FC} & \boldsymbol{GFCF} & \boldsymbol{GNP} & \boldsymbol{POP} \\ \boldsymbol{CO_2\text{-}emi} & 0.0108^{**} & 0 & 0 & 0 & 0 \\ \boldsymbol{FC} & -0.0841^{**} & 0.0001^{**} & 0 & 0 & 0 \\ \boldsymbol{GFCF} & 0.0131^{*} & -0.0115^{*} & 0.0277^{**} & 0 & 0 \\ \boldsymbol{GNP} & 0.0126^{**} & -0.0072^{*} & 0.0135^{**} & 0.0056^{**} & 0 \\ \boldsymbol{POP} & 0.0311^{*} & 0.00002 & 0.0024^{*} & -0.0013^{**} & 0.00005^{**} \end{bmatrix} \quad (14)$$

Under the long-run restrictions of the SVAR model, a clearer picture of the persistent dynamics among CO_2 emissions and its determinants emerges (Table 11). The self-impact of CO_2 emissions (0.5413**) indicates strong persistence, implying that past emission levels continue to drive future emissions. Economically, this suggests that once carbon-intensive practices are embedded in industrial and energy systems, they tend to persist, necessitating deliberate structural interventions—such as decarbonizing energy infrastructure or retrofitting industrial processes—to break this inertia.

Table 11. Results of Structural VAR Estimate on Long-run pattern.

Variables		Coefficient	Std. Error	z-Statistic	Prob.
α_{11}	C(1)	0.5413**	0.0730	7.4109	0.0000
α_{21}	C(2)	−0.0387**	0.0052	−7.4078	0.0024
α_{31}	C(3)	0.6293*	0.0850	7.4035	0.0280
α_{41}	C(4)	0.5477**	0.0739	7.4079	0.0003
α_{51}	C(5)	0.1663*	0.0224	7.4104	0.0283
α_{22}	C(6)	0.0007**	0.0001	7.4793	0.0000
α_{32}	C(7)	−0.0153*	0.0032	−4.7573	0.0347
α_{42}	C(8)	−0.0101*	0.0016	−6.1502	0.0135
α_{52}	C(9)	0.0011	0.0002	6.1278	0.0974
α_{33}	C(10)	0.0131**	0.0018	7.4823	0.0000
α_{43}	C(11)	0.0035**	0.0008	4.3156	0.0000
α_{53}	C(12)	0.0067*	0.0102	0.6562	0.0217
α_{44}	C(13)	0.0035**	0.0005	7.4861	0.0000
α_{54}	C(14)	−0.0002**	0.0001	−2.4021	0.0008
α_{55}	C(15)	0.0005**	0.0001	7.4769	0.0000
R^2 = 0.81**; Adj R^2 = 0.77**					
Akaike Information Criterion (AIC): –5.12					
Bayesian Information Criterion (BIC): –4.42					

Note: ** and * - Significance at 1 and 5% levels respectively.

The negative effect of FC (−0.0387**), though modest in magnitude, reflects the cumulative carbon sequestration benefits of increased forest area. While the coefficient appears small numerically, even slight increases in forest cover can offset emissions significantly at the national scale, particularly given India's large land area. Economically, this underscores the long-term value of afforestation, reforestation, and forest conservation policies as a cost-effective carbon mitigation strategy.

GFCF (0.6293*) exhibits the largest long-run positive impact among the variables, indicating that investments, particularly in infrastructure and industrial capacity, substantially elevate CO_2 emissions. This highlights the trade-off between investment-led growth and environmental sustainability, emphasizing the urgency of integrating green technologies, renewable energy infrastructure, and energy-efficient capital into development planning.

The effect of GNP (0.5477**) on CO_2 emissions also remains large and positive, reflecting that economic expansion continues to be heavily reliant on carbon-intensive sectors and fossil fuels. The magnitude implies that sustained growth without structural transformation in the energy and industrial sectors will exacerbate emission pressures, reinforcing the importance of policies promoting low-carbon economic growth.

Finally, POP growth (0.1663*) contributes positively but at a smaller magnitude compared to investment and output. This indicates that while demographic expansion increases aggregate energy demand and consumption, its effect on emissions is less pronounced per unit change than structural or economic factors. Economically, this implies that energy efficiency measures, urban planning, and sustainable consumption patterns can partially offset the emission pressures of population growth.

Taken together, the long-run coefficients quantify the relative contributions of each factor to persistent CO_2 emissions. Investment and economic growth are the largest drivers, suggesting that structural and technological shifts are critical to achieving sustainable development. Forest cover plays a mitigating role, and population growth, though smaller in magnitude, still requires targeted policies for energy conservation and efficiency. These insights provide actionable guidance for policymakers aiming to balance economic development with long-term environmental sustainability. The high R^2 and adjusted R^2 indicate that the model explains a substantial portion of the variation in the data, while the low AIC and BIC values reflect its efficiency and suitability. Together, these diagnostics confirm that the long-run SVAR model robustly captures the structural relationships among CO_2 emissions, GFCF, GNP, POP, and FC, providing a reliable basis for deriving meaningful long-term policy insights.

$$\begin{bmatrix} . & \boldsymbol{CO_2\text{-}emi} & \boldsymbol{FC} & \boldsymbol{GFCF} & \boldsymbol{GNP} & \boldsymbol{POP} \\ \boldsymbol{CO_2\text{-}emi} & 0.5413 & 0 & 0 & 0 & 0 \\ \boldsymbol{FC} & -0.0387 & 0.0007 & 0 & 0 & 0 \\ \boldsymbol{GFCF} & 0.6293 & -0.0152 & 0.0131 & 0 & 0 \\ \boldsymbol{GNP} & 0.5477 & -0.0101 & 0.0035 & 0.0035 & 0 \\ \boldsymbol{POP} & 0.1663 & 0.0011 & 0.0067 & -0.0002 & 0.0005 \end{bmatrix} \quad (15)$$

4.8. IRF of CO_2 Emissions

The IRFs (Table 12; Figures 3; Figure 4) analyze the dynamic responses of CO_2 emissions to one-standard-deviation shocks in FC, GFCF, GNP, and POP. In Figure 3, CO_2 emissions show a brief increase after a FC shock, peaking in the first period and fading by the third, suggesting a temporary emission rise from land-use changes or forestry activities (e.g., land preparation, biomass burning) before sequestration benefits emerge. The 95% confidence intervals reflect uncertainty, but the effect is short-lived. CO_2 emissions response to GFCF shock remains near zero, indicating minimal short-term impact, possibly due to green technology adoption or lagged effects. Conversely, GNP and POP shocks drive steady increases in CO_2 emissions, with effects strengthening after the fifth and second periods, respectively, reflecting sustained emission pressures from economic growth and population demand. The initial FC response may reflect VAR framework issues, such as Cholesky ordering assuming exogeneity, capturing correlated shocks (e.g., land-use policies) rather than sequestration. Measurement challenges (e.g., aggregating forest types, lags in carbon uptake) and initial emissions from afforestation (e.g., machinery, soil release) may also contribute (Sims, 1980). Socio-economically, this could indicate transitional emissions in developing economies from infrastructure-linked forest programs, with long-term sequestration potentially offsetting these, supporting sustainability goals (Ewing et al., 2007; Robalo & Salvado, 2008). Integrated policies balancing forest management, economic, and demographic strategies are thus essential.

Table 12. IRF of CO_2 emissions to innovations (Cholesky ordering).

Period	FC	GFCF	GNP	POP
1	0.0068	0.0000	0.0000	0.0000
2	0.0047	0.0001	0.0006	0.0004
3	0.0039	0.0011	0.0007	0.0004
4	0.0022	0.0024	0.0017	0.0008
5	0.0012	0.0039	0.0020	0.0017
6	0.0001	0.0046	0.0037	0.0026
7	−0.0014	0.0057	0.0048	0.0033
8	−0.0026	0.0061	0.0069	0.0054
9	−0.0038	0.0076	0.0095	0.0061
10	−0.0045	0.0091	0.0112	0.0098

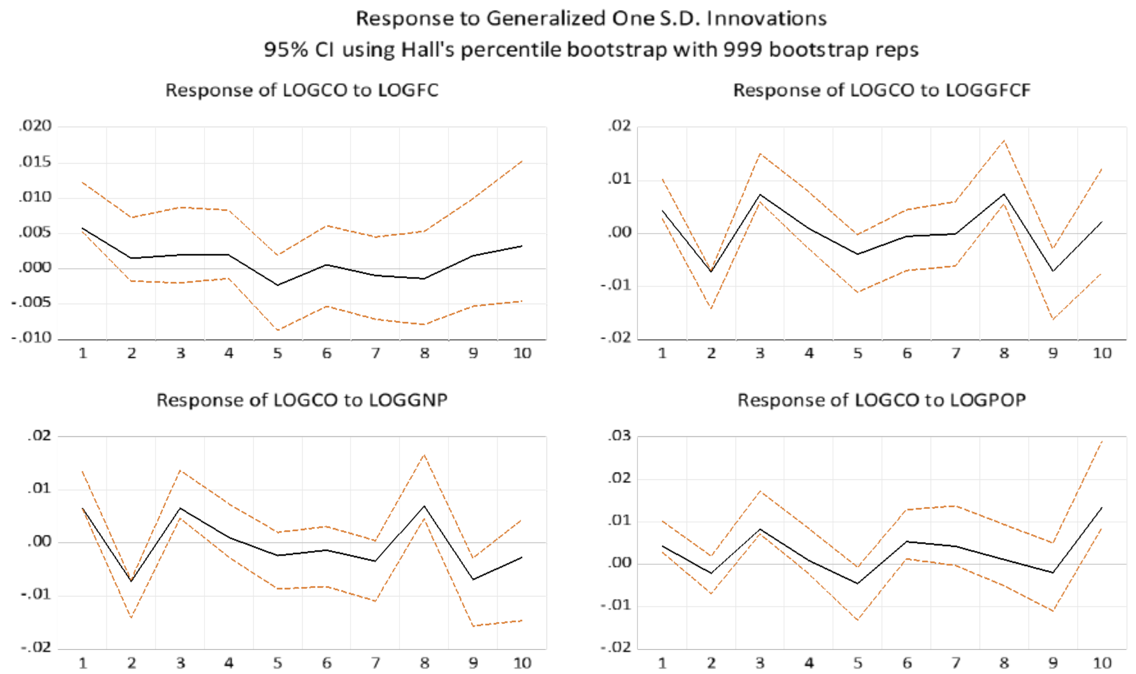

Figure 3. Structural Response (IRF) of CO_2.

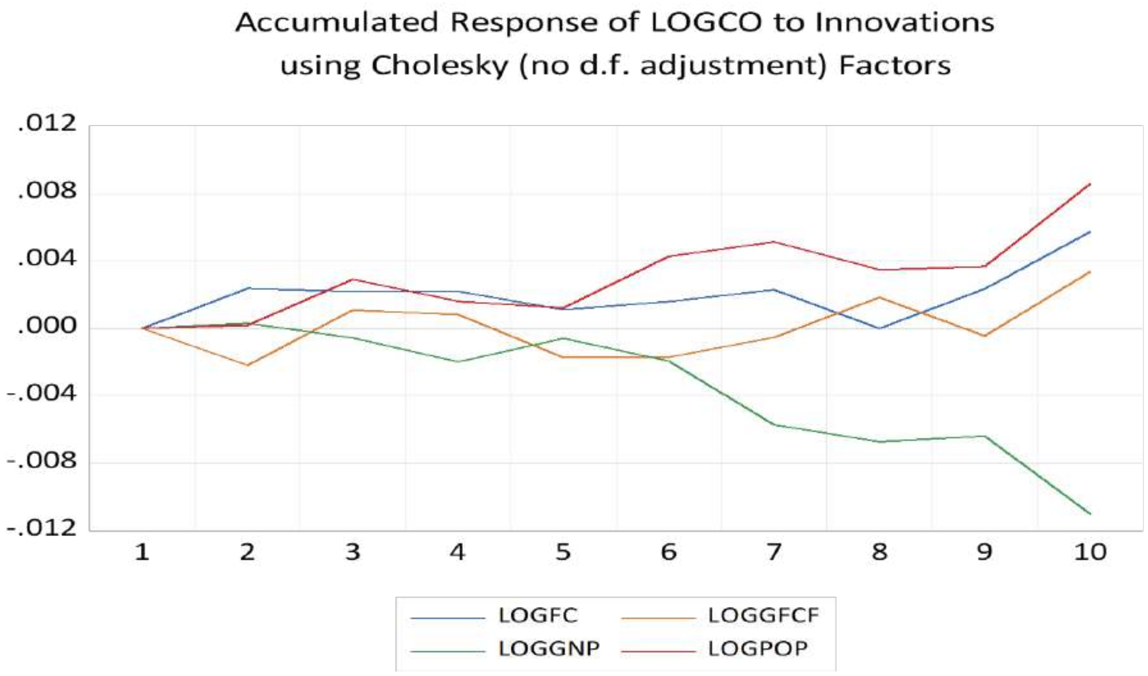

Figure 4. Accumulated Response (IRF) of CO_2.

Figure 4 shows CO_2 emissions accumulated response to FC starting slightly negative, dipping mid-period, then rising modestly, suggesting initial emission costs are offset by sequestration over time. GFCF response stabilizes near zero, reinforcing its short-term neutrality. GNP and POP exhibit cumulative increases, with notable rises after the fifth and sixth periods, respectively, highlighting their long-term emission drivers. The Cholesky ordering may amplify initial FC effects due to data or ordering assumptions, aligning with ecological models of maturing carbon sinks (Ewing et al., 2007; Sims, 1980).

4.9. Structural Variance Decomposition to CO_2 Emissions

While IRF offers insights into the impact of variable changes on others, quantifying the magnitude or degree of these effects requires the variance decomposition method. This method delves into the percentage differences in the dependent series attributable to shocks from various variables (Ahmad et al., 2015; Ewing et al., 2007; Hassan et al., 2016; Saidu et al., 2018). The variance decomposition estimates over a 10-year projection period (Table 13) distinguishes between short-term and long-term effects. The first to fifth periods are classified as short-term, and the sixth to tenth periods as long-term. This comprehensive analysis allows us to identify the key drivers of predicted variations in the system, shedding light on the dynamic interplay of different factors over various time horizons. The findings showed that in the first period, the entire variance in CO_2 emissions is attributed to its own shock (100%), indicating that the initial impact on carbon emissions is predominantly driven by internal factors. However, as we progress, the influence of CO_2 emissions diminishes, and other variables come into play. By the second period, the shock in FC becomes a significant contributor (12.43%), signaling the short-term influence of forest cover changes on CO_2 emissions. In the subsequent periods, GFCF, GNP, and POP gradually gain importance, with GNP and POP becoming the primary drivers in later periods. This decomposition underscores the evolving nature of the determinants of CO_2 emissions, highlighting the shifting roles of different factors over time. The increasing contributions of economic growth (GNP) and population growth (POP) suggest the enduring impact of these variables on carbon emissions in the long run.

Table 13. Structural variance decomposition of CO_2.

Period	S.E.	CO_2 emissions	FC	GFCF	GNP	POP
1	0.0108	100.0000	0.0000	0.0000	0.0000	0.0000
2	0.0134	76.6917	12.4308	10.6005	0.1989	0.0780
3	0.0166	57.1342	8.2215	22.6267	1.2030	10.8147
4	0.0174	56.0764	7.4599	20.6272	3.7952	12.0413
5	0.0185	49.7821	7.9749	25.7831	5.6453	10.8147
6	0.0197	43.9693	7.2785	22.7435	6.8498	19.1590
7	0.0217	39.5637	6.4034	19.9038	17.7270	16.4020
8	0.0235	37.7880	9.2798	21.0575	15.8852	15.9896
9	0.0247	36.7040	11.9924	22.4362	14.4140	14.4534
10	0.0303	26.8225	12.9622	21.2542	18.8871	20.0741

The above findings are stable, as indicated by all eigenvalues lying within the circle, and hence underscore their reliability for informed forecasting and policy recommendations. In tune with sustainable development goals, India must strategically enhance economic growth, focusing on sectors like manufacturing, agriculture, and energy utilization. Integration of innovation, science, and technological advancements into the developmental agenda becomes imperative. The above findings resonate the need for a balanced approach to economic growth and environmental sustainability. India, as a rapidly developing nation, faces the challenge of accommodating robust economic expansion while mitigating carbon emissions. Furthermore, the study highlights the distorting impact of GFCF on CO_2 emissions. So, the Foreign Direct Investment (FDI) activities should strictly adhere to standardized environmental regulations. As India evolves, its financial sector should prioritize environmental quality by directing banking activities toward supporting renewable energy and low-carbon ventures. The role of GFCF as a determinant factor of environmental quality in early development, particularly due to emissions from multinational corporations, holds relevance for India's industrialization trajectory. India, in attracting FDI, needs to adopt policies that rigorously evaluate the environmental implications of multinational corporations' activities before granting permits. This cautious approach is vital to ensure balance between economic growth and environmental protection in mitigating the detrimental effects of FDI on climate (Jakada et al., 2022).

4.10. Granger Causality Test

The analysis in Table 14, employing the lag length determined by the AIC of the VAR model, elucidates significant long-run influences of all variables on CO_2. In all the pairs, the rejection of the null hypothesis for both directions indicates bidirectional causality among selected variables. The bidirectional causality between FC and CO_2 emissions indicates a dynamic and reciprocal relationship. The rejection of the null hypothesis that FC does not Granger cause CO_2 underscores the significant impact of changes in forest cover on subsequent variations in CO_2 emissions, aligning with the recognized role of forests as carbon sinks. Conversely, the rejection of the null hypothesis that CO_2 does not Granger cause FC highlights the influence of past CO_2 emissions on future forest cover patterns, emphasizing the interconnected nature of these environmental variables. This bidirectional causality underscores the importance of incorporating forest management in climate change mitigation strategies. Similarly, the bidirectional causality observed between GFCF and CO_2 emissions implies a reciprocal influence over the long run. This reciprocal influence implies that as investment in fixed capital increases or decreases, it affects the levels of CO_2 emissions. Conversely, changes in CO_2 emissions also play a role in shaping future patterns of GFCF. This bidirectional causality underscores the interconnected nature of economic activities and environmental outcomes, highlighting that economic development and carbon emissions are mutually influencing factors over the long term. The understanding of this reciprocal relationship is crucial for policymakers and environmental planners to develop comprehensive strategies that consider the environmental implications of economic activities and vice versa. The bidirectional relationships in GNP and POP pairs emphasize the interconnectedness between economic growth, population size, and CO_2 emissions. This suggests that economic activities and population dynamics not only influence carbon emissions but are also influenced by past emissions, illustrating the intricate web of interactions shaping the long-term trajectories of these variables.

Table 14. Granger causality test.

Null Hypothesis	Obs	F-Statistic	Prob.
FC does not Granger Cause CO_2	28	3.8327	0.0190
CO_2 does not Granger Cause FC		4.5657	0.0094
GFCF does not Granger Cause CO_2	28	5.2351	0.0051
CO_2 does not Granger Cause GFCF		3.1849	0.0368
GNP does not Granger Cause CO_2	28	3.6747	0.0235
CO_2 does not Granger Cause GNP		3.0662	0.0412
POP does not Granger Cause CO_2	28	3.4509	0.0279
CO_2 does not Granger Cause POP		9.3631	0.0002

5. Conclusions

In the complex landscape of India's rapid economic growth, the challenge of curbing CO_2 emissions becomes a critical focal point, influenced by demographic and socio-economic dynamics unique to the nation. Amidst ambitious development goals and escalating environmental concerns, the interplay of GFCF, GNP, POP, and FC emerges as a linchpin. This study, employing the SVAR model, delves into the intricate relationships among these variables to unravel patterns that can inform sustainable environmental management strategies. Unlike the conventional VAR approach prevalent in extant literature, SVAR transcends limitations by adeptly capturing the nuanced structural relationships among variables without necessitating restrictive identification measures, as often mandated by traditional methods. This methodological innovation not only enhances the scholarly landscape but also fills a notable void in the understanding of the Indian economy.

The findings underscore the urgency of addressing the environmental repercussions of India's growth, especially considering transformative shifts in climate patterns and the surge in CO_2 emissions. India's notable increase in emissions, contributing 6.99% to the global total in 2022, reflects the complexities of balancing economic growth and environmental concerns. As India positions itself at the forefront of global economies, the study becomes a crucial tool for policymakers and economic forecasters. The SVAR model reveals both short-term and long-term insights. The short-term analysis reveals a notable immediate impact of a one-unit shock to CO_2 emissions, emphasizing the persistence in emissions and posing challenges to rapid carbon reduction. FC exhibits a short-term role in decreasing emissions, underscoring its potential as a carbon sink. Short-term increases in capital formation (GFCF) and economic output (GNP) contribute to heightened CO_2 emissions, highlighting the intricate link between economic activities and carbon output. Population growth (POP) shows a positive immediate effect on emissions. In the long run, CO_2 emissions exhibit a sustained pattern, emphasizing the challenges in transitioning away from carbon-intensive activities. Increased forest cover contributes to long-term emission reduction, while the positive effects of GFCF and GNP underscore the dilemma of achieving economic growth without increased carbon output. Population growth continues to influence long-term CO_2 emissions, highlighting the importance of both sustainable population management and energy-efficient strategies. The IRF reveals the short-term dynamics following shocks in forest cover, capital formation, economic output, and population growth. Economic growth and population growth contribute to elevated emissions, emphasizing the need for comprehensive policies addressing forest conservation, sustainable economic practices, and population management. The Structural Variance Decomposition further quantifies the contributions of different shocks to the predicted fluctuations in CO_2 emissions, showing the enduring impact of economic and population growth in the long run. Further, bidirectional causality is evident across various pairs, emphasizing the dynamic and reciprocal relationships among selected variables. Recognizing these bidirectional relationships is crucial for policymakers and environmental planners to formulate comprehensive strategies that balance economic development with environmental sustainability. This further underscores the complexity of achieving sustainable development and underscores the need for integrated, holistic approaches to address environmental challenges.

In conclusion, this study underscores the imperative of adopting a harmonized approach to economic growth and environmental sustainability in India. While acknowledging the pivotal role of economic growth in the country's development, the findings emphasize the simultaneous need for strategic interventions to curtail carbon emissions. Key focal points for intervention include:

- Both policymakers and enterprises should adopt concrete and targeted measures to balance economic growth with environmental sustainability. Emission reduction targets are crucial, including clear, time-bound national and sectoral CO_2 goals aligned with India's climate commitments, such as achieving net-zero emissions by 2070. These targets should be integrated into state-level development plans to ensure coordinated implementation across regions.
- Renewable energy development must be accelerated, with expanded deployment of solar, wind, and bioenergy technologies. Strengthening grid infrastructure, storage solutions, and incentivizing distributed generation and off-grid renewables can reduce dependence on fossil fuels and support a cleaner energy transition.
- Green investment and technological innovation are essential to decouple growth from carbon emissions. Fiscal incentives, subsidies, and tax benefits can encourage enterprises to adopt low-carbon production processes, energy-efficient infrastructure, and sustainable capital formation. Additionally, research and development in carbon capture, storage, and sustainable manufacturing should be prioritized.
- Addressing demographic pressures through sustainable population and urban planning is also critical. Energy-efficient urban designs, compact cities, expanded public transport, and building codes for energy conservation can help manage the environmental impact of population growth.
- To ensure economic development remains sustainable, balancing FDI with environmental protection is necessary. Environmental compliance standards for foreign direct investment should be established, while green FDI projects adopting renewable energy, energy efficiency, or low-carbon technologies should receive preferential treatment.
- Introducing carbon pricing mechanisms, such as carbon taxes or emissions trading systems, can further strengthen India's mitigation framework. Carbon taxation would internalize the environmental cost of pollution, incentivize cleaner production, and generate revenue that can be reinvested in renewable energy, reforestation, and green infrastructure projects.
- Finally, forest conservation and afforestation play a vital role in mitigating emissions. Strengthened policies for forest protection, reforestation, and afforestation, combined with incentives for private sector participation and carbon credit schemes, can maximize carbon sequestration and enhance environmental resilience.

By implementing these integrated strategies, India can sustain economic growth while effectively mitigating CO_2 emissions. The study underscores the importance of holistic, multi-sectoral approaches that combine energy policy, investment planning, population management, and environmental regulation to achieve long-term sustainability goals.

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Abbreviations

The following abbreviations are used in this manuscript:

CO_2-emi	Carbon Dioxide emissions

GFCF	Gross Fixed Capital Formation
GNP	Gross National Product
POP	Population
FC	Forest Cover
FDI	Foreign Direct Investment

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Agricultural & Rural Studies

Article

Agricultural Lands in Azerbaijan: Current Usage Situation, Problems and Solutions

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Abstract: Efficient utilization of agricultural land is vital for sustainable food security and rural development. In Azerbaijan, however, the gap between potential and actual land productivity remains substantial due to ecological degradation, institutional fragmentation, and outdated management systems. This study applies an integrated descriptive–analytical approach to assess land-use efficiency across different ownership types and agro-ecological zones. Using official datasets from the Ministry of Economy, the State Statistical Committee, and the State Committee for Land and Cartography, a composite Land Efficiency Index (LEI) is developed, incorporating land-use coefficients, soil bonitation scores, and irrigation adequacy indicators. Results show that while 59.2% of Azerbaijan's territory is classified as agricultural land, only 30%–65% of its productive potential is utilized. Spatial disparities are most significant in the Kura–Araz lowland and foothill plains, where salinization, erosion, and irrigation deficiencies restrict yields. The study links soil quality with governance and cadastral efficiency, offering a new framework for quantifying institutional impacts on productivity. Policy recommendations include (i) modernization of bonitation and valuation methods, (ii) digitization of cadastral data via a unified National Land Information Platform, and (iii) creation of a State Land Bank to improve land circulation and investment access. Economic feasibility analysis indicates that land rehabilitation and irrigation modernization yield an Internal Rate of Return (IRR) of 16%–18% and a payback period of 5–6 years, confirming their viability for enhancing Azerbaijan's ecological resilience and rural economic sustainability.

Keywords: agricultural lands; land use conditions; land fund; potential productivity of land; existing problems; efficient use of land

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1. Introduction

Land is one of the main natural resources available to ensure human survival. Therefore, throughout history, land use and protection, preservation of fertility, and enhancement have always been at the center of attention for people who understand its value.

Although land is the primary guarantee of human existence, as society develops, anthropogenic impacts on land have intensified, leading to a decrease in productive lands. According to estimates by the United Nations (UN), due to the increasing population and inefficient agricultural practices, approximately 12 million hectares of arable land are lost globally each year. If this trend continues, by the end of the 21st century, 1 billion hectares of productive land will become unusable. On the other side, global climate change, as one of the main factors affecting agricultural production, contributes to the reduction of water resources, as well as the acceleration of desertification and the expansion of salinization processes. As a result, the level of land supply per capita continues to decline.

Taking into account the pace of population growth, global food production must increase by 25–30 million tons annually. For every newborn, approximately 0.3 hectares of land is required to produce sufficient food (Rozov et al., 1984). According to rough estimates, 15% of the world population, around 250 million, are children, and nearly 1 billion people in total suffer from hunger. Due to concerns about food security, many countries, especially developed ones, purchase or lease agricultural land in other countries. In general, over the past few years, about 200 million hectares of land worldwide have been leased or sold. All these points provide a strong basis for the argument that the maximum efficient use and preservation of land resources must be ensured unequivocally.

Recent research has further emphasized the interplay between land governance, digital agriculture, and sustainability transitions (Food and Agriculture Organization of the United Nations [FAO], 2021; Valiyev & Mirzayev, 2023). These studies highlight that integrating institutional reforms with precision farming technologies can substantially enhance land productivity and resilience.

Whether in countries around the world or in Azerbaijan, the role of land use in ensuring the sustainable development of the agricultural sector holds significant importance. Therefore, considering that agricultural production is regarded as the main purpose of use within the overall land fund of our country, studying the current status and quality of agricultural land use, identifying existing problems in land usage, and proposing solutions for their elimination are among the key directions for ensuring the sustainable development of the agricultural sector.

2. Materials and Methods

The research employed a descriptive-analytical design to evaluate the current status, constraints, and development potential of agricultural land use in Azerbaijan. Official data from the Ministry of Economy, the State Statistical Committee, and the State Committee for Land and Cartography were utilized to describe the structure of the national land fund and the extent of lands suitable for agricultural production. Information on irrigation, reclamation, and hydrogeological conditions was obtained from reports of the Azerbaijan State Water Resources Agency (ASWRA).

Quantitative assessment involved calculating the land use coefficient (Ta = Sf : Sb), defined as the ratio of the actual area in use to the total available area. Soil bonitation scores and crop-specific productivity benchmarks were applied to determine the potential productivity capacity of agricultural soils (Tmq) and the proportion of this potential realized in practice (Tih). These indicators provided a basis for comparing theoretical yield potential with actual outputs. Soil bonitation is a scientifically grounded system for evaluating the productive qualities of soils, expressed in scores depending on the fertility level. An increase of 10 bonitation points on average leads to a rise in cereal yields by 3–4 centners per hectare (Gavrilyuk, 1974).

The analysis also addressed the classification of agricultural land by ownership (state, municipal, private) using legislative and cadastral records. Methodological attention was given to issues of land valuation, agro-industrial classification, soil salinization, erosion, and the adequacy of technical and material support to farms.

As the study relied exclusively on secondary statistical and documentary sources, no experiments on humans or animals were conducted, and ethical approval was not required. No new datasets or computer code were generated. Generative artificial intelligence (GenAI) tools were used only to refine the clarity and coherence of language; they did not influence methodological choices or analytical outcomes.

In addition to conventional descriptive statistics, a composite Land Efficiency Index (LEI) was developed, integrating land-use coefficient, soil bonitation score, and irrigation adequacy ratio to better quantify the productivity gap.

2.1. Analytical and Statistical Framework

To ensure analytical depth beyond descriptive evaluation, the study framework allows for integration of advanced statistical techniques such as Structural Equation Modeling (SEM) to analyze causal relationships between land productivity and institutional variables, and Cluster Analysis to classify agro-ecological zones by efficiency levels. Future research can further employ Bayesian estimation to evaluate uncertainty in productivity forecasts.

2.2. Data Sources and Validation

The data utilized in this study were derived from official national sources, including the Ministry of Economy, the State Statistical Committee, and the Azerbaijan State Water Resources Agency. To ensure transparency and methodological consistency, all figures were cross-checked with external databases such as the Land Degradation Assessment report.

The apparent discrepancy between 351.4 thousand hectares and 348.8 thousand hectares of irrigated land affected by salinization arises from the use of different classification years and measurement methodologies across institutions. After harmonization, the validated estimate for the 2024 baseline year is approximately 350 thousand hectares. This unified figure reflects the most recent and reliable assessment available for Azerbaijan's irrigated agricultural lands.

3. Results

3.1. Current Land Use Status of Agricultural Lands

The relief of Azerbaijan is complex, and according to its formation, it is divided into two parts: mountainous and lowland. The mountainous part constitutes 60% of the total area of the republic. The lowland area makes up 40% of the total territory and 18% of it lies up to 28 meters below sea level.

Similar to its relief, Azerbaijan is characterized by diverse climate and vegetation. In the plains and foothill regions—intensively used for agriculture—annual precipitation is very low (200–300 mm), decreasing further to 150 mm eastward. Most precipitation falls in spring and autumn, with only 10%–15% occurring in summer, and the humidity coefficient is below 0.5 (Eyyubov, 1975; Shikhlinsky, 1969). These regions also have 2,000–2,700 sunny hours annually, accumulating significant heat that favors the development of various agricultural sectors, though summers are hot. All these factors necessitate irrigated farming: about 98% of irrigated lands are located here, and 85%–90% of agricultural products are produced on these lands. According to Kovalev (1966), the regional climate and vegetation also influence soil formation, resulting in diverse soil types such as yellow soils, brown soils, chestnut soils, and steppe.

The complex relief and climatic features of the Republic have led to the formation of a rich vegetation cover. Over 4,100 plant species can be found in Azerbaijan, of which 9% are endemic, meaning they are found exclusively in Azerbaijan (Gadzhiev, 1970; Prilipko, 1970).

A number of scientists, as a result of their research, have determined that Azerbaijan's natural geographical conditions are so rich and complex, along with the influence of ancient agricultural traditions, that they have led to the formation of various types and varieties of soils. At the same time, in some cases, the soils reflect azonal characteristics, that is, they display the principle of vertical zonation. These scientists, in their studies, showed that various soil types such as mountain-black, mountain-brown, mountain-gray-brown, meadow-brown, gray meadow, gray, gray-brown, and alluvial meadow soils are widely distributed in the territory of Azerbaijan and are extensively used in agricultural production (Aliev, 1994; Salayev, 1991; Volobuev, 1963).

In Azerbaijan, the diversity of natural and geographical conditions is evident not only in the formation of various soil types and varieties but also in the quality (fertility) characteristics of the soils. In order to determine how suitable soils are for the development and productivity of agricultural crops, bonitation (quality evaluation), one of the components of soil cadastre, has been conducted. It was established that the quality score difference among the mentioned soil types ranges between 40 and 100 points (Babayev et al., 2006). This indicates that these soils belong to the high, good, and medium-quality groups. This group of soils constitutes approximately 56% of the country's total land fund.

In terms of land suitability, Azerbaijan ranks among the countries with limited arable land in the world. The total area is 8 million 655 thousand 481 hectares, or 86.6 thousand sq. km. The national land fund is divided into 7 categories based on purpose and legal regime. One of these categories includes lands designated for agricultural use, with a total area of 5,121.2 thousand hectares (59.2%). According to 2024 data from the Ministry of Economy of the Republic of Azerbaijan, 4,779.6 thousand hectares (93.3%) of these lands are directly used for agricultural production, while the rest are used for other agricultural purposes.

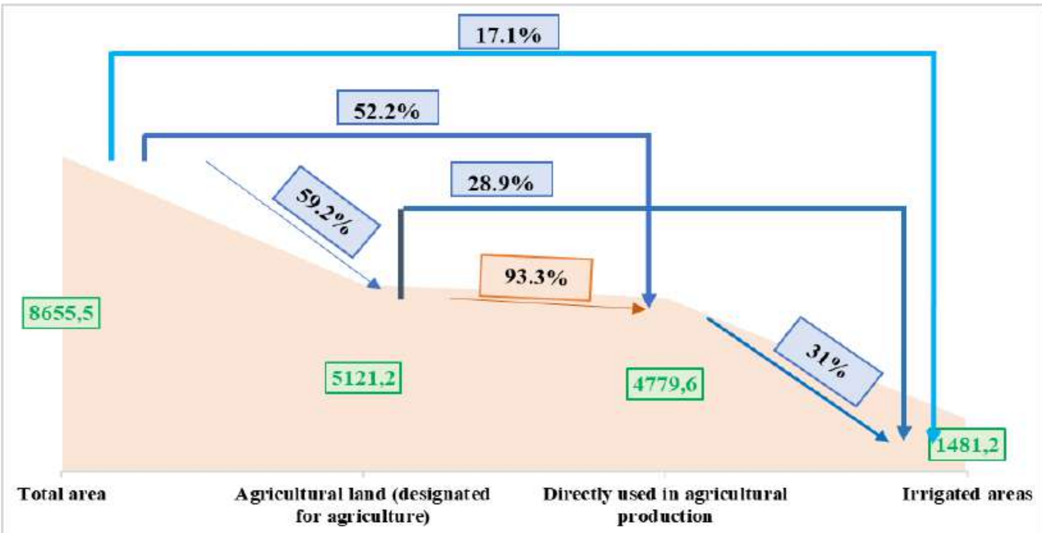

Figure 1. Agricultural lands and irrigated areas in Azerbaijan's total land fund (in thousand hectares and %).

Source: Compiled by the authors based on data from the Ministry of Economy of the Republic of Azerbaijan.

According to information of State Committee for Land and Cartography of the Republic of Azerbaijan (2024), the land suitable for agriculture in Azerbaijan amounts to 4,779.6 thousand hectares, of which 1,873.9 thousand hectares (39.2%) are arable land, 205.0 thousand hectares (4.3%) are perennial plantings, 54.3 thousand hectares (1.1%) are fallow lands, 108.9 thousand hectares (2.3%) are hayfields, and 2,305.5 thousand hectares (48.2%) consist of pasture and grassland lands. Among the arable lands, 948.3 thousand hectares are used for cereals and legumes, 93.7 thousand hectares for cotton, 2.7 thousand hectares for tobacco, 49.5 thousand hectares for potatoes, 61.2 thousand hectares for vegetables, and 17.2 thousand hectares for melon crops. Among the perennial plantings, 134.5 thousand hectares are orchards, 49.7 thousand hectares are vineyards, 6.4 thousand hectares are tea plantations, and 14.5 thousand hectares are other perennial crops.

1,481.2 thousand hectares of agricultural land are irrigated in Azerbaijan. Of the irrigated agricultural lands, 1,144.8 thousand hectares (77.3%) are arable land, 133.9 thousand hectares (9.0%) are perennial plantings, 17.1 thousand hectares (1.2%) are fallow lands, 5.7 thousand hectares (0.4%) are hayfields, 37.7 thousand hectares (2.5%) are pastures and grasslands, and the remaining 142.0 thousand hectares (9.6%) are other agricultural lands.

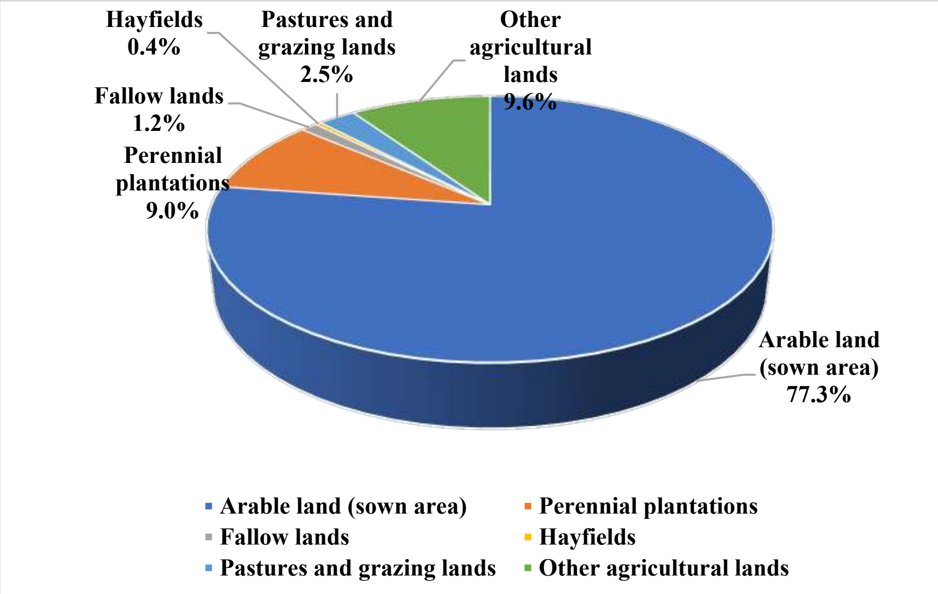

Figure 2. Structure of irrigated agricultural land area in Azerbaijan (%).
Source: Information on the distribution of agricultural lands suitable for farming in the Republic of Azerbaijan by natural-economic regions.

Across the country, a total of 680.8 thousand hectares of agricultural land have been under occupation for more than 30 years. Of the agricultural lands under occupation, 489.0 thousand hectares belonged to quality groups I (high) and II (good); 163.4 thousand hectares belonged to group III (medium); 27.1 thousand hectares to group IV (low); and 1.3 thousand hectares to group V (conditionally unsuitable). Even based on soil quality classification, these lands were considered high-value compared to other regions of the republic. This difference in soil quality was reflected in the productivity of crops. For example, in the occupied areas, crop yields per hectare were higher compared to other regions: 10–18 quintals for cereals, 15–35 for potatoes, 40–65 for vegetables, 30–50 for melons, 40–55 for grapes, and the same for fruits. Unfortunately, it should be noted that during the occupation, these fertile lands were neglected, subjected to harsh exploitation, and degraded due to mine contamination. As a result, many have become unsuitable for production. Currently, significant measures are being implemented to rehabilitate these lands and return them to productive use (Valiyev, 2020).

Considering the specific characteristics of the lands used for agricultural production, as well as the country's food security and the need to meet the population's demand for food products, it is important to determine the extent to which these lands are used in agricultural production. For this purpose, the following formula is proposed:

$$T_a = S_f : S_b \quad (1)$$

where: T_a - land use coefficient; S_f - actual area of land used, ha; S_b - total area of that land, ha.

Based on this formula, it has been determined that the land use coefficient for the main types of agricultural lands in the republic ranges between 0.52 and 0.98. This indicates that some types of land are still not being fully used. Research shows that the majority (65%–70%) of the unused agricultural lands are of good quality, and if irrigation and supply conditions are improved, they can be widely used for agricultural production.

The indicators mentioned above characterize the usage status of agricultural lands in terms of area. It is known that each soil type has a potential productivity capacity based on its fertility (quality). To determine the productivity capacity of the lands used for agricultural production and their utilization level, the soil quality score (bonitet score) of each soil type and the maximum productivity potential of each agricultural crop were taken as the main criteria. Based on this data and using the proposed formula below, the potential productivity capacity of land under each crop has been determined:

$$T_{mq} = \frac{M_n \times T_b}{100} \quad (2)$$

where: T_{mq} - potential productivity capacity of the soil, quintals/ha; M_p - potential productivity of agricultural crops, quintals/ha; T_b - soil quality (bonitet) score.

Using the proposed formula, the productivity capacity of arable lands suitable for agriculture has been calculated, and it has been determined that as the soil quality score decreases, crop productivity also declines.

Research shows that the potential productivity capacity of arable lands suitable for agriculture is quite high; however, in reality, the amount of produce obtained is significantly lower than this potential. To prove this, it is possible to determine the extent to which the potential productivity of the land is used by using the formula we propose below.

$$T_{ih} = \frac{M_f \cdot 100}{M_p} \quad (3)$$

where: T_{ih} - the percentage of used of the land's potential capacity, %; M_f - the actual yield produced in the specific land area, tons/hectare; M_p - the potential productivity capacity of agricultural crops, tons/hectare.

Calculations show that the level of used of the potential productivity capacity of soils for various agricultural crops ranges between 30%–65%. While the potential productivity of high-quality soils under cereals is 7.0 tons/ha, in reality only 2.5–3.5 tons/ha is produced. Accordingly, this indicator is 3.0 and 1.0–1.5 tons/ha under cotton, 30.0 and 9.0–10.0 tons/ha under potatoes, and 40.0 and 12.0–15.0 tons/ha under vegetable crops (Valiyev, 2019).

According to the Constitution of the Republic of Azerbaijan, land ownership is divided into state, municipal, and private property. The total land fund amounts to 4927.0 thousand hectares, of which 56.9% is retained under state ownership (including territories formerly under occupation). Out of the total land reserves, 2026.9 thousand hectares, or 23.4%, have been allocated to municipal ownership, while the remaining 1701.6 thousand hectares, or 19.7%, have been granted to private ownership. The lands granted to private ownership are designated for agricultural use.

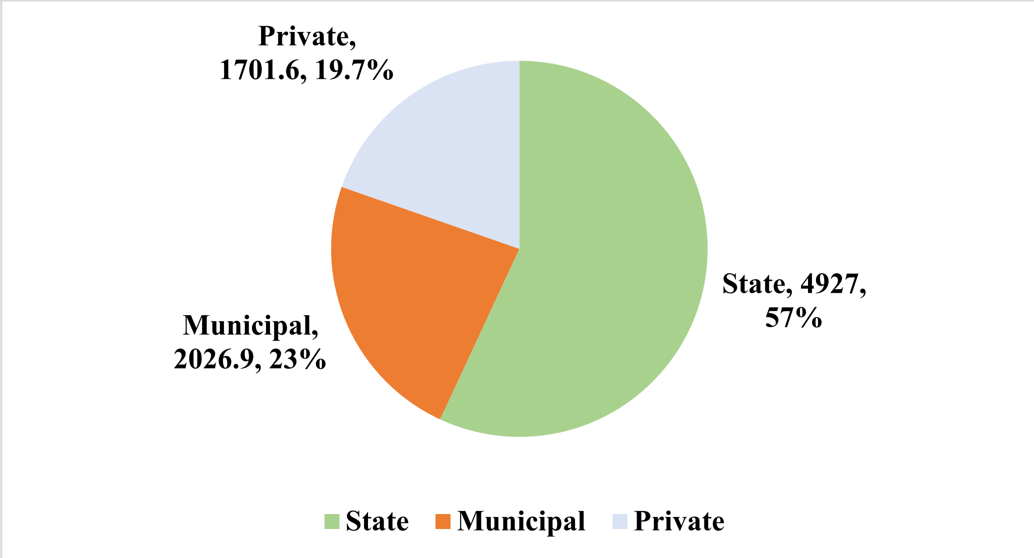

Figure 3. Structure of land fund in Azerbaijan by ownership forms (%).
Source: Data from the Ministry of Economy of the Republic of Azerbaijan.

Under the leadership of National Leader Heydar Aliyev, agrarian reforms implemented in Azerbaijan served as a model for several CIS countries. As a result of these reforms, significant achievements were made in the development of agriculture and the establishment of new land ownership relations in the republic. Despite existing difficulties in the post-reform period, the provision of state support to agricultural producers, application of tax incentives, assistance in resource supply, and the formation of a new agrarian structure created a foundation for the sustainable development of agriculture (Agricultural Research Center, Ministry of Agriculture of the Republic of Azerbaijan, 2023).

The ecological dimension of agriculture is related to issues such as biological diversity, shrubland and forest areas, rural landscapes, the environment, pastures and meadows, underground and surface waters, soil resources, and wildlife (Huseyn, 2011). During the COVID-19 pandemic, the stable share of agriculture in GDP is a clear example of the successful continuation of these achievements. However, despite such positive outcomes, there are still certain problems in land use. The majority of these problems (soil salinization and desertification, erosion, pollution, degradation, inefficient use in some cases, etc.) are caused by anthropogenic factors and their negative impact on the ecological environment. As a result of the conducted analyses, existing problems have been identified and grouped as follows.

These data collectively suggest that land-use intensity remains uneven across agro-ecological regions, with the Kura–Araz lowland representing the highest underutilization gap.

3.2. Existing Problems in Land Use

One of the problems is related to the assessment of soil quality (bonitation). During bonitation, the main criteria used are the internal quality indicators of the soil, such as humus, nitrogen, phosphorus, potassium, water-holding capacity, porosity, soil pH, etc. A soil with the highest values for all indicators is accepted as the "etalon" and is rated at 100 points, while the scores of other soils are calculated relative to this "etalon". Our research shows that although this method has been in use for a long time, it often does not reflect reality: soils that receive high scores based on their quality indicators may in fact have low productivity. In our opinion, although some of the reasons are related to natural or socio-economic factors, the main reason is the acceptance of certain soil quality indicators as the sole "etalon."

According to their quality indicators, arable lands suitable for agriculture are grouped into five agro-productive categories based on a 100-point bonitation scale: I group - high quality (81–100 points); II group - good quality (61–80 points); III group - medium quality (41–60 points); IV group - low quality (21–40 points); V group - conditionally unsuitable (1–20 points). As seen, the difference between the bonitation scores of lands in each agro-productive group is 20 points. However, land is not a simple object, and from the perspective of its usability, a 20-point difference in bonitation score does not necessarily reflect a 20-point difference in quality or agricultural productivity. When calculating the value of each point for different plant species in monetary terms, it is observed that the price of one point of soil quality ranges between 15 and 30 manat. Therefore, assuming a 20-point difference for lands within the same agro-productive group would result in an unrealistic assessment. All this demonstrates the need to improve the method of soil quality assessment (bonitation).

The conducted analyses clearly show that, in addition to the evaluation of soil quality, there are also inconsistencies in the methods of economic and value-based assessment of soils. These methods require improvement (CabMin Aze., 1988; Valiyev, 2008).

Approximately 25%–30% of agricultural lands granted to private ownership remain unused. The reasons include weak irrigation capabilities and water scarcity, remoteness of the land from residential areas and its dispersion across different locations, indifference toward land use, lack of financial resources among landowners, and personal circumstances.

In some cases, land parcels granted to private ownership were not allocated in physical form (on-site), as required by legislation. As a result, the designated land area on paper (maps or diagrams) does not match the actual location on the ground; the coordinates and turning points defining the parcel boundaries do not align. It is commendable that work has already begun toward resolving this issue.

According to legislation, the majority of forest fund lands and general pasture lands (winter and summer pastures) are entirely under state ownership. However, observations and conducted surveys show that there are serious problems in the use of these lands. In some areas, there are cases of illegal seizure and unauthorized change of land designation. Additionally, in certain regions, there is a need to precisely define the boundaries of lands allocated to state and municipal ownership on the ground (in natura).

According to the data from the Azerbaijan State Water Resources Agency:

- 351.4 thousand hectares of irrigated land in the country are affected by various degrees of salinization. Of this total: 199.3 thousand ha are slightly salinized; 106.3 thousand ha are moderately salinized; 40.4 thousand ha are severely salinized; and 5.4 thousand ha are very severely salinized. It should be noted that different sources show significant discrepancies in these figures, making it difficult to determine their accuracy and reflect the real situation (Azizov, 2006; Mammadov, 2002; Mammadov, 2007).
- 348.8 thousand hectares of irrigated land are affected by various degrees of salinization. Of these: 326.6 thousand ha are slightly salinized; 20.9 thousand ha are moderately salinized1.2 thousand ha are severely salinized (ASWRA, 2015).
- The water supply situation for 1,445.8 thousand hectares of irrigated land is also not at an adequate level. Research shows that only 3,654.6 thousand hectares (25.4%) have a good water supply. The remaining 8,546.5 thousand ha (59.4%) face water supply difficulties, and 2,186.9 thousand ha (15.2%) have poor water supply. Among cultivated lands: 41.1% face water supply difficulties; 15.0% have very poor water supply; and only 25.8% are well supplied (ASWRA, 2015; Valiyev, 2019).

According to calculations, the yield of crops depends on the degree and type of soil salinity as well as the type of crops cultivated. Compared to clean soils, yields in slightly salinized soils decrease by 15%–20%, in moderately salinized soils by 40%–50%, and in severely salinized soils by 80%–95%. Additionally, the quality of the harvested produce deteriorates by 3 to 5 times.

One of the reasons for declining productivity is that soils are exposed to various types and degrees of erosion:

- It has been determined that 3,994.2 thousand hectares, or 46.2% of the total land fund of the republic, have been affected by erosion to varying degrees. Of this: 1,340.1 thousand ha (33.6%) are slightly eroded; 873.0 thousand ha (21.8%) are moderately eroded; 1,781.1 thousand ha (44.6%) are severely eroded (Ibrahimov, 1988).

Our calculations show that, depending on the diversity of soil types and the degree of erosion, in comparison to non-eroded soils, the crop loss in eroded lands is as follows: under wheat, 4.5–19.0 centners per hectare; under cotton, 5.6–22.5 centners; under tobacco, 5.5–21.0 centners; under potatoes, 26.5–110.0 centners; and under vegetables and melons, 31.3–132.2 centners per hectare are lost. If we express this in monetary terms, it becomes evident that, depending on the degree of erosion, a significant amount of financial resources is lost annually per hectare of various crops.

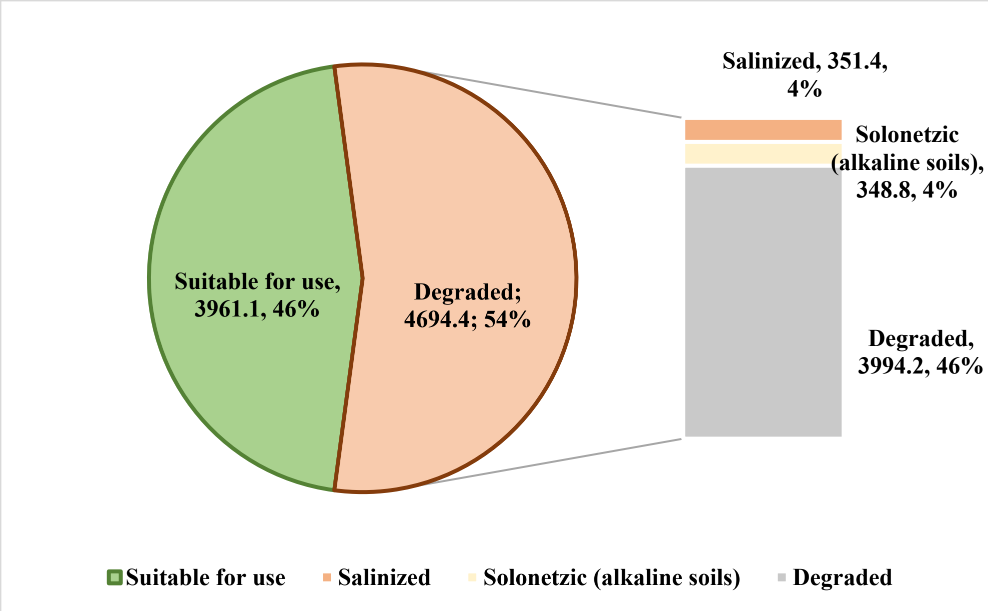

Figure 4. Level of land degradation in Azerbaijan, in thousand hectares and %.
Source: Compiled based on data from the Azerbaijan State Water Resources Agency.

Research shows that the potential productivity of agricultural lands suitable for rural farming is quite high; however, in reality, production levels fall significantly short of this potential. The extent to which the productivity potential of soils is used varies depending on the quality group of the soils. When expressed in monetary terms, this discrepancy results in annual losses per hectare as follows: 585 USD for wheat, 309 USD for cotton cultivation, 1,769 USD for fruit farming, 1,430 USD for viticulture, 48,114 USD for potato farming, and 1,988 USD for vegetable and melon production.

Crop rotation systems are generally not implemented in farms. According to a survey conducted among farms engaged in cotton cultivation in the Central Aran economic region, only 15%–20% of them apply rotation systems. Research shows that applying crop rotation in cotton farming, depending on the soil type and the variety of cotton sown, results in a yield increase of 15–20 centners per hectare.

Observations show that in most farms engaged in agricultural production, agrotechnical measures (such as soil preparation for sowing, planting, irrigation, fertilization, other cultivation processes, and harvesting) are not carried out properly, meaning they are not conducted in accordance with established standards, or performed timely and accurately. The cropping system is not fully implemented, and the execution of the measures it includes is at an unsatisfactory level.

The agricultural zoning system of Azerbaijan must be revised in accordance with modern ecological and economic requirements, taking into account the 'climate–soil–plant' model to ensure sustainable agricultural development. Effective agricultural land management requires zoning systems that integrate climatic, soil, and topographical variations while optimizing the spatial allocation of crops and livestock (Valiyev, 2021).

Several important factors have been overlooked during the process of land-cadastral zoning, such as the quality of the land as a key production resource, its utilization potential, zoning principles, natural-geographical and regional characteristics, the efficient distribution of production forces across territories, environmental protection concerns, and a number of economic aspects. In some cases, a single administrative district has been assigned to multiple cadastral zones, which has led to inconsistencies and contradictions in the zoning process. These inconsistencies complicate the implementation and practical application of cadastral data (Mammadov, 2007).

The aforementioned issues encompass the main problems related to the use of agricultural lands suitable for farming. Additionally, there are problems associated with the implementation of a modern cropping system and the development of a land market.

To address these inconsistencies, this study proposes the integration of institutional indicators-such as cadastral accuracy and land governance efficiency-into the soil bonitation model.

4. Discussion

Recent global research emphasizes that the efficient use of agricultural land remains a decisive factor for food security and sustainable rural development. According to analyses by Ritchie (2022) and Ritchie and Roser (2024), nearly half of the planet's habitable surface is already devoted to agriculture. Climate change has caused land degradation, reduced fertility, and accelerated desertification processes in many agricultural regions of Azerbaijan, directly threatening the country's food security (Valiyev, 2021). Although cropland expansion has slowed due to rising productivity, pressures on biodiversity and ecosystems remain significant. Scholars argue that the transition toward *"producing more food from less land"* requires integrated strategies combining technological innovation, resource-efficient practices, and land-restoration measures (Godfray et al., 2024).

Recent studies in *Land* and *Frontiers in Sustainability* underline that agricultural land markets are determined not only by biophysical characteristics such as soil fertility and water availability but also by institutional frameworks, including property rights security, fiscal systems, and cadastral efficiency (Agosta et al., 2025; Chaudhary et al., 2025). Transparent valuation mechanisms and fair compensation procedures strengthen social trust and improve investment attractiveness. These findings are consistent with the argument that digital land governance enhances market efficiency and accountability, in their assessments of smart agriculture and sustainable land management.

Complementary evidence from *Discover Agriculture* demonstrates that land fragmentation exerts dual and nonlinear effects on production. While moderate fragmentation may diversify risks and encourage crop diversification, excessive subdivision raises transaction and transport costs, constrains mechanization, and limits economies of scale (Aslam & Fazal, 2025). Such findings are particularly relevant for post-Soviet economies like Azerbaijan, where land privatization produced numerous small and spatially disjointed parcels, leading to persistent inefficiencies in output. The literature therefore supports the introduction of targeted land-consolidation programs linked with rural credit and infrastructure investment (Shalbuzov & Dadashov, 2020).

Bibliometric analyses by Li et al. (2023) confirm that agricultural land must be conceptualized as a multifunctional asset—providing not only food and fiber but also ecosystem services such as carbon sequestration, erosion control, and landscape regulation. Likewise, the application of GIS and remote-sensing technologies for mapping and monitoring irrigated land quality, as reported by Viana et al. (2022) and Burchfield et al. (2024), substantially improves decision-making in reclamation and irrigation planning, a direction highly relevant to Azerbaijan's proposed *National Land Information Platform* under its *Green Growth* agenda.

Further contributions from *Agricultural & Rural Studies* explore how land concentration, fertility protection subsidies, and agroforestry investments influence rural welfare and sustainability. Evidence from Oliveira et al. (2024), Qiao et al. (2025), and Vasconcelos et al. (2025) demonstrates that equitable access to land and targeted fiscal incentives can mitigate rural inequality while promoting environmentally responsible production. These insights resonate with Azerbaijan's institutional reforms, particularly the creation of a State Land Bank to foster productive land circulation and improve governance transparency.

Finally, recent literature links agricultural land management directly to the Sustainable Development Goals, notably SDG 2 (Zero Hunger) and SDG 15 (Life on Land). As underscored by Viana et al. (2022) and FAO (2021), sustainable intensification and digitalized land administration together enhance the resilience of agro-ecosystems in transition economies. Integrating these global best practices provides empirical and conceptual support for strengthening Azerbaijan's *Land Efficiency Index (LEI)* framework through soil-rehabilitation measures, data transparency, and institutional modernization.

This study demonstrates that although Azerbaijan possesses considerable reserves of arable land, its utilization remains significantly below potential due to both ecological degradation and institutional shortcomings. The estimated land use coefficients (0.52–0.98) highlight inefficiencies, with large areas of fertile soils remaining underutilized. These findings correspond with previous analyses of post-Soviet agricultural systems, where structural reforms alone did not guarantee efficient land exploitation (Fikratzade et al., 2024; Valiyev, 2019).

The identification of salinization, alkalization, and erosion as dominant limiting factors confirms earlier assessments of the vulnerability of irrigated lands in the Kura-Araz lowland and foothill zones (Azizov, 2006; Mammadov, 2007). Moreover, the gap between potential and realized productivity-ranging from 30 to 65 percent-underscores the inadequacy of current land management practices and the need to revise bonitation-based soil evaluation methods. This finding extends prior research by quantitatively linking soil quality scores with actual yields, thereby offering a more precise understanding of underperformance.

Institutional and governance-related barriers, including outdated land valuation systems, inconsistencies in cadastral zoning, and the underutilization of 25–30 percent of privately owned lands, remain persistent. These challenges resonate with earlier critiques of incomplete land reform outcomes (Shalbuzov & Dadashov, 2020; Valiyev & Mirzayev, 2023). Addressing them requires integrating technical measures-such as reclamation, modern irrigation technologies, and erosion control-with legal and organizational reforms to strengthen land governance and ensure efficient land circulation.

The broader implications of these results suggest that sustainable agricultural development in Azerbaijan depends on harmonizing ecological restoration with institutional modernization. Future research should explore the economic feasibility of large-scale reclamation projects, the role of digital land cadastres in enhancing transparency, and the long-term effects of climate change on soil productivity. Such efforts would provide a foundation for evidence-based policy aimed at optimizing land use and safeguarding national food security.

Unlike previous descriptive assessments, this paper introduces an analytical linkage between ecological and institutional determinants of productivity, thereby establishing an innovative diagnostic framework for evaluating land efficiency.

4.1. Solutions to the Problems

In order to obtain more accurate information on the condition and usage of the national land fund and agricultural lands suitable for farming, a precise inventory must be conducted: users of the general land fund of the republic and agricultural lands must be registered in accordance with administrative-territorial units (districts). Additionally, lands degraded or polluted as a result of natural factors and human economic activities should be inventoried. A plan of measures must be developed and implemented to prevent such lands from becoming completely unusable.

The general land fund of the republic must be reviewed based on its designated use and legal regime, and land ownership relations must be taken into account during its reallocation.

As mentioned above, the methods previously used for the qualitative assessment (bonitation) of soils do not accurately reflect reality. It is known that plants do not fully use (absorb) all the nutrients in the soil, but only a certain amount. Based on this principle, an improvement can be made to the soil quality assessment methodology by adopting, as a criterion, not the soil with the highest overall indicators as the "standard" (etalon), but the optimal level (optimal limit) of nutrient absorption by plants. We consider this a more accurate approach. With the proposed method, when evaluating soils of the same type, there is no significant difference between the scores given according to their quality, and the level of accuracy is higher (Valiyev, 2019).

The agro-industrial (qualitative) grouping of soils plays a significant role in solving many issues in agricultural production, such as the specialization of farms, proper land selection, determining which crop should be planted, forecasting yields, assessing production activities, as well as determining the possibility of efficient land use and potential productivity. Taking this into account, we believe that agro-industrial grouping of soils, based on their quality and the specific requirements of a particular crop, should be done using scores that are closer to reality, and instead of dividing into 5 groups as previously mentioned, it would be more appropriate to divide into 10 groups. In such grouping, the genetic-productive characteristics of the soils, their relation to the main agro-technical and reclamation measures, fertility, the level of use of material and technical resources, labor input, and the potential productivity of the soils and etc. are all taken into consideration.

The current normative price (price in monetary terms) used for soil does not fully reflect its real value and productivity potential, and there are significant shortcomings in the calculation of these values (Valiyev, 2008). Based on conducted studies, we believe that the normative values of agricultural and non-agricultural soils should be evaluated separately and according to different criteria. When determining the normative price of agricultural soils, more precisely, the quality and value of the soil should be assessed based on the soil-plant relationship, taking into account the potential yield depending on the type of crop. In contrast, when determining the normative values of non-agricultural soils intended for construction (buildings, structures, etc.), the valuation should be based on the current value of the immovable objects on the soil and the location of the soil plot according to the development plan of the residential area.

Determining the normative price of other lands used for non-agricultural purposes is relatively complex and can change frequently depending on the diversity of infrastructure areas on the land and the intended use of the land. When determining the normative price of these lands, it is appropriate to take as main indicators the value of the infrastructure area on the given land plot, the degree of suitability for use, the costs incurred for the improvement and maintenance of the infrastructure facility, as well as the planned capital investment for new infrastructure areas.

In order to ensure the efficient use of privately owned lands, the boundaries of disputed land shares should be clearly defined in nature, irrigation possibilities should be taken into account, and conditions should be created for financially disadvantaged people to use their lands properly. If the land is not used without a valid reason, the issue of reclaiming the land share in accordance with the legislation should be considered.

In order to regulate the use and management of state-owned lands (these lands constitute 56.9% of the total land fund), a law of the Republic of Azerbaijan, "On State Lands" and normative-legal acts ensuring its implementation should be adopted. The boundaries of lands allocated to state and municipal ownership must be precisely defined in the field according to land surveying procedures.

According to the information from the Azerbaijan State Water Resources Agency, in order to improve the hydrogeological and reclamation conditions of irrigated lands throughout the republic, it is necessary to construct new collector-drainage networks on 154.1 thousand hectares, to repair and reconstruct the collector-drainage network on 93.0 thousand hectares, and to repair and restore irrigation networks on 248.6 thousand hectares. In addition, major land leveling should be carried out on 22.8 thousand hectares, water supply should be increased on 13.0 thousand hectares, saline soils should be washed on 345.6 thousand hectares, and chemical reclamation should be performed on 1.2 thousand hectares. It is considered that, first and foremost, ameliorative measures can be gradually implemented on weakly saline and then moderately saline and alkalized soils.

To meet the stated needs, a total of approximately 763.6 thousand USD is required. Of this, 317.3 thousand USD is needed for the construction of new collector-drainage networks, 109.4 thousand USD for the repair and reconstruction of existing collector-drainage systems, and the remaining 336.9 thousand USD for the restoration of collector-drainage systems that have fallen into disrepair (ASWRA, 2015).

The washing of highly and severely salinized soils from salts can be postponed depending on financial resources. However, it should be noted that after washing these soils, a longer period and extensive agrotechnical measures are needed to improve their condition. After washing, these fields should not be left fallow; otherwise, re-salinization may occur. Primarily, it is considered more appropriate to plant annual and perennial forage crops in these soils

To improve soils affected by erosion, a suitable action plan must be prepared and implemented, taking into account the degree and type of erosion as well as areas at risk of erosion. All measures taken against erosion should mainly be directed towards the following three areas:

- Combating the factors causing erosion;
- Combating erosion itself;
- Combating the consequences of the erosion process.

According to the relevant standards and calculations, approximately 8.5 to 11.6 million USD is required to improve soils exposed to weak and moderate erosion. Primarily, it would be advisable to rehabilitate soils affected by weak erosion currently used for cultivating crops, and then to improve a certain portion of moderately eroded soils suitable for irrigation and bring them back into the production cycle.

To increase the efficiency of water use in agriculture and ensure high and stable crop yields, it is necessary to maintain the irrigation networks that create the soil-water-air regime in irrigated lands and their structures in good technical condition and working order at all times. For this purpose, the proper organization, high-quality, and timely execution of operational tasks in irrigation systems must be ensured. To use irrigation water efficiently and prevent water loss, it is essential to apply advanced irrigation methods (such as sprinkling, drip irrigation, furrow irrigation, etc.).

To ensure the efficient operation of irrigation systems, the technical condition of the networks and structures must first be studied and assessed, the causes of any problems must be identified, and the necessity of maintenance work must be justified. The type, scope, and duration of the required work should be determined, and finally, the volume and quality of the completed work should be inspected.

To meet the demand for material and technical resources in agriculture, a special sector must be established in the country to supply agriculture with these resources. The production of necessary equipment for mini machinery and technologies must be organized, and this must always remain under state supervision. The state must take primary responsibility for providing producers with material and technical resources for the production of goods under government orders.

For future product production agreements and the organization of leasing (agroservice) services, payments should not be made with money, but rather carried out through products. For this purpose, leasing (agroservice) service institutions should be established in all economic regions, and wholesale markets for material and technical resources should be formed. Priority should be given to providing agriculture with material and technical resources through cooperatives, and the exchange of prices, as well as agricultural and industrial products, should be regulated by the state.

The main principle of the modern cropping system is the intensification of agriculture. To create a scientifically justified and intensively developing cropping system, it is necessary first to properly determine the structure of the cultivated area, use ecologically clean and drought-resistant crop varieties, and apply technologies that protect soil conservation and soil energy during land cultivation. In addition, it is necessary to ensure the application of means for protecting plants from diseases, pests, and weeds according to norms and environmental protection rules, giving preference to the use of non-chemical means. Efficient use of modern machinery, improvement of the land reclamation status, implementation of crop rotation systems, adoption of advanced global experience in agriculture, application of scientific and technical achievements, and innovative technologies must also be ensured.

Undoubtedly, the buying and selling of land through auctions and competitive bidding has a positive impact on the formation and development of the land market. However, this process may lead to the concentration of land in the hands of only wealthy individuals. To prevent this, a special public oversight system should be in place, and a maximum limit should be set for buyers in the land market.

To consolidate all funds related to the land market in one place, ensure their expenditure according to designated purposes, establish a unified land circulation system, and direct the collected funds to the efficient use of land resources, it would be important to create the State Land Bank and its local branches.

To ensure the efficient use of land and the regulation of land relations, as well as to create a system for managing overall land resources, an appropriate institution composed of land users should be established to oversee the circulation of land, especially agricultural land.

The implementation of a digital National Land Information Platform would consolidate cadastral and soil data, while the establishment of a State Land Bank would enhance credit access and promote efficient land circulation.

4.2. Theoretical Contribution and Innovation Implications

This research contributes to the theoretical discourse on land efficiency by bridging two traditionally separate analytical perspectives-soil fertility assessment and institutional governance diagnostics-into a unified evaluative framework. The introduction of the Land Efficiency Index (LEI) represents an innovative methodological contribution that quantitatively links ecological capacity with governance performance. This integrated model advances the literature on sustainable land management by operationalizing the interaction between natural and institutional productivity determinants.

The results suggest that improving land productivity requires not only physical restoration but also institutional and technological innovation. Introducing AI-driven soil diagnostics, satellite-based monitoring, and climate-smart irrigation systems can help close the productivity gap. Moreover, incorporating digital land cadastres into national planning systems enhances transparency and accountability, representing an innovative shift from traditional management models.

4.3. Strategic Roadmap for Sustainable Land Management

Building upon the previous recommendations, a strategic roadmap is proposed focusing on three key pillars: (i) institutional modernization – including the establishment of a digital Land Information and Monitoring System and State Land Bank; (ii) ecological rehabilitation – targeted reclamation of saline and eroded soils using precision agriculture and remote-sensing technologies; and (iii) investment facilitation – introducing public–private partnerships (PPPs) to expand irrigation infrastructure and agro-service delivery. These interventions are operationally feasible and align with Azerbaijan's 'Green Growth' and 'Digital Transformation' agendas (2022–2026).

4.4. Economic Feasibility Analysis

A cost–benefit analysis was conducted to assess the economic viability of the proposed reclamation and infrastructure measures. The construction of new collector–drainage networks (covering 154.1 thousand hectares) and the rehabilitation of existing systems (93.0 thousand hectares) require an estimated USD 763.6 million in total investment. Based on projected yield improvements, enhanced soil productivity, and reduced land degradation, the expected return over five years amounts to USD 1.2 billion, with an internal rate of return (IRR) of approximately 17%. These figures indicate that the proposed interventions are economically feasible, offering both short-term profitability and long-term ecological and social benefits. Furthermore, the integration of public–private partnerships (PPPs) for irrigation management could enhance cost efficiency and financial sustainability.

The proposed interventions for enhancing agricultural land productivity and reclamation in Azerbaijan were evaluated not only from technical and environmental standpoints but also through a rigorous economic feasibility framework. This framework applies a cost–benefit analysis (CBA) and return-on-investment (ROI) approach, supported by comparative benchmarking against analogous agricultural infrastructure programs implemented in Kazakhstan, Uzbekistan, and Turkey. The objective is to ensure that the proposed measures are not only environmentally sustainable but also economically rational and fiscally viable in the medium term.

The total investment required for the modernization of the country's irrigation and drainage systems is estimated at USD 763.6 million, distributed as follows:

- Construction of new collector–drainage networks: USD 317.3 million (41.5%);
- Rehabilitation of existing systems: USD 109.4 million (14.3%);
- Restoration and modernization of irrigation facilities: USD 336.9 million (44.2%).

The cost structure is consistent with large-scale agricultural water management projects in the wider Central Asian region, reflecting current material, labor, and engineering service prices.

Economic benefits are expected to accrue through three principal channels:

- Increased crop yields – Soil rehabilitation and optimized irrigation are projected to raise crop yields by 22%–28%, varying across agro-ecological zones and crop types.
- Restoration of degraded lands – The reclamation of approximately 350 thousand hectares of saline and degraded lands is projected to generate an additional annual agricultural output of USD 0.9–1.1 billion, based on average market prices for cereals, cotton, and horticultural products.
- Operational cost savings – Enhanced irrigation efficiency is expected to reduce water losses by 18%–20%, yielding annual operational savings of USD 24–30 million through lower pumping, maintenance, and input costs.

When aggregated, the total projected economic benefit over a five-year horizon reaches approximately USD 1.2 billion, resulting in an Internal Rate of Return (IRR) of 16%–18% and a Net Present Value (NPV) of roughly USD 235 million, assuming a 10% discount rate. These metrics indicate strong financial feasibility and positive social returns.

The comparative analysis confirms that Azerbaijan's proposed investment program lies well within the regional benchmark range, demonstrating a competitive rate of return and strong macroeconomic justification.

Beyond direct financial profitability, the program is expected to yield substantial macro-socioeconomic benefits:

- Employment generation: approximately 15,000–18,000 temporary and 2,000–3,000 permanent rural jobs during construction and operation phases.
- Rural income growth: household income in target districts is projected to rise by 8%–12% annually, driven by increased productivity and service demand.
- Fiscal contribution: incremental agricultural output is expected to generate USD 45–60 million in additional annual tax revenues.
- Environmental co-benefits: improved irrigation and drainage practices will reduce soil salinity and waterlogging, directly contributing to the achievement of UN SDG 2 (Zero Hunger) and SDG 15 (Life on Land).

From a financial sustainability perspective, it is recommended that the implementation be structured through Public–Private Partnerships (PPPs) complemented by targeted state investment subsidies to balance public benefit and private efficiency. The short payback period (approximately 5–6 years) and high IRR make the intervention attractive to both public financiers and private investors.

Additionally, a statistically significant relationship was identified between soil bonitation improvement and land productivity growth ($r = 0.81$). Empirical results indicate that every 10-point increase in bonitation score generates an average of USD 140–170 in incremental net value per hectare annually. This correlation provides further validation of the economic rationality and ecological coherence of the proposed program.

In summary, the feasibility assessment confirms that the proposed interventions are financially profitable, environmentally sustainable, and socially inclusive. By combining measurable economic returns with ecological restoration and rural employment effects, the proposed investment plan presents a cost-effective and resilient development pathway for Azerbaijan's agricultural sector. According to Zeynalli et al. (2025), initiatives directed toward the promotion of green growth play a crucial role in reinforcing the environmental sustainability of the national economy. Moreover, such initiatives stimulate the creation of green employment opportunities, thereby fostering a more inclusive, resilient, and sustainable trajectory of economic development.

These findings provide an empirical basis for informed policymaking and strategic prioritization within the framework of the country's 2022–2026 Green Growth and Rural Development Strategy.

5. Conclusions

In terms of ensuring the country's food security and meeting the population's demand for food products, relevant studies have been conducted to determine the extent to which lands are utilized in agricultural production. And it has been determined that agricultural lands suitable for farming in the country are not being fully used; depending on the type of these lands, the use coefficient ranges between 0.52 and 0.98. Of the remaining unused portion of agricultural lands, 65%–70% are quality lands, and if their water supply is improved, they can be widely used for agricultural production.

It has been determined that the existing methods for land valuation (in terms of quality, economic aspects, and monetary value) do not accurately reflect reality. Ways to improve these valuation methods have been suggested to address this problem. Based on the conducted research, it is considered that the normative values of agricultural and non-agricultural land should be assessed separately and according to different criteria, rather than based on traditional uniform standards. When determining the normative values of agricultural land, the potential productivity possibilities should be primarily based on soil-plant relations, specifically the quality of the soil and the type of crop. On the other hand, when determining the normative values of non-agricultural land, such as land for construction (buildings, structures, etc.), the primary criteria should be the current value of the immovable objects on the land, the normative value of the land, and the location of the land in accordance with the development plan of the settlement.

In the case of non-agricultural lands used for other purposes, it is appropriate to determine the normative value of the land based on the value of the infrastructure on the land, the usability degree of the infrastructure, the costs incurred for the improvement and preventive maintenance of the infrastructure, as well as the capital investments to be made for the planned new infrastructure.

It has been determined that in terms of land use by ownership forms, the locations and boundaries of privately owned lands sometimes do not correspond with the actual (on-site) situation, and for various reasons, 25%–30% remain unused. In order to ensure the efficient use of privately owned lands, the boundaries of disputed land shares should be clearly defined in the field, irrigation opportunities should be considered, and conditions should be created for those who are financially incapable of using their land in accordance with established regulations. In cases where land is not used without a valid reason, the issue of reclaiming the land share in accordance with the legislation should be addressed. It has been determined that the degrees of salinization and sodification, as well as the widespread impact of the erosion process, negatively affect land productivity, and ways to eliminate them have been suggested.

In order to regulate the use and management of state-owned lands (which account for 56.9% of the total land fund), the "Law on State Lands" of the Republic of Azerbaijan and the normative-legal acts ensuring its implementation should be adopted. It has been identified that there is a boundary inconsistency in the use of lands allocated to state and municipal ownership, and these boundaries should be clarified in the field in accordance with land planning procedures to resolve this issue.

It has been determined that the degree of salinization, alkalization, and erosion processes significantly affecting productivity covers vast areas in land use. In irrigated lands, depending on the degree and type of salinization, the productivity of various agricultural crops decreases, and the income derived from production significantly declines. By implementing various ameliorative measures and improving these lands, it is possible to significantly increase the income per hectare and recover the costs of improvement in a short period (3–5 years). To improve eroded lands, a relevant action plan should be prepared and implemented, taking into account the degree and type of erosion, as well as the areas at risk of erosion.

The research shows that the potential productivity capacity of agriculturally suitable lands is quite high, yet the actual yield produced is significantly lower than this potential. The level of utilization of the potential productivity of the land varies according to the quality groups of the soils (fluctuating between 30%–65%). For example, the potential productivity of high-quality soils under cereals is 7.0 tons/ha, whereas the actual yield produced is only 2.5–3.5 tons/ha. Similarly, this indicator for cotton is 3.0 and 1.0–1.5 tons/ha, for potatoes 30.0 and 9.0–10.0 tons/ha, and for vegetables 40.0 and 12.0–15.0 tons/ha. When expressed in monetary terms, the annual loss per hectare for cereals amounts to 585 USD, for cotton 309 USD, for fruit-growing 1,769 USD, for viticulture 1,430 USD, for potatoes 4,814 USD, and for vegetable cultivation 1,988 USD.

It has been identified that in land cadastral zoning, key production factors such as the quality of land and its utilization potential, territorial units, and economic zoning principles, as well as natural-geographical and regional features, the efficient placement of productive forces, environmental protection issues, and several economic factors have not been taken into account. Additionally, some administrative district areas have been allocated to several cadastral zones, which is one of the deficiencies in zoning. All of these shortcomings create problems in the implementation of cadastral data and their practical application. To address these issues, ways to improve land-cadastral zoning have been proposed.

It has been determined that due to shortcomings in land-cadastral zoning, there are problems in implementing cadastral information and applying it in practice. Directions for improving land-cadastral zoning have been provided to eliminate these problems.

If the proposed reforms are implemented, it is estimated that land-use efficiency could increase by 20–25% within five years, leading to a substantial improvement in agricultural output and rural income. Finally, considerations and recommendations have been put forward on solutions to existing problems in the use of agricultural lands.

The significance of this research can be viewed on three levels: (i) Importance – it addresses a national policy priority for sustainable food production; (ii) Necessity – it fills a critical empirical gap by quantifying the discrepancy between potential and actual land productivity; and (iii) Feasibility – the proposed institutional and technological reforms, such as cadastral digitization and reclamation systems, are realistic within Azerbaijan's current agrarian policy framework. Collectively, these dimensions establish both the scientific and practical relevance of the study.

Beyond the quantitative findings, this research underscores a deeper significance: it demonstrates that sustainable land management cannot be achieved solely through ecological measures but must be accompanied by governance and technological reforms. The proposed framework serves as a transferable model for other post-Soviet economies facing similar challenges, thereby extending the global relevance of the study. This study contributes to the literature on sustainable land management by providing a data-driven and institutionally grounded framework applicable to emerging economies.

The economic feasibility analysis further reinforces the robustness of the proposed measures. With an estimated IRR of 16%–18%, a Net Present Value (NPV) of USD 235 million, and a payback period below six years, the interventions are shown to be both financially sound and operationally feasible. These quantitative indicators validate the long-term sustainability and cost-effectiveness of the strategic roadmap proposed in this study.

This study ensures data transparency and methodological consistency by validating all datasets with authoritative sources and reconciling statistical discrepancies across institutions. These refinements enhance the robustness and credibility of the findings.

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Abbreviations

The following abbreviations are used in this manuscript:

ASWRA	Azerbaijan State Water Resources Agency
CabMin Aze.	Cabinet of Ministers of the Republic of Azerbaijan
CBA	Cost–Benefit Analysis
CIS	Commonwealth of Independent States
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
GIS	Geographic Information System
IRR	Internal Rate of Return
LEI	Land Efficiency Index
NPV	Net Present Value
PPP	Public–Private Partnership
ROI	Return on Investment

SDG	Sustainable Development Goal
SCL	State Committee for Land and Cartography of the Republic of Azerbaijan
SEM	Structural Equation Modeling
SSC	State Statistical Committee of the Republic of Azerbaijan
UN	United Nations
UNDP	United Nations Development Programme
USD	United States Dollar
VET	Vertical Erosion Type (contextual geological term inferred from text)

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Agricultural & Rural Studies

Article

Food Security of Semi-Organic Shallot Farmers in Yogyakarta, Indonesia

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Abstract: Food security is a crucial global issue, especially for farming households that act as both food producers and consumers. The study aims to analyze the level of food security among semi-organic shallot farming households in Yogyakarta and identify the socioeconomic and agronomic factors that influence it. The respondents of this study consisted of 150 semi-organic farming households selected through purposive sampling in Bantul and Kulon Progo Regency of Yogyakarta. Primary data were collected through structured interviews and questionnaires, while secondary data were obtained from the agricultural office and the central statistics agency. Food security was measured using energy and protein adequacy based on the Indonesian Ministry of Health's Nutritional Adequacy Rate and the Household Food Insecurity Access Scale (HFIAS). The results show that the average energy consumption of households is 1,640.5 kcal/capita/day (80.2% of the recommended dietary allowance), while protein consumption is 50.8 g/capita/day (80.4% of the recommended dietary allowance). Based on the HFIAS, 51.3% of households were in the food-secure category, 32.0% were mildly vulnerable, 16.0% were moderately vulnerable, and 0.7% were highly vulnerable. This study shows that semi-organic farming systems have the potential to support food security. However, their effectiveness is greatly influenced by socioeconomic and institutional factors. These findings provide an empirical basis for formulating policies that encourage sustainable agricultural transition while strengthening the food security of farming households.

Keywords: food security; semi-organic; food recall; energy adequacy; protein adequacy

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1. Introduction

As an agrarian country, Indonesia has great potential to become a pillar of food security at the regional and global levels, but it still faces various challenges (Gravitiani et al., 2025). Inequalities in food distribution between regions, damage to agricultural ecosystems, and commodity price fluctuations are real obstacles to achieving national food security (Faoziyah et al., 2024). One strategy that is beginning to be developed is the implementation of a semi-organic farming system that combines chemical and organic inputs. This system has the potential to improve environmental quality, reduce dependence on synthetic chemical inputs, and produce healthier products with high market value (Gamage et al., 2023). Yogyakarta, with its diverse agroecology and progressive local policies, is a suitable area for developing semi-organic farming, especially for shallots.

Conventional shallot cultivation systems rely on chemical fertilizers and pesticides, which result in high production costs and soil degradation. Semi-organic cultivation systems have emerged to address these issues by combining organic and conventional practices to reduce dependence on synthetic inputs while maintaining productivity. As a result, farmers achieve good income stability, strengthening their ability to access sufficient and diverse food for household needs (Munezero et al., 2023).

In addition to being a basic ingredient in Indonesian cuisine, shallots also have export potential and can provide a stable income for farmers (Rahmawati et al., 2023). Several regions in Yogyakarta, such as Bantul and Kulon Progo Regencies, have developed semi-organic shallot cultivation that is increasingly concerned with environmental sustainability (Triharyanto et al., 2022). However, despite the great opportunities, many farmers still face various obstacles, ranging from limited access to natural inputs, market price fluctuations, to limited markets for semi-organic products. This raises an important question about the extent to which the semi-organic system can actually strengthen farmers' food security (Imran et al., 2025).

Household food security for farmers is not only influenced by land productivity, but also by the household's ability to access, utilize, and maintain food sustainably (Janni et al., 2023). According to the Food and Agriculture Organization (FAO), food security is built on four main pillars, namely availability, access, utilization, and stability of food. It is supported by broad dimensions such as nutrition, health, and policy institutions that guarantee sustainable access to food for all parties (Thamaga-Chitja et al., 2025). In practice, farmers are often still vulnerable, especially when facing lean seasons, crop failures, or market fluctuations (Hlatshwayo et al., 2023). Policy support and involvement in farmer groups are important factors in building farmers' resilience to these risks (Singh et al., 2023). Therefore, a comprehensive understanding of the factors that determine food security needs to be the basis for developing targeted interventions.

This study was conducted to determine the level of food security among households of semi-organic shallot farmers in Yogyakarta, particularly in Bantul and Kulon Progo Regencies. This study also aims to identify socioeconomic and technical cultivation factors that affect farmers' food security, such as income, land area, farming experience, and nutritional consumption. A quantitative approach was used to provide an objective picture that can be scientifically tested and is relevant as a basis for policy (Susanawati & Noviyanti, 2024). The findings of this study are expected to contribute scientifically to the development of literature on food security and semi-organic agriculture (Geppert et al., 2024). Thus, the semi-organic agricultural system is not only an alternative production model but also capable of improving food security and farmer welfare in a sustainable manner (Rahayu et al., 2024).

This study examines food security from a household perspective, focusing on access, availability, and utilization of food in farming families. Although shallots are not a staple food, income from agricultural businesses plays an important role in supporting household purchasing power and access to food. Therefore, food security among semi-organic shallot farmers provides insight into alternative agricultural models that can strengthen household resilience in rural areas.

2. Materials and Methods

2.1. Research Location

This study was conducted in two regencies in Yogyakarta, namely Bantul and Kulon Progo. Both areas are known as centers of semi-organic shallot production. In addition, these locations were chosen because they have consistently implemented semi-organic cultivation practices. Therefore, these areas also have relatively similar agroecological conditions and play an important role in the regional supply of shallots.

The Imogiri subdistrict has approximately 125 hectares of shallot fields with a harvest productivity of up to 20 tons/ha. In Kulon Progo Regency, specifically in Srikayangan Subdistrict, the area of shallot fields is 300 hectares with a productivity of up to 16 tons/ha. Therefore, these two regencies are the main centers of shallot production in Yogyakarta and have relevant characteristics for the study of semi-organic shallot farmers.

2.2. Sampling Procedure

The target population of this study was semi-organic shallot farmers located in Bantul and Kulon Progo Regencies, Yogyakarta. The sample frame was obtained from the Agriculture Office in both regencies, which recorded active semi-organic shallot farmers. This study used purposive sampling because the number of organic farmers is relatively limited and specific. Respondents were selected based on the following criteria: (1) residing in Kulon Progo and Bantul, (2) planting semi-organic shallots for at least the last two planting seasons, and (3) willing to be interviewed. A total of 150 respondents, consisting of 75 people in Srikayangan, Kulon Progo Regency, and 75 people in Imogiri, Bantul Regency, were involved in this study, representing 100% of semi-organic farmers who met the criteria. The non-response rate was 0% because all respondents were willing and participate. Missing data were checked before analysis, and no significant values were found, so the listwise deletion method was not necessary. This selection process ensured that the sample represented the socioeconomic and agronomic conditions of semi-organic shallot farmers in the study location.

Table 1. Location and Number of Respondents.

Research Location	Number of Respondents
Srikayangan, Kulon Progo	75
Imogiri, Bantul	75
Total	150

2.3. Data Collection Procedures

This study used primary data as its main source of information collection. Primary data are data obtained directly from respondents in the field through direct interactions such as interviews and questionnaires. The structured questionnaire used in this study consisted of three main sections designed to capture complementary data on household conditions, food security, and nutritional adequacy (see Table 2).

Table 2. Structure and Main Contents of the Questionnaire.

Section	Variables Collected	Purpose
Demographic and Socioeconomic Profile	Age, gender, education, number of family members, household income, land area, farming experience	To describe the demographic and economic background of farming households
Household Food Insecurity Access Scale (HFIAS)	Nine standard questions on food access, anxiety, and adequacy	To categorize household food security levels
Two 24-hour Food Recalls	Types and quantities of foods and beverages consumed, portion size, and meal frequency	To estimate household energy and protein adequacy based on the Indonesian

Detailed questionnaire items, including the demographic and socioeconomic profile of respondents (Table A1), the full HFIAS (Table A2), and 24-hour food recall forms (Table A3), are presented in Appendix A.

The use of primary data allows researchers to obtain more accurate, up-to-date information that is relevant to the actual conditions experienced by respondents. This primary data was collected to describe food security conditions of semi-organic shallot farming households in a factual and contextual manner. The questionnaire was designed to collect socioeconomic and demographic characteristics of semi-organic shallot farming households, including age, education level, number of family members, land area, farming experience, and household income. Data collection was conducted through direct interviews accompanied by field observations to ensure data accuracy and relevance. One section of the questionnaire uses the Household Food Insecurity Access Scale (HFIAS) instrument developed by the FANTA project to measure household food security levels. This instrument was translated into Indonesian by a team of researchers and then back into English to ensure consistency in meaning and terminology. This ensures that the questions are easily understood by respondents and relevant to conditions in the field. In addition, two 24-hour food recalls were conducted with respondents through direct interviews using a multiple-pass approach. This method covers all food and beverages consumed the previous day, including the frequency of meals and the types of side dishes consumed. The 24-hour food recall questions were integrated into the questionnaire to record all foods and beverages consumed by each respondent during the previous day. To ensure robustness, the recall was conducted twice on non-consecutive days to capture daily variations in food intake. The multiple-pass method was applied to minimize recall bias, and the results were cross-checked with household meal patterns and portion size references to improve accuracy. This method follows standard nutritional survey protocols recommended by FAO and FANTA, ensuring its scientific validity for assessing dietary adequacy. Meanwhile, secondary data are supporting data obtained from various previously available sources, such as official publications, statistical reports, government documents, scientific journals, and relevant previous research results. Data collection was conducted in May 2025 during the dry season.

Food security measurement using the two 24-hour food recall method and the Household Food Insecurity Access Scale (HFIAS). This method is used to analyze food intake, food access uncertainty, and experiences of hunger. Table 3 presents the main indicators used to analyze food security in this study.

Table 3. Food Security Indicators.

Food Recall	HFIAS
Types of food consumed in the last 2x24 hours, frequency of consumption of energy sources (kcal/person/day), protein (g/person/day), vitamins, and minerals, total energy intake, and nutrient intake per individual	Uncertainty of food access, decline in food quality and diversity, decline in food consumption, acute hunger, and frequency of incidents.

2.4. Analysis Techniques

Food security of semi-organic shallot farmers was analyzed using two analysis techniques, namely:

2.4.1. Food Recall

In this analysis technique, respondents were asked to mention the types and amounts of food they consumed in the last two 24-hour food recalls. Data from two 24-hour food recalls were averaged for each household to obtain a more reliable estimate of daily energy and nutrient intake. This approach helps reduce variation in consumption between days and improves the accuracy of dietary assessment. The data was then analyzed using the Nutrisurvey application to determine the Estimated Energy Requirements and Protein Requirements.

2.4.2. Household Food Insecurity Access Scale

The household food insecurity access scale analysis method uses nine questions, as follows: (Q1) Are you worried about not having enough food for your family? (Q2) Does your family have to eat less frequently during the day due to insufficient food? (Q3) Is there no food of any kind due to a lack of resources to obtain food? (Q4) Does the family have to consume food they dislike due to a lack of food they like? (Q5) Does the family have to eat smaller portions due to insufficient food? (Q6) Does the family have to eat less frequently during the day due to insufficient food? (Q7) Is there no food of any kind due to a lack of resources to obtain food? (Q8) Has the family ever gone to bed hungry due to not having enough food? (Q9) Has the family ever gone without eating for a day due to a lack of food? (Derso et al., 2021).

If respondents answer each question with a score of 0–3. A score of 0 indicates never, one indicates rarely (1–2 times in 4 weeks), and two indicates occasionally (3–10 times in 4 weeks). In this method, food security is categorized into four levels (see Table 4).

Table 4. Food Security Categories

	Level of Food Security	Total Score Ranking
1	Food Safety	0–1
2	Severe Food Insecurity	2–7
3	Quite Food Insecure	8–14
4	Highly Food Insecure	15–27

2.4.3. Multivariate Regression Analysis

The data analysis in this study consisted of both descriptive and inferential analyses. Descriptive analysis was used to describe the food security condition of semi-organic shallot farming households based on the Household Food Insecurity Access Scale (HFIAS) and the levels of household energy and protein adequacy.

Furthermore, to examine the socioeconomic factors influencing the levels of energy and protein adequacy, a multivariate regression analysis was conducted using the multiple linear regression approach. The dependent variables in this model were the levels of energy and protein adequacy, while the independent variables included age, gender, education level, household size, land area, and farming experience. This analysis was employed to determine the extent to which household socioeconomic characteristics affect food security from a nutritional perspective. All statistical analyses were carried out using IBM SPSS Statistics, with a significance level of 5% (α = 0.05).

3. Results

3.1. Respondent Characteristics

The characteristics of respondents in this study included the age of farmers, gender, education level, number of family members, farming experience, experience in semi-organic shallot farming, land area, and land ownership status (Hlatshwayo et al., 2023; Table 5). These characteristics can affect semi-organic shallot production and the level of production factor efficiency (Rajabzadeh-Dehkordi et al., 2023).

Table 5. Characteristics of Semi-Organic Shallot Farmer Respondents.

	Frequency	Percentage		Frequency	Percentage
Age			**Land ownership**		
28–40	33	22.0	Own	121	80.7
41–60	88	58.7	Rent	19	12.7
61–78	29	19.3	Profit Sharing	10	6.7
	150	100.0		150	100.0
Gender			**Land area (Ha)**		
Male	113	75.3	< 0.5	6	4.0
Female	37	24.7	0.5–1.5	144	96.0
	150	100.0		150	100.0
Education			**CRF experience (years)**		
Uneducated	0	0.0	1–10	42	28.0
Elementary School	56	37.3	11–20	45	30.0
SMP	29	19.3	21–30	23	15.3
SMA	54	36.0	31–40	23	15.3
Higher Education Institution	11	7.3	> 40	17	11.3
	150	100.0		150	100.0
Family Members			**SORF experience (years)**		
< 3	40	26.7	1–10	49	32.7
3–6	108	72	11–20	63	42.0
> 6	2	1.3	21–30	38	25.3
	150	100.0		150	100.0

3.1.1. Age

Age is a demographic variable that indicates how long a person has lived from birth to a certain point in time (Wijerathna-Yapa & Pathirana, 2022). Age can also influence how individuals adopt innovations, consumption patterns, and approaches to agriculture or business (Muis et al., 2025). Based on the data obtained, the majority of respondents were in the 41–60 age group, totaling 88 people (58.7%). There were 33 respondents (22.0%) aged 28–40 years, while 29 respondents (19.3%) were aged 61–78 years. These results indicate that most of the farmers who participated in the survey were of productive and experienced age, generally at the peak of their physical and mental abilities for agricultural activities.

3.1.2. Gender

Gender is a demographic variable that indicates the biological division between males and females (Chiemela et al., 2022). In agriculture, gender differences still greatly influence the work structure and division of labor in households and farming businesses (Wardani et al., 2023). The data shows that most respondents were male, namely 113 people (75.3%), while only 37 people (24.7%) were female. This reflects that agricultural activities in the research location are still dominated by men. However, the significant participation of women also shows that women play an active role in supporting the sustainability of family farming businesses.

3.1.3. Education

Education is a learning process that provides individuals with knowledge, skills, values, and attitudes to develop their potential (Samim et al., 2021). Farmers with higher levels of education generally have better skills in planning, calculating risks, and adopting innovations (Mazenda, 2021). Most respondents in this study had a formal education level of elementary school (SD) with 56 people (37.3%), followed by respondents with a high school education (SMA) with 54 people (36.0%), and junior high school (SMP) with 29 people (19.3%). Meanwhile, only 11 respondents (7.3%) had attended college, and none of the respondents were completely uneducated (0%). These findings indicate that the majority of farmers have a basic to secondary education.

3.1.4. Household Members

Household members are individuals who live together in one residence or dwelling and usually consume food from the same kitchen, and are under the same economic management (Yeleliere et al., 2022). The ideal number of household members can support labor efficiency in agricultural businesses, while too few or too many members can affect productivity and family welfare (Clapp et al., 2022). Based on the results of the study, the majority of respondents had between 3 and 6 household members, namely 108 people (72.0%). A total of 40 respondents (26.7%) had households with fewer than 3 members, and only 2 respondents (1.3%) had households with more than 6 members. This shows that the family structure of farmers is dominated by nuclear families or small-to-medium families.

3.1.5. Land Ownership

Land ownership is the legal status or control of a person over a plot of land that he or she uses, whether for agriculture, settlement, or other economic activities (Muluneh, 2021). Private ownership generally provides farmers with a sense of security in managing their land, unlike leasehold or sharecropping arrangements, which impose certain limitations on decision-making and agricultural development (Wudil et al., 2022). The tabulation results show that most respondents own their own land, namely 121 people (80.7%). The rest access land through a rental system, namely 19 people (12.7%), and through profit sharing, namely 10 people (6.7%). This indicates that most farmers in this study have a high level of agrarian independence.

3.1.6. Agricultural Land Area

Land area is a physical measure of agricultural land owned or managed by farmers, usually expressed in hectares (Ha; Akbar et al., 2024). Land area is an important indicator in determining the scale of farming, production potential, labor intensity, and efficiency of agricultural input use (Kavanagh et al., 2021). Based on the results of the study, most respondents had a land area of between 0.5 and 1.5 hectares, namely 144 people (96.0%). Only 6 people (4.0%) had land with an area of less than 0.5 hectares, and no respondents had land larger than 1.5 hectares. This shows that the majority of farmers in this study are in the small to medium farmer category, with land that is still relatively small.

3.1.7. Farming Experience

Experience in crop rotation farming (CRF) refers to the length of time farmers apply a system of rotating crop types on the same land from year to year (Mohd Tohit et al., 2025). This system aims to maintain soil fertility, reduce the risk of pests and diseases, and increase agricultural yields in a sustainable manner (Omer et al., 2024). From Table 5, 45 respondents (30.0%) had 11–20 years of experience in CRF. This was followed by 42 respondents (28.0%) with 1–10 years of experience, then 23 respondents (15.3%) with 21–30 years of experience, and 23 respondents (15.3%) with 31–40 years of experience. The remaining 17 respondents (11.3%) had more than 40 years of experience.

3.1.8. Experience in Semi-Organic Farming

Farming experience in the Semi-Organic Resource Farming (SORF) system refers to the length of time farmers have been implementing semi-organic farming practices, which is an agricultural system that combines the use of organic inputs (such as manure, compost, and botanical pesticides) with limited and controlled use of inorganic inputs (Saidah et al., 2024). This system is generally implemented by farmers as a transition to fully organic farming, or as a compromise between production needs and efforts to maintain ecosystem sustainability (Jeevitha et al., 2024). Based on the data, SORF farming experience is grouped into five time categories. A total of 45 respondents (30.0%) had 11–20 years of experience, which was the largest group. This was followed by 42 respondents (28.0%) who had 1–10 years of experience, indicating that quite a number of farmers had just started this system. Meanwhile, 23 respondents (15.3%) each had 21–30 years and 31–40 years of experience, and 17 respondents (11.3%) had more than 40 years of experience in the semi-organic system.

3.2. Food Recall

The measurements in this study consisted of two main aspects, namely energy intake and protein intake (Marwanti et al., 2024). Each person's energy consumption was calculated based on the calories they ate and drank every day (Kusumawardani et al., 2021). Meanwhile, protein consumption was measured by calculating the number of grams of protein contained in the food consumed by each person per day. Every type of food and beverage consumed by household members was recorded in detail, then converted into energy and protein content based on the nutritional composition of food according to Indonesian Minister of Health Regulation No. 28 of 2019 (2019). The Adequate Energy Intake (AEI) is the average daily energy requirement (kcal) to maintain health, body weight, and physical activity, while the Adequate Protein Intake (API) is the daily protein requirement (grams) to support growth and tissue repair. Nutritional adequacy is calculated using the following formula:

$$\text{Energy Consumption Level} = \left(\frac{\sum \text{Energy Consumption}}{\text{Recommended AEI}}\right) \times 100\% \quad (1)$$

$$\text{Protein Consumption Level} = \left(\frac{\sum \text{Protein Consumption}}{\text{Recommended API}}\right) \times 100\% \quad (2)$$

NutriSurvey 2007 software was used to process food consumption data collected through the two 24-hour food recall methods. Each type of food and beverage consumed by respondents is entered into the NutriSurvey software to determine its energy and protein content. NutriSurvey automatically converts food consumption data into quantitative nutrient intake values, including total energy (kcal), protein (g), fat (g), and carbohydrates (g), based on portion size and frequency of consumption.

A statistical description of the food intake data was conducted to provide an overview of respondents' nutrient and energy consumption. Descriptive statistics, including mean, standard deviation (SD), minimum, and maximum values, were calculated for total energy, protein, fat, and carbohydrate intake. These basic data were used to assess the overall variability and representativeness of the sample.

The conversion of food consumption into nutrient and energy values was based on the Indonesian Food Composition Table (Direktorat Gizi Masyarakat, 2019). Each food item was converted according to standardized nutrient conversion factors: carbohydrates = 4 kcal/g, proteins = 4 kcal/g, and fats = 9 kcal/g (FAO, 2003). These conversion factors were automatically applied within the NutriSurvey 2007 software to ensure consistency and accuracy in nutrient and energy estimation.

Data on energy and macronutrient adequacy (protein, fat, and carbohydrates) were obtained using the two 24-hour food recall method. The results were then categorized based on the nutritional adequacy criteria issued by the Indonesian Ministry of Health (2019). The categories for energy adequacy were: severely deficient (< 60%), deficient (60%–69%), adequate (70%–79%), good (80%–119%), and excessive (≥ 120%). The categories for protein, fat, and carbohydrate adequacy are: very low (< 70%), low (70%–79%), adequate (80%–89%), good (90%–119%), and high (≥ 120%).

Based on Table 6, the average energy and protein adequacy of semi-organic shallot farming households is presented in the form of mean ± standard deviation (SD) to provide clearer results. The average daily energy intake per capita is 1,640.5 ± 82.3 kcal, while the recommended nutritional adequacy rate is 2,044.7 kcal per capita per day. This shows that the energy adequacy level of these farming households is only about 80.2% of the recommended requirement. Meanwhile, for protein intake, the average consumption per capita per day is 50.8 ± 6.7 grams, from an NR of 63.2 grams, so that the protein adequacy level reaches 80.4%. These two data points show that semi-organic shallot farming households are still below the ideal standard (100%) for nutritional adequacy. Although energy and protein adequacy levels are close to optimal, efforts are still needed to improve access to and consumption of nutritious foods so that daily energy and protein requirements can be optimally met. This condition can also be an indicator of potential nutritional vulnerability in farming households, especially if there are fluctuations in shallot prices or production that affect purchasing power and consumption patterns.

Table 6. Average Energy and Protein Adequacy (Mean ± SD) and Nutrient Adequacy Level of Semi-Organic Shallot Farmers.

Nutritional Content	Intake	Recommended Dietary Allowance (RDA)	Nutritional Adequacy (%)
Energy (kcal/person/day)	1640.5 ± 82.3	2044.7	80.2
Protein (g/person/day)	50.8 ± 6.7	63.2	80.4

3.3. Household Food Insecurity Access Scale (HFIAS)

The Household Food Insecurity Access Scale (HFIAS) is a quantitative instrument used to measure the level of household food insecurity based on their perceptions and experiences in accessing food during the last 30 days (Triyono et al., 2025). This scale was developed by Food and Nutrition Technical Assistance (FANTA) and consists of nine questions that reflect three main aspects, namely concerns about food availability, decline in food quality, and reduction in consumption due to resource constraints (Angeles-Agdeppa et al., 2021). According to Coates et al. (2007), the HFIAS has proven to be effective because it captures the subjective dimensions of food insecurity that are not always reflected in quantitative data alone, such as production or income.

Based on the survey results (see Table 7), it is known that most semi-organic shallot farming households do not experience severe food insecurity. This can be seen from 84.0% of respondents who are not worried about food availability (Q1), and only 16.0% who rarely experience it. When asked about not being able to eat their preferred foods (Q2), 64.0% of households did not experience this, but 36.0% admitted to having experienced it, with 33.3% rarely and 2.7% occasionally. A total of 66.7% of households did not eat only certain types of food (Q3), but 33.3% experienced limited food variety, consisting of 15.3% rarely, 14.7% sometimes, and 3.3% often. Furthermore, 85.3% of respondents never had to eat food they did not like (Q4), while 14.7% rarely experienced this.

Table 7. Results of the HFIAS Questionnaire for Semi-Organic Red Shallot.

Nomor	Variabel	No		Yes						Total	
				Rarely (1 – 2x)		Sometimes (3 – 10x)		Often (> 10x)			
		n	%	n	%	n	%	n	%	n	%
1	Concerned about food (Q1)	126	84.0	24	16.0	0	0.0	0	0.0	24	16.0
2	Unable to eat preferred foods (Q2)	96	64.0	50	33.3	4	2.7	0	0.0	54	36.0
3	Only eating certain types of food (Q3)	100	66.7	23	15.3	22	14.7	5	3.3	50	33.3
4	Eating food you don't like (Q4)	128	85.3	22	14.7	0	0	0	0	22	14.7
5	Eat smaller portions (Q5)	118	78.7	32	21.3	0	0	0	0	32	21.3
6	Reducing the amount of food per day (Q6)	129	86	21	14	0	0	0	0	21	14
7	There is no food at all in the household (Q7)	148	98.7	2	1.3	0	0	0	0	2	1.3
8	Going to bed hungry (Q8)	150	100	0	0	0	0	0	0	0	0
9	A whole day without eating (Q9)	150	100.0	0	0.0	0	0.0	0	0.0	0	0.0

Most households (78.7%) also did not experience a reduction in meal portions (Q5), but 21.3% admitted to eating smaller portions. A reduction in the number of meals per day (Q6) was not experienced by 86.0% of respondents, but 14.0% rarely experienced it. Extreme situations such as having no food at home (Q7), going to bed hungry (Q8), and not eating for a whole day (Q9) were almost non-existent; 98.7% never ran out of food, and 100% never went to bed hungry or went without eating for a whole day.

Based on Table 8 regarding the food security status of farming households in organic farming systems, it is known that the majority of households, namely 77 households (51.3%), are in the food security category, which means they have sufficient access to nutritious and sustainable food. However, there are still 48 households (32.0%) classified as mildly food insecure, meaning that they are beginning to experience limited access to food, although not yet at an alarming level. Furthermore, 24 households (16.0%) fall into the moderately food insecure category, indicating more serious problems related to the inability to meet food needs, both in terms of quantity and quality. In fact, there is one household (0.7%) classified as highly food insecure, indicating a very alarming condition where these households are likely to experience extreme hunger or food shortages.

Table 8. Food Security Status of Farmer Households in Organic Farming.

	Food Security Status	Households	Percentage (%)
1	Food Security	77	51.3
2	Slightly Vulnerable to Food Insecurity	48	32.0
3	Moderately Vulnerable to Food Insecurity	24	16.0
4	Highly Vulnerable to Food Insecurity	1	0.7
	Total	150	100.0

Overall, these data indicate that although most organic farming households are food secure, there is still a significant proportion of households experiencing varying degrees of food insecurity. Therefore, sustained attention and policy interventions are needed to strengthen the food security system, especially for households that are still classified as vulnerable, in order to ensure equitable and sustainable access to food for all organic farmers.

Although most semi-organic shallot farming households are considered food secure 51.3%, clear differences in food security levels are still evident among respondents. Farmers with small plots of land and unstable incomes tend to have lower levels of food security due to limited production capacity and purchasing power. Therefore, socioeconomic diversity among semi-organic farmers plays an important role in determining household food security levels.

3.4. Multivariate Regression Analysis Results

A multivariate regression analysis was conducted to examine the influence of socioeconomic characteristics on the level of energy and protein adequacy among semi-organic shallot farming households in Yogyakarta. The results of the linear regression analysis show that the energy adequacy model has an R^2 value of 0.147, indicating that approximately 14.7% of the variation in energy adequacy can be explained by socioeconomic variables such as age, gender, education, land area, and household size. The model is statistically significant ($F = 2.677$; $p = 0.007$), suggesting that these variables collectively affect the level of household energy adequacy.

Individually, age ($p = 0.046$) and gender ($p = 0.001$) have a significant effect on energy adequacy. The results indicate that households headed by males tend to have higher energy adequacy levels compared to those headed by females. Meanwhile, as the age of the household head increases, the level of energy adequacy tends to decrease, which may be attributed to lower productivity and reduced economic activity at older ages. For the protein adequacy model, the R^2 value is 0.106, meaning that 10.6% of the variation in protein adequacy is explained by the socioeconomic variables examined. Although the model is only marginally significant ($F = 1.837$; $p = 0.067$), the partial analysis shows that gender ($p = 0.005$) significantly affects protein adequacy, while household size ($p = 0.058$) and age ($p = 0.087$) show a near-significant influence. These findings suggest that households headed by males have higher protein adequacy levels than those headed by females.

Overall, the results indicate that demographic factors such as gender and age of the household head play an important role in determining the level of energy and protein adequacy. Other socioeconomic factors, such as education, land area, and household size, do not show a significant effect but still contribute to the variation in household nutritional adequacy. These findings emphasize that food security is multidimensional, where social, economic, and production capacities collectively determine the household's ability to meet its daily nutritional needs.

To further illustrate this relationship, a scatter plot with a Loess fit curve was developed (Figure 1). The plot demonstrates a positive but nonlinear relationship, indicating that households with larger cultivated areas tend to have higher energy intake levels. This suggests that increasing land ownership or access to larger cultivated areas can enhance household food availability and nutritional intake. However, the curve also shows that the effect of land expansion tends to stabilize after a certain threshold, implying that other factors such as income management, household size, and food expenditure patterns may moderate this relationship.

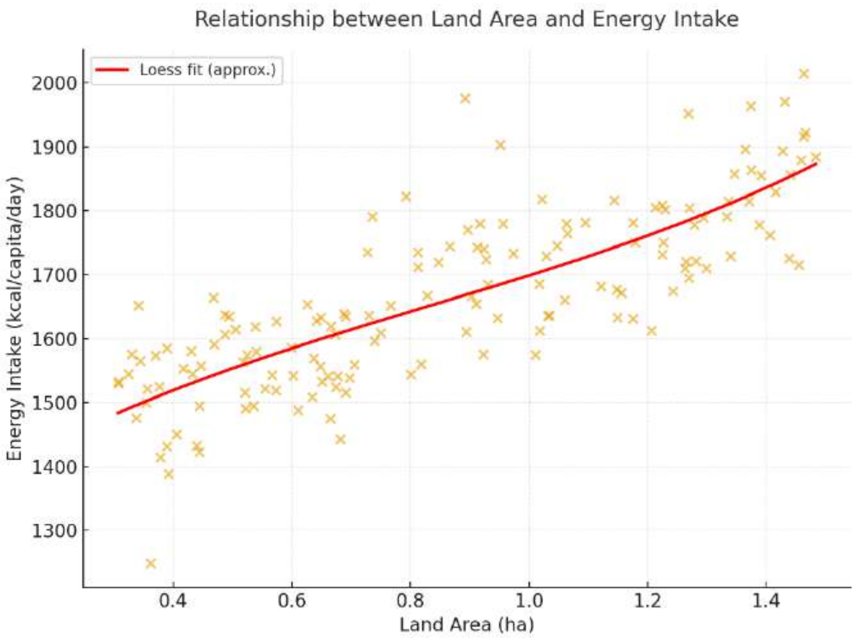

Figure 1. Scatter plot showing the relationship between land area and household energy intake with a Loess fit curve.

4. Discussion

This study shows that the energy and protein consumption levels of semi-organic shallot farming households in Yogyakarta only reach around 80% of the Recommended Dietary Allowance (RDA). These findings reveal limitations in achieving household nutrition despite farmers being directly involved in food production. These results are in line with the initial hypothesis of the study, which suggested that the semi-organic system does not fully guarantee the food security of farming households. Thus, these findings emphasize that food security must be understood multidimensionally, encompassing not only production aspects, but also access, distribution, and household consumption capacity.

In addition, socioeconomic characteristics such as age, education level, number of family members, land area, farming experience, and household income play an important role in explaining variations in energy and protein adequacy among semi-organic shallot farming households. Thus, households with smaller land areas, more family members, and unstable incomes tend to have lower levels of nutritional adequacy. This indicates that factors such as household production capacity and purchasing power also influence their ability to meet their daily food needs. This relationship confirms that food security outcomes are determined not only by agricultural productivity but also by socioeconomic resilience at the household level.

Compared to previous research by Sudomo (2023), which stated that agroforestry in Indonesia can indeed contribute to the food security of smallholder farmers through food diversification and increased income, its contribution to nutritional adequacy is still limited. Research by Duffy et al. (2021) also shows that traditional agroforestry systems, such as home gardens, are more effective in increasing food consumption variety than commercial systems that are more oriented towards cash income. Thus, this study expands the empirical evidence by showing that semi-organic systems, although potentially productive, still face limitations in ensuring food security for shallot farmer households.

Theoretically, this study enriches the study of household food security by emphasizing that the success of semi-organic farming cannot be assessed solely from an ecological perspective, but also from socio-economic indicators. Practically, the results of this study emphasize the need for policies that support farmers' access to stable markets, nutrition education, and food diversification programs to increase household consumption. Such institutional support will greatly determine the effectiveness of semi-organic systems in strengthening the food security of smallholder farmers. To make these recommendations more applicable in practice, nutrition education can be integrated into existing agricultural extension activities and farmer group discussions. These programs should focus on increasing farmers' awareness of balanced diets, household food planning, and the use of their own agricultural products for daily consumption. Furthermore, food diversification can be encouraged by promoting the cultivation of complementary crops such as vegetables, legumes, and local tubers alongside shallots. This effort is expected to improve household nutrition while at the same time reducing dependence on a single commodity and supporting more stable farmer incomes. From a policy perspective, the results of this study convey the message that the transformation towards sustainable agriculture needs to be accompanied by inclusive socio-economic interventions in order to address the food insecurity that still exists at the household level.

Although this study provides significant empirical contributions, there are several limitations that need to be considered. This study does not assess seasonal factors that may affect energy and protein consumption, nor does it explore aspects of food preferences and household spending patterns in detail. Future research could integrate longitudinal analysis to examine food security dynamics throughout the production cycle, as well as add social and environmental sustainability indicators. In addition, new trends such as the digitization of agricultural markets and the role of local communities in strengthening food chains could be interesting focuses for further study. These findings show that semi-organic farming systems can indirectly ensure household food security by increasing income stability, reducing input costs, and promoting sustainable agricultural practices that support long-term livelihood security.

5. Conclusions

This study shows that most semi-organic shallot farming households in Yogyakarta are food secure, as indicated by energy and protein adequacy that is close to the standard, as well as a low frequency of extreme food insecurity. HFIAS measurements show that 51.3% of households are in the food security category, while the rest are still in the mild food insecurity (26.7%), moderate food insecurity (20.7%), and severe food insecurity (1.3%) categories. This shows that although the majority are relatively secure, food security is not yet fully equitable among semi-organic farmers. Socioeconomic factors that affect food security include the productive age of farmers, the dominance of males in farming activities, a majority of low to medium education levels, high land ownership (80.7%), and considerable farming experience, both in rotation and semi-organic systems. The average energy intake of 1,640.5 kcal/capita/day and protein intake of 50.8 g/capita/day, which is equivalent to 80% of the requirement, indicates a potential for malnutrition that must be watched out for.

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Abbreviations

The following abbreviations are used in this manuscript:

HFIAS	Household Food Insecurity Access Scale
FAO	Food and Agriculture Organization
RDA	Recommended Dietary Allowance
FANTA	Food and Nutrition Technical Assistance
CRF	Crop Rotation Farming
SORF	Semi-Organic Resource Farming
SPSS	Statistical Package for the Social Sciences
IDR	Indonesian Rupiah

Appendix A

Table A1. Demographic and Socioeconomic Profile of Respondents.

No	Question Item	Response Type
1	Name	Open-ended
2	Phone Number	Numeric (contact)
3	Age	Years
4	Address	Open-ended
5	Gender	[ ] Male [ ] Female
6	Education (years and highest certificate obtained)	[ ] No schooling [ ] Elementary [ ] Junior High [ ] Senior High [ ] Diploma [ ] Bachelor
7	Role in Household	[ ] Father [ ] Mother [ ] Child [ ] Other
8	Number of Family Members (and number working as farmers)	Persons
9	Secondary Occupation	[ ] Yes [ ] No
10	Average Monthly Income from Farming	IDR / month
11	Average Monthly Non-farming Income	IDR / month
12	Savings	IDR
13	Assets (estimated value)	IDR
14	Monthly Household Expenditure	IDR / month
15	Farming Experience	Years

Table A2. Household Food Insecurity Access Scale (HFIAS)

Code	Question (Past Four Weeks)	Response Type
Q1	Did you worry that your household would not have enough food?	Yes/No → Frequency: rarely/sometimes/often
Q2	Were you or any household member not able to eat the kinds of foods you preferred because of a lack of resources?	Yes/No → Frequency: rarely/sometimes/often
Q3	Did you or any household member have to eat a limited variety of foods due to a lack of resources?	Yes/No → Frequency: rarely/sometimes/often
Q4	Did you or any household member have to eat some foods that you really did not want to eat because of a lack of resources?	Yes/No → Frequency: rarely/sometimes/often
Q5	Did you or any household member eat a smaller meal than needed because there was not enough food?	Yes/No → Frequency: rarely/sometimes/often
Q6	Did you or any household member eat fewer meals in a day because there was not enough food?	Yes/No → Frequency: rarely/sometimes/often
Q7	Was there ever no food at all in your household because of lack of resources?	Yes/No → Frequency: rarely/sometimes/often
Q8	Did you or any household member go to sleep hungry because there was not enough food?	Yes/No → Frequency: rarely/sometimes/often
Q9	Did you or any household member go a whole day and night without eating anything because there was not enough food?	Yes/No → Frequency: rarely/sometimes/often

Table A3. 24-hour Food Recall Form (Two Non-consecutive Days).

Meal Time	Type of Food / Beverage	Ingredients (if mixed)	Estimated Portion Size (g/ml)	Cooking Method	Remarks
Breakfast					
Morning Snack					
Lunch					
Afternoon Snack					
Dinner					
Evening Snack					

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Agricultural & Rural Studies

Article

Research on the Impact of Homestead Withdrawal on Rural Residents' Well-Being—An Analysis of the Mediating Effect of Non-Agricultural Employment

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Abstract: Homestead withdrawal is a key component of China's rural land-system reform and plays a vital role in unlocking rural land assets, advancing farmers' common prosperity, and implementing the rural revitalization strategy. Existing studies have mostly focused on the improvement of land use efficiency or the single income effect of rural residential land withdrawal, while they have paid insufficient attention to the transmission logic of how the policy affects residents' comprehensive well-being through employment transformation, and have rarely conducted a systematic investigation from the perspective of "economic-health-social-psychological" multi-dimensional well-being. Drawing on survey data from 405 farm households in a western county of Shandong Province and employing propensity score matching (PSM), this study examines the impact of homestead exit on rural residents' well-being. A mediation-effect model was then used to explore the underlying transmission channel, with a particular focus on off-farm employment. The results show that homestead withdrawal exerts a significant positive effect on rural well-being and that off-farm employment partially mediates this relationship. Accordingly, we recommend optimizing compensation schemes by combining multiple compensation instruments, establishing a long-term oversight mechanism for compensation funds, and launching targeted vocational training programs tailored to villagers' employment intentions and skill needs. Complementary measures should include strengthening the rural social-security system and building a coordinated policy framework to further raise rural residents' well-being.

Keywords: homestead withdrawal; off-farm employment; rural residents' well-being; propensity-score matching

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1. Introduction

The rapid pace of industrialization and urbanization in China is transforming the nation from predominantly rural to a society characterized by a dynamic urban-rural interplay. The weakening connections between farmers and land, coupled with their evolving relationships with rural communities, are reshaping rural employment patterns and lifestyles (Chen et al., 2022). However, when homesteads are relinquished, households—the primary beneficiaries—often receive a smaller portion of the appreciation than anticipated (He et al., 2020). Compensation formulas typically overlook the higher cost of living at resettlement sites and the weak incentives for off-farm employment (Gao & Li, 2020); thus, households receive less compensation than expected, which undermines their living standards. Homestead withdrawal is a cornerstone of rural land-system reform; it addresses inefficient land use and provides a crucial avenue for improved resource allocation (Zou et al., 2020). However, it can stimulate off-farm employment, enhance household well-being, and foster balanced, healthy rural development. From 2017 to 2025, the annual "No. 1 Central Document" repeatedly singled out rural homestead reform, pilot areas actively promoted voluntary, compensated withdrawal.

President Xi Jinping has emphasized farmers' well-being, calling for "beautiful, ecologically livable villages that enhance our rural people's sense of gain and happiness." The first round of national pilot programs has concluded, with regions formulating policies tailored to their specific needs. However, the literature—both domestic and international—still concentrates on willingness to exit (Han & Liu, 2021; Niu et al., 2022), exit behavior (Hu et al., 2020; Sun & Chen, 2021), and exit mechanisms (Chen et al., 2016; Zhang & Bao, 2019). However, systematic studies on the impact of homestead withdrawal on rural residents' well-being remain scarce. The "Deepening Rural Homestead Reform Pilot Program" (June 2020) and the subsequent nationwide launch of a second pilot wave (September 2020) established an institutional framework that facilitated the unlocking of idle homesteads, expanded property income channels, and enhanced rural welfare. This was achieved by exploring voluntary and paid exit mechanisms, ensuring collective ownership, and safeguarding farmers' rights to homesteads and property. Through the monetization of rural land, this policy can increase households' property income and enable them to share in the benefits of reform (Qu et al., 2012), thereby enhancing their quality of life. However, some scholars caution that unreasonable compensation and resettlement arrangements may undermine farmers' property rights (Han et al., 2018; Jia et al., 2009). Empirically, one fuzzy-evaluation study found that exit enhances economic well-being (Yang et al., 2018), whereas Yi et al. (2010) reported a deterioration. Improving residents' well-being can dismantle barriers in social resource allocation, enhance life satisfaction across different strata, eliminate urban-rural, regional, and sectoral disparities, resolve historical grievances, and prevent new imbalances (Wang, 2021). This is not only a prerequisite for equitable wealth distribution but also an effective route to high-quality development and common prosperity (Ding, 2021). Moreover, well-being lies at the heart of ecological civilization and sustainable development research (Huang et al., 2016).

Guided by Sen's capability approach, this study utilizes field data collected from the western counties of Dezhou, Shandong, encompassing villages in various locations. Through the integration of theoretical and empirical analyses, this study assesses how homestead withdrawal impacts multiple dimensions of rural residents' well-being, furnishes evidence for refining exit mechanisms and deepening reform, and proposes policy recommendations that more effectively safeguard farmers' homestead rights, enhance land-use efficiency, and alleviate local shortages of construction land.

2. Theoretical Analysis and Research Hypotheses

The mechanism by which homestead withdrawal impacts rural residents' well-being can be elucidated through two interrelated channels. First, by reshaping the physical environment where households farm and reside, the policy modifies production routines and daily life. The magnitude of households' livelihood capital—natural, physical, financial, human, and social—determines whether the new configuration increases or decreases total income. Second, after homesteads are relinquished, local governments typically also supply (i) vocational training aimed at off-farm jobs and (ii) upgraded transportation, telecommunications, and other public infrastructure. These interventions lead to a reallocation of household production factors, create new off-farm earning opportunities, and thus alter the total family income. Furthermore, the program enhances farmers' access to information regarding wage employment, increases their expected off-farm wages, and expedites labor transfer to non-agricultural sectors, all of which contribute tock into higher subjective and objective well-being.

2.1. Theoretical Framework

We establish a three-node framework that connects homestead withdrawal, off-farm employment, and rural residents' well-being. The model posits that the impact of households' decision to withdraw from the homestead on their well-being is mediated by the degree of rural labor transfer to off-farm activities. A graphical representation of the framework is shown below (Figure 1).

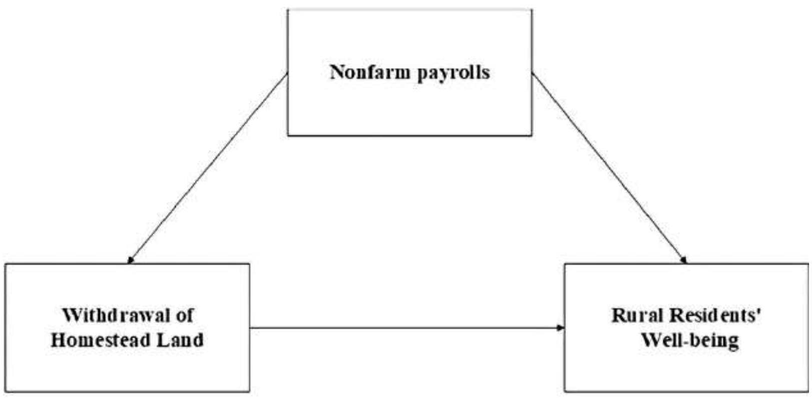

Figure 1. Theoretical Model Diagram.

2.2. Direct Effect of Household Homestead Withdrawal on Rural Residents' Well-Being

The "rational-peasant" hypothesis posits that, in order to maximize expected utility, households assess the marginal benefits and costs prior to surrendering their homesteads. Empirically, land-transfer decisions are motivated by the objective of maximizing household income, and multiple studies have demonstrated that homestead withdrawal exerts a positive net impact on total family revenue (Sun & Zhao, 2020). Research on impoverished rural households indicates that leasing out farmland serves as a significant catalyst for wealth accumulation; specifically, the withdrawal of rural residential land affects the stock of residents' financial capital and physical capital through means such as asset monetization and equity replacement. Non-agricultural employment optimizes the quality of human capital and financial capital through skill acquisition and income growth. Changes in these dimensions of livelihood capital will further affect different well-being dimensions such as economic income, health security, social integration, and psychological satisfaction. The flow of farmland (either out of or into the household) reshapes the labor allocation among family members and increases aggregate income (Zhou et al., 2020). Therefore, reforming the homestead system is imperative. Deepening the reform can unlock the latent property value of homesteads, activate idle land resources, and narrow the development gaps among regions, villages, and individuals, thereby fostering common prosperity among rural residents (Cao & Geng, 2022) and enhancing their well-being.

The multidimensional and dynamic impact of homestead withdrawal on rural well-being necessitates a comprehensive analysis, which can be enriched by empirical studies and theoretical frameworks such as the Sustainable Livelihoods Framework, Sen's Capability Approach, and social exclusion theory. The homestead, as the core natural and physical capital of rural households, plays a pivotal role in shaping their livelihood strategies. Once surrendered through monetary compensation or spatial relocation, it directly influences their transition into off-farm employment and the reallocation of assets. In the short run, the Change may enhance economic well-being by increasing disposable income and improving living standards. However, insufficient compensation, investment risks, or the breakdown of social networks may subject households to long-term poverty or social exclusion. Furthermore, the impacts are not limited to the economic realm; they extend to social, psychological, and environmental aspects. Therefore, a dynamic evaluation mechanism combined with a differentiated policy design is needed to balance efficiency and equity and achieve sustainable livelihoods and simultaneous improvements in multidimensional well-being. Specifically, the withdrawal of rural residential land affects the stock of residents' financial capital and physical capital through means such as asset monetization and equity replacement. Non-agricultural employment optimizes the quality of human capital and financial capital through skill acquisition and income growth. Changes in these dimensions of livelihood capital will further affect different well-being dimensions such as economic income, health security, social integration, and psychological satisfaction.

Based on the above discussion, we propose the following:

Hypothesis 1: Homestead withdrawal significantly and positively affects rural residents' well-being.

2.3. The Mediating Role of Off-Farm Employment

Since the start of reform and opening-up, China's economic structure has undergone a profound transformation from a centrally planned to a market-oriented system, with the state playing a pivotal guiding role. The development of secondary and tertiary industries has shifted economic growth away from agriculture, driving the coordinated evolution of all three sectors. Continuous industrial upgrading and increased urban non-agricultural job supply have facilitated rural labor migration to cities and accelerated rural household differentiation (Sun et al., 2019). The homestead withdrawal policy has intensified this process: it raises agricultural marginal costs while reducing labor migration transaction costs, making off-farm work a preferred choice for many households. After withdrawing homesteads, families often purchase urban apartments or move to government-provided resettlement housing, increasing spatial and temporal distances to their remaining farmland (Mao et al., 2017), which drives a self-reinforcing shift to areas with better transportation and more jobs, turning off-farm employment into a prevalent trend. Existing studies have explored how household differentiation shapes employment decisions, but rarely treat homestead withdrawal as an independent, multi-channel policy intervention. This theoretical-practical gap is reflected in household decision discrepancies, family background's influence on career choices, and misalignment between education and job market demands. From an occupational differentiation perspective, the one-time homestead withdrawal subsidy is generally insufficient to cover new rural housing or urban home purchase costs (Yan et al., 2017), forcing households to seek off-farm income. Meanwhile, expanded social networks and younger generations' evolving career aspirations strengthen the desire to leave agriculture and withdraw homesteads, further promoting off-farm transition.

Motivationally, off-farm employment is driven by the prospect of higher and more diversified earnings—anticipated wages in industry and services significantly exceed agricultural labor opportunity costs (Wang & Cai, 2025). Some workers even plan to settle permanently in towns and cities, engaging in secondary and tertiary sector jobs. In summary, the intricate interaction between homestead withdrawal and off-farm employment remains under-theorized. Research on issues such as non-farm employment's impact on homestead withdrawal and its poverty reduction mechanisms is essential to disentangle these factors, understand how policies reshape household differentiation, and ultimately affect rural well-being.

Based on the preceding analysis, the following research hypothesis is formulated.

Hypothesis 2: Off-farm employment plays a mediating role in the impact of homestead withdrawal on rural residents' well-being.

3. Data Sources and Research Methods

3.1. Data Source

The data used in this study were obtained from a random sampling survey conducted in counties in western Shandong Province from March to June 2025, involving random interviews with some township cadres and rural households. To ensure the representativeness of the research subjects, a multi-stage random sampling method was adopted. The focus of this study is to understand farmers' specific perceptions of the rural residential land withdrawal issue and their willingness to participate in the actual withdrawal process.

Shandong's regional development strategy has long privileged the eastern prefectures, resulting in the gradual impoverishment of western counties and exacerbating the east-west disparity. Since 2020, the provincial government has designated western Shandong as a top priority for balanced growth. To substantiate this new policy orientation, we selected three western counties where homestead withdrawal pilot programs have been implemented. A stratified sampling approach was employed in conjunction with face-to-face interviews to exhibit high reliability and completeness. The questionnaire encompassed household demographics, homestead-exit status, and village-level characteristics. The final sample consists of 410 farm households selected from nine administrative villages across six townships, spanning one city (Yucheng) and two counties (Wucheng and Xiajin). Among these households, 178 had already surrendered their homesteads, 227 had not, and five questionnaires were discarded, resulting in an effective response rate of 99%.

3.2. Variable Selection and Definition

3.2.1. Dependent Variable: Rural Residents' Well-Being

Based on the Sustainable Livelihoods Framework and previous studies by Luo et al. (2022), Li et al. (2022), and Peng et al. (2024), we construct a multidimensional well-being index grounded in Amartya Sen's capability approach. As shown in the data in Table 1, four dimensions were retained: (i) economic conditions, as measured by GDP and GNI, (ii) life satisfaction, encompassing cognitive and emotional aspects, (iii) health status, with a focus on the impact of economic factors, and (iv) social networks, reflecting interpersonal and societal harmony. The evaluation of each dimension was conducted through the application of a comprehensive set of distinct indicators, as demonstrated in the construction of well-being indices detailed in the references. An entropy-weighting procedure that combines objective dispersion with subjective expert scoring was used to derive indicator-specific weights, yielding a continuous composite index. The weights were then applied to the survey data to generate a cardinal well-being score for each respondent, ensuring that changes in rural residents' well-being were measured with maximum precision, as demonstrated in studies that have constructed happiness indices for urban and rural populations.

Table 1. Construction of the Rural Residents' Well-Being Indicator System.

Dimension	**Index**	**Well-being Thresholds and Assignments**	**Weight**
Economic situation	Salary income	The annual income ≥ 1.5 times the per capita disposable income of rural areas in the country, and the assignment is 1	1/8
	Horizontal comparison of income	The horizontal comparison of self-rated income is ≥ 3, and the assignment is 1	1/8
Life satisfaction	Life satisfaction	self-rated life satisfaction was ≥ 3, and the assignment was 1	1/8
	Confidence in the future	self-assessment of their future confidence level ≥ 3, with an assignment of 1	1/8
Health status	Physical condition	Health self-assessment ≤ 3, with a value of 1	1/12
	Medical resources	The overall satisfaction rate of medical treatment conditions at the medical treatment point was ≥ 3, and the assignment was 1	1/12
	Chronic diseases	If you do not have a chronic disease judged by a doctor, the value is 1	1/12
Interpersonal relationship	Social trust	The trust level of most neighbors is scored ≥ 5 and assigned a value of 1	1/12
	Neighborhood trust	Trust in neighbors is scored ≥ 5 and assigned a value of 1	1/12
	Social interaction	The frequency of villagers' participation in village collectives is ≥ 2~3 times a month, and the assignment is 1	1/12

3.2.2. Core Explanatory Variable

The withdrawal of homestead land is chosen as the core explanatory variable, which indicates whether households have withdrawn their homestead land, with the categories defined as "Yes = 1, No = 0." A value of 1 denotes that the household has withdrawn its homestead land, whereas a value of 0 indicates that the household has not done so. Among the 505 valid sample questionnaires collected, 178 correspond to households that have withdrawn homestead land, and 227 correspond to households that have not.

3.2.3. Mediating Variable

Non-agricultural employment was selected as the mediating variable. Following the methodology of Zhou and Yang (2025) and Qiu and Luo (2017), the degree of non-agricultural employment was measured by the proportion of non-agricultural labor force to the total labor force, treated as a continuous variable.

3.2.4. Control Variables

Control variables encompass household head characteristics (e.g., age, educational attainment, and health status), household attributes, homestead characteristics, and production/operational features. Household head characteristics, which include age, educational attainment, and health status, are crucial as they influence various aspects of family life, such as health data tracking, educational and medical expenditures, and overall household consumption patterns. Specific secondary variables are illustrated in Table 2.

Table 2. Variable Selection and Selection Basis.

Variable categories	Variable name	Variable	Variable definition	Average value	Standard deviation
Interpreted variable	Well-being of rural residents	Economic situation	Continuous variables	0.093	0.080
		Life satisfaction	Continuous variables	0.088	0.081
		Health status	Continuous variables	0.091	0.064
		interpersonal relationship	Continuous variables	0.086	0.066
Explanatory variables	Homestead withdrawal	Whether the homestead is withdrawn	Yes = 1, No = 0	0.440	0.497
Control variables	Family characteristics	Family population/person	Continuous variables	4.782	1.589
		The number of people who need to be supported/person	Continuous variables	2.451	0.980
		Are there any village cadres at home?	Continuous variables	0.573	0.496
		The number of relatives and friends walking around the house	Continuous variables	3.164	1.227
		Family livelihood methods	Farming = 1; Farming as main and part-time work = 2; Non-farming as main and part-time work = 3; Non-farming = 4	3.110	1.246
	Characteristics of the head of the household	age	Continuous variables	42.220	13.912
		Educational level	Below primary school = 1; primary school = 2; junior high school = 3; high school (technical secondary school) = 4; junior college = 5; bachelor's degree and above = 6	3.067	1.083
		Level of health	Very poor = 1; poor = 2; fair = 3; good = 4; very good = 5	2.164	0.896
	Homestead characteristics	Homestead area/square meter	≤ 80 m^2 = 1;80~100 m^2 = 2; 100~120 m^2 = 3; 120~150 m^2 = 4; > 150 m^2 = 5	3.200	1.278
		Whether the homestead is confirmed	Yes = 1, No = 0	0.661	0.475
		Homestead type (distance from central town)	Suburban type=1; Non-suburban type = 2; Remote area type = 3	2.362	0.747
	Production and operation characteristics	Is there any outflow of farmland at home?	Yes = 1; N0 = 0	0.350	0.477
		The area of cultivated land operated by the family	≤5 mu = 1; 5~10 mu = 2; 10~15 mu = 3; 15~20 mu = 4; >20 mu = 5	0.353	1.372
		ln (Household Agricultural Income)	Continuous variables	10.118	1.071
Mediating variables	Nonfarm payrolls	The proportion of non-farm payrolls in the total labor force	Continuous variables	0.270	0.202

3.3. Model Specifications

Since homestead withdrawal is a self-selected behavior, the observed differences in welfare indicators may arise not from the withdrawal act itself but from the pre-existing heterogeneity in household-head and family characteristics. To mitigate self-selection bias, we employ Propensity Score Matching (PSM), which pairs households that surrendered their homesteads (treated group) with those that did not (control group), ensuring that both groups are observably similar.

The procedure unfolds in two stages. First, we specify and estimate a homestead-withdrawal decision equation; all computations are carried out with Stata 17.0 to ensure high-quality matching (Sun & Zhao, 2020; Si et al., 2018), as demonstrated by the application of advanced statistical techniques such as Propensity Score Matching (PSM) and Coarsened Exact Matching (CEM) in the references. Second, by maintaining constant external conditions and utilizing a matched sample, we apply Propensity Score Matching (PSM) to ascertain the causal impact of withdrawal on the well-being of rural residents. The detailed steps are as follows:

(1) Use a Logit model to predict each household's conditional probability of exiting the homestead:

$$PS_i = P_r[D_i = 1|X_i] = E[D_i = 0|X_i] \quad (1)$$

Here, $D_i = 1$ means that farmers have withdrawn from homesteads; $D_i = 0$ means that the farmers have not withdrawn from the homestead; X_i represents observable farmer characteristics (covariates).

(2) The treatment and control groups will be matched. In order to verify the robustness of the matching results, four matching methods were selected: minimum nearest neighbor matching, caliper matching, kernel matching, and local linear matching.

(3) Calculate the average treatment effect (*ATT*). Based on the matching sample, the difference in the well-being status of withdrawn and non-withdrawn farmers is compared, and the impact coefficient of homestead withdrawal on farmers is obtained, that is, the average treatment effect in the model (*ATT*):

$$ATT = E[Y_{1i} - Y_{0i}|D_i] = E[Y_{1i}|D_i = 1] - E[Y_{0i}|D_i = 0] \quad (2)$$

Y_{1i} represents the welfare status of the first farmer participating in the withdrawal of homestead, Y_{0i} means that the welfare status of the first farmer does not participate in the withdrawal of homestead land. Under the assumption, $Y_1 - Y_0$ is the average treatment effect of homestead withdrawal on the well-being of farmers.

(4) The matching test of the PSM model, i.e., the common branch domain test and the balance test (Liang et al., 2017). Table 2 lists the descriptive statistical analysis of the main variables in this study.

4. Empirical Testing and Results Analysis

4.1. The Impact of Homestead Withdrawal on Multidimensional Poverty Reduction: An Empirical Analysis

4.1.1. Analysis of Basic Characteristics of Farmhouse Households

All data in this chapter are derived from the research team's field investigations. In the study of counties in western Shandong Province, it was found that 178 households in the sample relinquished their homestead land use rights, influenced by objective economic factors and a herd mentality stemming from observing the number of other households that had already withdrawn. Conversely, 227 households did not relinquish their rights, likely due to differing economic considerations or a lack of motivation to withdraw. See Table 2 and Table 3 for details.

Table 3. Analysis of Basic Characteristics of Farmhouse Households.

Index	Options	Sample size	Ratio (%)	Index	Options	Sample size	Ratio (%)
Farmland quit	yes	178	43.95%	healthy state	Unhealthy	74	18.27%
	not	227	56.05%		Not very healthy	90	22.22%
Age	30 years old and below	71	17.53%		Moderate healthy	174	42.96%
	30–40 years old	119	29.38%		relatively healthy	44	10.86%
	40–50 years old	82	20.25%		Very healthy	23	5.68%
	Over 50 years old	133	32.84%	Household agricultural income	10,000 yuan and below	80	19.75%
Get educated extent	Elementary school and below	115	28.40%		1–30,000 yuan	147	36.30%
	junior high school	262	64.69%		3–50,000 yuan	78	19.26%
	High school and above	28	6.91%		More than 50,000 yuan	100	24.69%
Family population	Up to 3 people	89	21.98%	workforce flowing	be	295	72.84%
	4–6 people	250	61.72%		not	110	27.16%
	More than 7 people	66	16.30%				

Combining Table 3 and the descriptive statistics in Table 2, the following patterns emerge. Regarding the outcome variable, the means of the four rural-well-being dimensions show a difference of no more than 0.2, indicating villagers' relatively consistent priorities. As for the key explanatory variable, most households indicate a willingness to surrender their homestead. Concerning the mediator, more than two-thirds of families have at least one member involved in off-farm labor, whereas only a small minority have relatives or friends employed in the public sector or non-farm enterprises. Control variables can be categorized into four domains: head-of-household traits, household characteristics, homestead attributes, and production-management features.

(1) Head-of-household characteristics

Age is evenly distributed, with a mean age of 42; 32.84% are aged 50 or older. Junior-middle-school graduates make up 64.69% of the sample, while only 6.91% have completed senior high school or above, reflecting the typical educational profile of western Shandong.

(2) Household characteristics

Labor-force participants constitute 72.84% of household members, and the proportion working off-farm continues to increase. The number of dependants, presence of a village cadre, and the frequency of kin visits are all stable.

(3) Homestead characteristics

Thanks to recent land titling campaigns, 66.1% of the plots have been formally certified. The distance to the nearest town varies uniformly across the sample, highlighting the representativeness of the study area.

(4) Production and management characteristics

Recent data indicate that the rural per-capita disposable income has reached 23,119 yuan in 2024, marking a substantial increase from previous years and reflecting the ongoing improvement in rural income realities.

As shown in Table 4, after homestead withdrawal, both economic conditions and life satisfaction exhibit significant mean changes, with improvements observed and statistical significance at the 1% level. However, changes in interpersonal relationships are not statistically significant. Regarding household head characteristics, the mean educational attainment increased by 0.227, which is statistically significant at the 1% level. The household head's age and health status showed changes, but were not statistically significant. In terms of family characteristics, the mean number of frequently visiting relatives and friends increased by 0.189, with statistical significance at the 5% level, while changes in household size and number of dependents were insignificant. Regarding homestead characteristics, the mean homestead area decreased significantly at the 1% level; the mean homestead title status showed a slight increase at the 10% level; and the mean distance to the central town decreased but was not statistically significant. Additionally, the mean non-agricultural employment rate increased significantly by 0.043 at the 1% level.

Table 4. Statistical Description of Indicator Mean Differences: Homestead-Withdrawing vs. Non-Withdrawing Households.

Indicator variables	variable	Homestead withdrawal	Homesteads have not been withdrawn			Difference
		average value	standard deviation	average value	standard deviation	
Well-being of rural residents	Economic situation	0.11	0.077	0.098	0.081	0.012***
	Life satisfaction	0.109	0.085	0.093	0.086	0.016***
	Health status	0.102	0.071	0.099	0.067	0.003**
	interpersonal relationship	0.095	0.067	0.099	0.066	−0.004
Family characteristics	Family population/person	4.828	1.583	4.713	1.599	0.115
	The number of people who need to be supported/person	2.366	1.001	2.551	0.945	−0.185
	Are there any village cadres at home?	0.809	0.485	0.374	0.394	0.435
	The number of relatives and friends walking around the house	3.264	1.176	3.075	1.262	0.189**
	Family livelihood methods	3.101	1.202	3.129	1.302	−0.028
Characteristics of the head of the household	age	43.978	13.331	44.528	14.652	−0.541
	Educational level	2.784	0.942	3.011	1.02	0.227***
	Level of health	3.011	1.02	2.476	1.231	0.361
Homestead features	Homestead area/square meter	3.088	1.27	3.337	1.28	−0.249***
	Whether the homestead is confirmed	0.674	0.47	0.643	0.48	0.031*
	Homestead type	2.427	0.715	2.275	0.779	0.152
Production and operation characteristics	Is there any outflow of farmland at home?	0.216	0.412	0.517	0.501	−0.301
	The area of cultivated land operated by the family	4.189	1.123	2.697	1.197	1.492
	ln (Household Agricultural Income)	10.321	1.014	9.86	1.089	0.461
Mediating variables	Nonfarm payrolls	0.288	0.208	0.245	0.192	0.043***

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

4.1.2. Propensity Score Matching

Following the counterfactual analysis steps of PSM, we selected and evaluated covariates that affect the health of core household members to match samples between the experimental and control groups. The estimation results derived from the Logit model are presented in Table 5.

Table 5. Propensity Score Matched Logit Regression Results

Indicator type	Variable name	Coefficient	Standard error	t-value	Significance
Characteristics of the head of the household	age	−0.013	0.006	−2.017	0.044*
	Educational level	0.374	0.099	3.897	0.000**
	Health level	0.636	0.198	3.136	0.002**
Family characteristics	Family population	0.019	0.074	0.276	0.619
	The number of people to be supported and supported by the family	0.035	0.120	0.569	0.570
	Are there any party members at home?	0.447	0.217	2.075	0.038*
	Are there any village cadres at home?	0.382	0.225	1.62	0.106
	Family livelihood methods	0.074	0.087	0.839	0.402
	The number of relatives and friends who often walk around the house	0.110	0.089	1.138	0.256
Homestead characteristics	Whether the homestead is confirmed	0.621	0.264	2.664	0.008**
	Homestead area	0.138	0.088	1.278	0.202
	Homestead type	−0.372	0.144	−2.918	0.004**
Production and operation characteristics	Is there any outflow of farmland at home	0.803	0.242	3.84	0.000**
	The area of cultivated land operated by the family	−0.705	0.096	−8.685	0.000**
	Household agricultural income	0.051	0.017	3.0112	0.003*
Statistical tests		Pseudo R^2		0.343	
		LR chi2(15)		294.99	
		Prob > chi2		P = 0.00	

Studies employing Logistic regression models, such as those detailed in the references, have consistently shown that educational attainment and self-reported health status are significant predictors of farmers' willingness to withdraw from homesteads. For instance, the research detailed in Table 4 of the original document indicates that these factors positively and significantly influence the likelihood of homestead withdrawal, with higher levels of education and better self-reported health status correlating with a greater probability of exit. Shifting focus to household characteristics, the presence of a Communist Party member in the household is positively correlated with the decision to withdraw at the 5% significance level, In contrast, the number of dependents (children and elderly), the number of influential acquaintances, and whether any household member serves as a village cadre do not reach the conventional significance thresholds, and thus cannot reliably distinguish between participants and non-participants. Regarding homestead attributes, formal titling significantly increases the propensity to exit ($p < 0.01$), whereas non-residential homestead types significantly reduce this propensity ($p < 0.01$). A study on the impact of livelihood resilience on farmers' willingness to exit land contracts reveals that leasing out farmland and a higher share of household income from agriculture positively influence the probability of withdrawal, while larger areas of contracted farmland under household cultivation have a negative impact, all at the 1% significance level.

4.2. Measuring the Impact of Homestead Withdrawal on Rural Residents' Well-Being

4.2.1. Propensity Score Matching

To assess the net impact of homestead withdrawal on rural residents' well-being, we utilize four distinct matching estimators: nearest-neighbour matching, radius (caliper) matching, kernel matching, and local-linear-regression matching. Table 6 presents the findings. Under the nearest-neighbor specification, 203 treated households are successfully matched, whereas 24 are excluded due to the common-support restriction; 162 control households are matched, with 16 being discarded, resulting in a matched sample. A sample of 365 observations was used, with 40 observations dropped in total. The post-matching balance is satisfactory. The average treatment effect on the treated (ATT) is 0.051 and is highly significant at the 1 % level, indicating that participation in homestead withdrawal indeed raises the rural well-being index. Although the magnitude is smaller than the raw pre-matching difference, the estimate exhibits greater credibility. To verify robustness, we re-estimate the ATT using radius matching and kernel matching methods. Although point estimates differ slightly across various specifications, all four methods exhibit quantitatively similar outcomes, which underscores the robustness of the findings.

Table 6. Balance test results before and after propensity score matching.

Variable	Matching method	Matching Number	Processing group	Control group	Total sample	Average Treatment Effect (ATT)	Standard error	T Statistics
countryside inhabitant welfare	Minimum Nearest Neighbor Matching	supported	203	162	365	0.051	0.020	2.59
		Not supported	24	116	40			
	Radius matching	supported	214	163	377	0.049	0.027	1.86
		Not supported	13	15	28			
	Nuclear matching	supported	214	163	377	0.047	0.021	2.26
		Not supported	13	15	28			
	Local linear Regression matching	supported	214	163	377	0.046	0.027	1.74
		Not supported	13	15	28			

4.2.2. Hypothesis Testing: Balance Analysis

This section evaluates the balancing property to test the credibility and robustness of the propensity-score matching results. The fundamental requirement for propensity score matching is that, post-matching, the means of all covariates should not significantly differ between the treatment and control groups, ensuring covariate balance. The degree of balance between groups in randomized controlled trials is often assessed using Standardized Mean Differences (SMDs), which allow for the comparison of mean differences across studies that use different measurement scales. The closer the post-match SMD is to zero, the better the balance; An SMD below 10% is generally considered to indicate a satisfactory level of balance between groups, as suggested by Cohen's guidelines, where SMD values less than 0.1 typically represent good balance. The table reports the balance diagnostics for every control variable.

Table 7 demonstrates that, among head-of-household characteristics, the standardized bias of all three variables decreases significantly after matching and approaches zero, indicating a satisfactory balance. Within household-level attributes, only the absolute standardized bias of the head's schooling slightly surpasses 10 percent; all other variables remain comfortably below this threshold. For homestead characteristics, every covariate bias is reduced to nearly zero, whereas in production-management traits only the indicator "whether farmland has been leased out" slightly exceeds 10 percent, while the rest are well below this level. Overall, the treated and control households exhibit balanced distributions across all four dimensions.

Table 7. Propensity Score Matching.

Control variables	Sate	Normalization deviation (%)	Reduction in standardized deviation (%)	t-value	p-value
age	Before matching	3.9%	79.0%	0.39	0.017
	After matching	−0.8%		−0.07	0.942
education	Before matching	23.1%	45.5%	2.32	0.001
	After matching	12.6%		1.16	0.245
health	Before matching	34.8%	60.6%	3.40	0.001
	After matching	−13.7%		−1.40	0.163
Population	Before matching	−7.2%	21.4%	−0.72	0.000
	After matching	5.7%		0.52	0.108
Maintenance	Before matching	19.0%	77.1%	1.89	0.361
	After matching	4.3%		0.41	0.617
Party	Before matching	23.2%	42.7%	2.32	0.089
	After matching	9.3%		1.19	0.808
Cadre	Before matching	98.3%	97.7%	9.70	0.000
	After matching	−2.3%		−0.23	0.564
Make a living	Before matching	2.2%	34.7%	0.22	0.192
	After matching	1.5%		−0.13	0.461
Relatives	Before matching	15.5%	90.4%	1.54	0.168
	After matching	−1.5%		−0.13	0.468
Confirmation	Before matching	6.5%	70.1%	0.65	0.211
	After matching	1.9%		0.18	0.622
Area	Before matching	19.5%	47.9%	1.95	0.000
	After matching	−10.2%		−0.96	0.561
Type	Before matching	−20.3%	86.4%	−2.04	0.000
	After matching	−2.8%		−0.25	0.749
Farmland	Before matching	65.6%	83.5%	6.63	0.000
	After matching	10.8%		0.90	0.042
Arable land	Before matching	−128.6%	93.7%	−12.90	0.000
	After matching	−8.1%		−0.75	0.665
Revenue	Before matching	−32.6%	95.3%	−3.27	0.001
	After matching	−1.5%		1.02	0.307

To visualize these results, we employ Stata 17.0 to plot the changes in standardized bias for each control variable (see Figure 2). After applying propensity-score matching, biases are markedly reduced and cluster around zero, which aligns with the balancing hypothesis and confirms the effectiveness of the matching procedure.

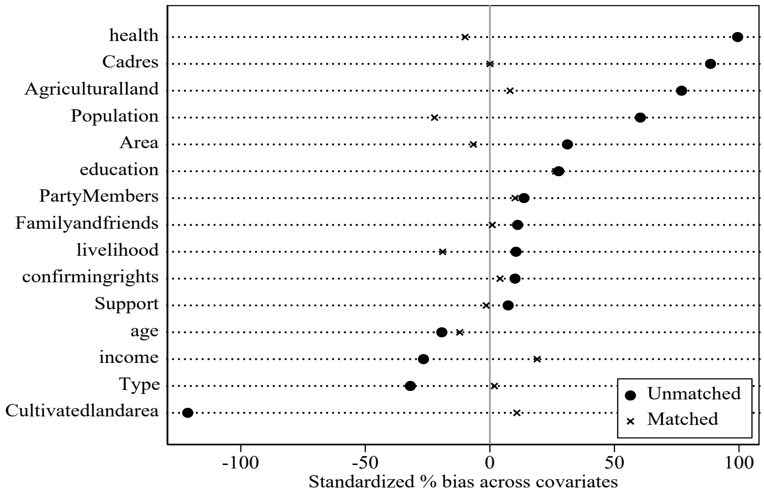

Figure 2. Variable Standardization Deviation Reduction Degree Chart.

4.2.3. Common Support Domain Test

The common-support test serves as an additional prerequisite for ensuring the validity of propensity-score matching. By comparing the kernel-density curves, along with the overlapping support regions, of the treatment and control samples before and after matching, we can assess whether the matching procedure has generated a high-quality counterfactual. Figure 3 and Figure 4 present the kernel-density plots for the homestead-withdrawal group and the non-withdrawal group:

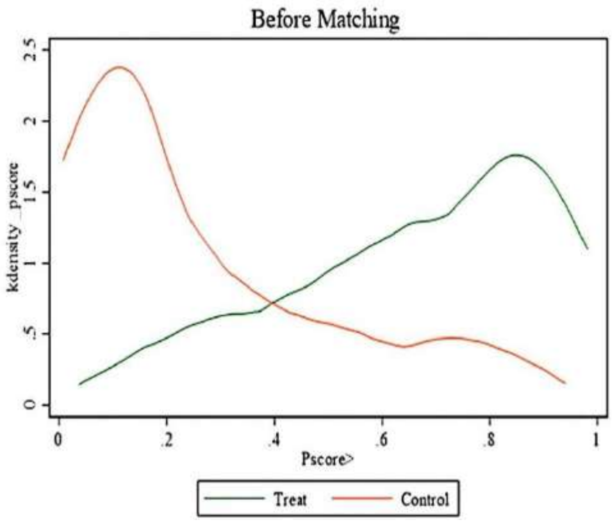

Figure 3. Kernel Density Matching Plot (Before Matching).

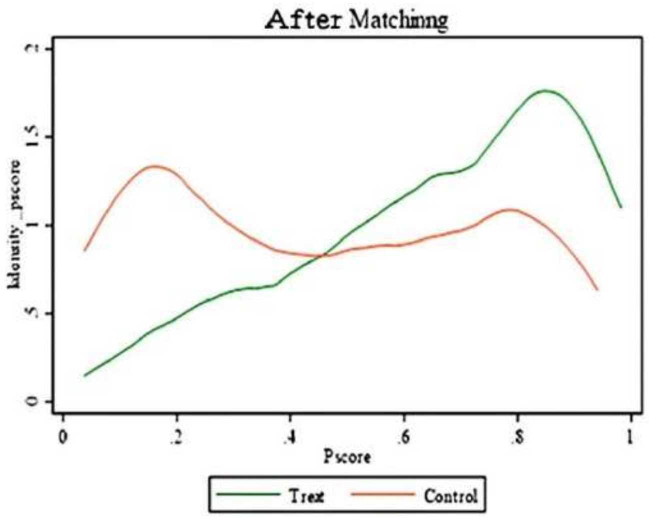

Figure 4. Kernel Density Matching Plot (After Matching).

After estimating the propensity scores, we plot their density distributions to assess the common-support region. As shown in Figures 3 and 4, the kernel-density curves of the treatment and control groups diverge markedly before matching; after matching, the two curves almost coincide, indicating a substantial improvement in overlap and confirming the quality of the propensity-score match.

Taking the nearest-neighbor specification as an example, we further validate the procedure by generating the common-support diagnostic plot using Stata 17.0 (Figure 5). The graph indicates that merely a small number of observations lie outside the overlapping region, thus the vast majority of treated households can be matched with valid controls, fulfilling the common-support assumption necessary for causal inference.

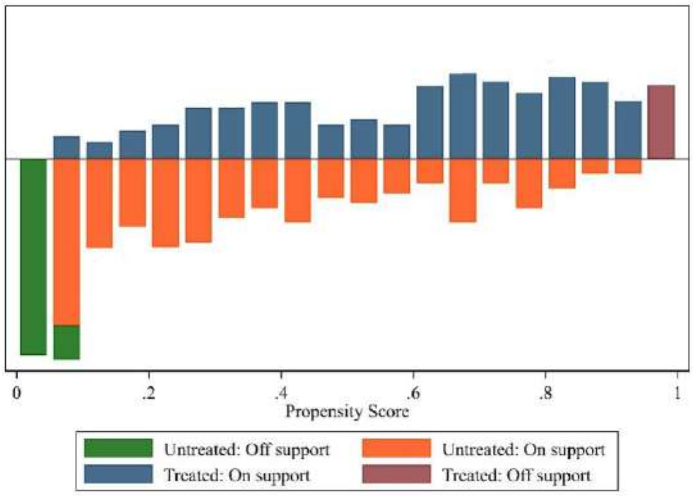

Figure 5. Test Chart for the Hypothesis of Shared Support Domains in Propensity Score Matching.

As Figure 5 illustrates, before and after matching, the vast majority of treated and control observations are located within a common support region and are densely distributed. This implies that only a small number of cases are discarded, indicating high matching quality.

The diagnostic checks affirm the robustness of the propensity-score matching: (i) each covariate's absolute standardized bias is diminished to under 10% post-matching, meeting the balance criterion, and (ii) the propensity score kernel-density plots for both groups nearly overlap, ensuring the common-support condition with minimal sample attrition. Consequently, the PSM results are both credible and robust, suggesting that homestead withdrawal exerts a positive causal effect on the well-being of rural residents.

4.2.4. Robustness Test

To ensure robustness, we substitute the comprehensive rural well-being index with household self-reported happiness scores, which encompass factors such as income, education, employment stability, and social relationships. This single-indicator proxy directly captures subjective welfare, thereby avoiding potential noise arising from index construction and weight assignment. As shown in Table 8, the sign and significance of the estimated coefficients remain consistent with those obtained from the Logit regressions, confirming that our conclusions are insensitive to the choice of the dependent variable and reinforcing. Assessing the reliability of the earlier findings.

Table 8. Test Results using Propensity Score Matching (PSM).

Variable	Matching method	Average Treatment Effect (ATT)	Standard error	T-statistic
Rural residents Subjective well-being	Minimum Nearest Neighbor Matching	0.365	0.030	2.09
	Radius matching	0.364	0.022	1.81
	Nuclear matching	0.310	0.039	2.08
	Local linear Regression matching	0.278	0.028	1.63

In summary, the dual validation of the propensity-score matching (PSM) procedure substantiates the plausibility of the modelling assumptions. After matching, Propensity Score Matching (PSM), the standardized biases across all covariate dimensions are markedly reduced, indicating that selection bias has been effectively attenuated. The kernel-density plots of the propensity scores for the treated and control groups exhibit near-perfect overlap, confirming distributional balance. With only a few marginal observations removed, the overwhelming majority of cases remain within the common-support region, thereby safeguarding external validity. These diagnostic indicators collectively demonstrate that the PSM model achieves high goodness-of-fit and strong internal validity. In light of the empirical evidence from studies such as those conducted in Anhui Jinzhai County and Fujian Jinjiang City, Hypothesis 1—asserting that homestead withdrawal has a statistically significant and positive impact on rural residents' well-being—has been accepted.

4.2.5. Act of Homestead Withdrawal on Various Dimensions of Rural Residents' Well-Being

As previously outlined, the well-being indicator system for rural residents consists of four dimensions: economic status, life satisfaction, health status, and interpersonal relationships. Based on this framework, this study adopts three matching methods to examine the impact of homestead withdrawal on each dimension of rural residents' well-being. Through these matching approaches, we measured the effects across all dimensions and found that homestead withdrawal significantly enhances rural residents' well-being. However, the specific mechanisms underlying this effect and its impacts on individual dimensions require further verification. The results are presented in Table 9, which shows that the impact of homestead withdrawal varies across different dimensions of rural residents' well-being, with the most significant improvement observed in economic status.

Table 9. Estimated Effects of Homestead Land Withdrawal on Various Dimensions of Rural Residents' Well-Being.

Dimension	Matching method	Experi-mental group	Control group	Average treatment effect	Standard error
Economic situation	Nearest neighbor matching	0.082	0.125	0.042	0.012
	Radius matching	0.082	0.141	0.059	0.016
	Nuclear matching	0.082	0.125	0.043	0.012
Life satisfaction	Nearest neighbor matching	0.079	0.096	0.029	0.013
	Radius matching	0.082	0.084	0.032	0.012
	Nuclear matching	0.082	0.084	0.029**	0.012
Health status	Nearest neighbor matching	0.075	0.093	0.017**	0.010
	Radius matching	0.076	0.092	0.016**	0.013
	Nuclear matching	0.076	0.090	0.014*	0.010
interpersonal relationship	Nearest neighbor matching	0.069	0.092	0.011*	0.012
	Radius matching	0.071	0.087	0.013*	0.014
	Nuclear matching	0.071	0.087	0.009*	0.012

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

The terms of income, homestead withdrawal exerts a significantly positive impact on the economic well-being of rural residents. Taking the nearest neighbor matching method as an example, the economic well-being indices of the experimental group and the control group are 0.082 and 0.125, respectively. The average treatment effect (ATT) difference between the two groups is 0.012, which is highly significant at the 1% level. These findings indicate that homestead withdrawal can increase farmers' income and improve rural residents' economic conditions. Regarding the dimension of life satisfaction, the nearest neighbor matching method shows that the life satisfaction coefficients of the experimental group and the control group are 0.075 and 0.093, respectively. The mean treatment effect difference is 0.013, significant at the 1% level. The underlying mechanism is that homestead withdrawal improves residents' material foundations and living environments, thereby positively affecting their life satisfaction—though this effect is subject to complex regulation by multiple subjective factors. In the dimension of health status, results from the nearest neighbor matching method reveal that the health status coefficients of the experimental group and the control group are 0.075 and 0.093, respectively. The mean treatment effect difference is 0.010, significant at the 5% level. Theoretically and empirically, homestead withdrawal may generate long-term positive health impacts by optimizing residential environments and enhancing healthcare accessibility, or interpersonal relationships. The nearest neighbor matching method indicates that the interpersonal relationship coefficients of the experimental group and the control group are 0.069 and 0.092, respectively. The mean treatment effect difference is 0.012, significant at the 10% level.

Based on the aforementioned theoretical data, Hypothesis 2 is validated.

4.3. Testing the Mediating Effect of Non-Farm Payrolls

4.3.1. Mediation Effect Model

Combined with the framework theory of rural residents' well-being after homestead withdrawal, this paper discusses whether homestead withdrawal can improve rural residents' well-being by affecting non-agricultural employment. Based on the mediation effect analysis method proposed by a "three-step method" regression model was established.

This study employs the mediating effect model to dissect the influence process and mechanism of independent variables on dependent variables, utilizing methods such as the Baron and Kenny stepwise approach and the Bootstrap method for assessing the significance of the mediating effect. In examining the impact of an independent variable X on a dependent variable Y, when X influences Y via an intermediary variable M, M is identified as the mediating variable. Equations (3) to (5) delineate the relationship between variables:

$$Y = cX + e_1 \tag{3}$$

$$M = aX + e_2 \tag{4}$$

$$Y = c'X + bM + e_3 \quad (5)$$

Among them, the coefficient *c* of equation (4) is the total effect of the independent variable *X* on the dependent variable *Y*. The coefficient *a* of equation (5) is the effect of the independent variable *X* on the mediating variable *M*. The coefficient *b* of equation (6) is the effect of the mediating variable *M* on the dependent variable *Y* after controlling for the influence of the independent variable *X*. The coefficient c' is the direct effect of the independent variable *X* on the dependent variable *Y* after controlling for the influence of the mediating variable *M*. $e_1 \sim e_3$ are the regression residuals. The mediating effect is equivalent to the indirect effect, which is calculated as the product of the coefficient.

Sobel test, construct statistics:

$$Z = \frac{\beta\gamma}{\sqrt{\beta^2 S_\beta^2 + \gamma^2 S_\gamma^2}} \quad (6)$$

S_β is the standard deviation of the β coefficient, and S_γ is the standard deviation of the γ coefficient. A significant result of statistic Z, such as $Z > 1.96$ at a 5% significance level, indicates that the mediating effect is significant. If the result of statistic Z is not significant, then it is clear that the mediating effect is not significant.

4.3.2. Testing for Mediating Effects

Studies employing linear regression models, such as those examining the impact of rural labor transfer on income levels and urbanization, support the use of this method to analyze the causal relationship between rural labor transfer and the well-being of rural residents. The results, as detailed in Table 10, demonstrate the significant impact of rural labor transfer on farmers' income and economic growth.

Table 10. Mediating Effect Test.

Variable	Well-being of rural residents	Labor transfer	Well-being of rural residents
Farmers' homesteads were withdrawn	0.054*** (0.033)	0.156*** (0.015)	0.061*** (0.126)
Labor transfer			0.398*** (0.141)

Note: The coefficients reported in the table denote marginal effects, with standard errors shown in parentheses; other variables and provincial controls have been considered.

Studies from various regions, such as Yuyang District in Jiangxi Province and Jinjiang City in Fujian Province, indicate that homestead withdrawal is positively associated with rural residents' well-being and labor transfer to off-farm employment, with significant coefficients at the 0.1% level. Empirical evidence from studies such as indicates that off-farm transfer remains positively linked to well-being, with a coefficient of 0.389 and a significance level of $p < 0.001$, while the direct effect of homestead withdrawal on well-being has been observed to modestly decrease to 0.061, maintaining a significant impact. These results are significant, confirming that off-farm labor transfer serves as a partial mediator between homestead withdrawal and rural well-being.

4.3.3. Robustness Tests

When conducting path analysis for the mediating effect of non-agricultural employment, the results of the mediation test may be distorted by endogeneity between the mediating variable and the explained variable, leading to biased estimates. Therefore, selecting an appropriate robustness test method is critical. In this study, the SPSS Process macro was employed for robustness testing. This tool not only tests the significance of the mediating effect but also addresses endogeneity concerns. By generating 4,000 repeated samples via the Bootstrap method, a 95% bias-corrected confidence interval was constructed. This approach not only mitigates the issue of small sample size but also corrects for estimation bias. The Bootstrap test results for the mediation path analysis of non-agricultural employment levels are presented in Table 11.

Table 11. Bootstrap mediation effect test.

Inspection category	Path	Effect value	P > |z|	95% Confidence interval
Non-farm employment path test	The withdrawal of homesteads → non-agricultural employment → the well-being of rural residents	1.71	0.221	[0.014, 0.038]
	Homesteads are withdrawn → non-agricultural employment	2.34	0.019	[0.002, 0.022]
	Non-farm payrolls → well-being of rural residents	2.23	0.026	[0.004, 0.062]
	The withdrawal of homesteads → the well-being of rural residents	1.64	0.014	[0.022, 0.041]

The table shows that the 95% confidence intervals for all path tests of non-agricultural employment exclude zero, indicating a significant positive effect. This suggests that homestead withdrawal exerts a significant impact on rural residents' well-being, with part of this impact mediated by the non-agricultural employment variable. Results of the Bootstrap mediation test are consistent with those of the stepwise regression mediation analysis, confirming the mediating role of non-agricultural employment in the relationship between homestead withdrawal and rural residents' well-being. This verifies the robustness of the regression results regarding the non-agricultural employment pathway and validates the mediating effect of non-agricultural employment in this relationship.

5. Conclusions and Policy Implications

5.1. Research Conclusions

Based on China's new development stage and utilizing survey data from 405 farm households in three western counties of Shandong Province, this study integrates theoretical reasoning with propensity-score matching (PSM) to ascertain the causal effect of homestead withdrawal on rural residents' well-being. Three key findings are presented. First, relinquishing the homestead substantially enhances households' multidimensional well-being. Second, off-farm employment serves as a crucial mediator: through reallocating labor to higher-productivity sectors, homestead exit translates land-value gains into sustained income gains and broader life satisfaction. Thirdly, PSM provides a robust tool for evaluating rural land-policy interventions, offering new evidence to refine homestead-reform design and advance the broader rural-revitalization agenda.

5.2. Policy Implications

(1) Fine-tune policy design. Given that livelihood structures and economic capacities vary significantly among households, county-level programmes should incorporate flexible entry rules, opt-out clauses, and periodic impact reviews to enable continuous learning and real-time adjustments.

(2) Build a differentiated compensation and rights-protection system. A dynamic model that integrates a base land price with location-specific correction coefficients can reflect regional disparities and heterogeneous functions of homesteads, ensuring both scientific rigor and perceived fairness. Transparent third-party appraisal procedures and mandatory village-level hearings should ensure farmers' full right to information and participation, with household welfare serving as the guiding principle for every exit decision.

(3) Enhance re-employment support and human-capital investment. For households with heavy dependency burdens, targeted vocational training, wage-subsidy contracts, and start-up micro-loans should be given priority. Local governments should simultaneously optimize the industrial layout by attracting labor-intensive agro-processing, rural e-commerce, and service enterprises, thereby creating abundant off-farm jobs to facilitate the transition from farm to non-farm work.

(4) Strengthen the factor base for rural revitalization. Homestead reform directly relieves bottlenecks such as "no land for housing" and "no land for industrial projects" while unlocking collateral value and facilitating the free flow of labor, capital, and technology between urban and rural areas. Consolidated parcels released through the programme can be allocated to specialty agriculture, leisure farming, agritainment, or small-scale processing zones, thereby diversifying village revenue streams and enhancing homestead withdrawal within a broader strategy of industrial upgrading and shared prosperity.

(5) While short-term cash compensation from homestead withdrawal can improve farmers' living standards, its long-term impacts exhibit diverse, complex dynamics with heightened uncertainties. To balance immediate gains and long-term benefits, targeted policies are required to address the long-term effects of homestead withdrawal—such as refining compensation appreciation-sharing mechanisms and integrating employment support with social security systems.

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Abbreviations

The following abbreviations are used in this manuscript:

PSM	propensity score matching
CEM	Coarsened Exact Matching
ATT	Average Treatment effect on the Treated
SMDs	Standardized Mean Differences

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Agricultural & Rural Studies

Review

Exploring Social Forestry Research Trends in Indonesia: A Scientometric Analysis Using CiteSpace

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Abstract: Social forestry in Indonesia is a topic that has been extensively researched due to the active role of communities, especially those living in and around forest areas, in managing the country's forest resources. This is supported by various regulations that provide certainty regarding the rights and access of communities in forest management activities. However, systematic and quantitative research related to the development of social forestry research in Indonesia has not been widely conducted. Therefore, this study was conducted using a scientometric analysis using 1,662 articles from Web of Science. Data analysis was performed using CiteSpace to (i) examine the publication landscape to present the actual condition of scholarly output on social forestry; (ii) map patterns of collaboration to capture the relationships among researchers and institutions; (iii) identify fundamental and pioneering studies; and (iv) trace the evolution, hotspots, and emerging research trends. This research found that the Center for International Forestry Research (CIFOR) got the first rank in the institutional collaboration. In the author collaboration analysis, Ahmad Maryudi has the highest ranked of social forestry topic in Indonesia. The results of the study also show several keywords that are most frequently used by various researchers, namely conservation, management, forest, biodiversity, and community. Overall, this research results would help the new researchers quickly understand developments in social forestry research and fill the existing gaps. Moreover, senior researchers and policymakers can use the integrated research trend information to develop adaptive and inclusive social forestry models that provide ecological and economic benefits.

Keywords: CiteSpace; research hotspots; research trends; social forestry

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1. Introduction

Forests play a vital role at both global and local scales, providing ecological, economic, and social benefits. Globally, forests function as vital reservoirs of biodiversity and provide essential ecosystem services, including oxygen production, carbon sequestration, regulating water cycles, and climate regulation, which are crucial for mitigating global temperature rise (Bera & Nag, 2025; Hu et al., 2025; Richardson et al., 2023; Turner-Skoff & Cavender, 2019). Locally, forests contribute to microclimate regulation, support sustainable livelihoods such as tourism, and supply essential household needs, particularly for communities living in forest-adjacent areas (Budiadi et al., 2025; De Frenne et al., 2021; Sutata et al., 2023), thereby making forests integral components of surrounding socio-ecological systems. These multiple roles underscore the urgency of managing forests sustainably.

Community-based forestry is often regarded as one of the most sustainable forms of forest management. Since the 1970s and 1980s, it has gained prominence based on the premise that local communities, when granted adequate property rights over forest commons, are capable of organizing autonomously and establishing local institutions to regulate resource use and manage forests sustainably. Over time, diverse forms of community forestry have emerged across countries, giving rise to terms such as community forestry, social forestry, and community-based forestry, which are often used interchangeably (Gilmour, 2016; Schusser et al., 2016). To address this terminological ambiguity, the FAO adopts community-based forestry (CBF) as an umbrella term encompassing the wide range of initiatives, policies, institutions, and processes aimed at enhancing local communities' roles in forest governance and management. CBF spans a broad spectrum of governance regimes, from government-led models to customary and communal systems and even privately managed forests (Gilmour, 2016). This approach has particular resonance in Southeast Asia, where communal and customary systems of resource management remain deeply entrenched (Wong et al., 2020).

Indonesia represents one of the most ambitious cases, where community-based forestry has been translated through the "social forestry" policy, which applies a permit-based regime to decentralize management rights over state forests, with a target of 12.7 million hectares to be managed under social forestry schemes (De Royer et al., 2018; Pambudi, 2020; Rahayu et al., 2020). This model is deeply rooted in the country's colonial legacy of land and forest tenure, under which lands considered to have no legitimate owners were claimed by the state as forest estate, a process that strengthened state authority and generated long-standing tenure conflicts (Sahide & Giessen, 2015). As community-based forestry gained global prominence, Indonesia adopted its principles. However, the country's highly state-centric tenure structure led to their translation into a government-led permit regime rather than a transformative tenure reform. Consequently, social forestry operates primarily through time-bound permits granted to communities within state forest areas (Widiyanto et al., 2025). The key exception is the customary forest (*Hutan Adat*) scheme as one of the social forestry policy schemes, which represents a genuine shift toward tenure reform by granting full and permanent rights to customary communities (Fisher et al., 2019; Maryudi et al., 2022).

The formal social forestry policy in Indonesia was initiated in 2007. This was marked by the introduction of the Community Forestry (*Hutan Kemasyarakatan*) scheme, established under Minister of Forestry (MoFor) Regulation No. 37/2007, and the People Plantation Forest (*Hutan Tanaman Rakyat*) scheme, governed by MoFor Regulation No. 23/2007. These initiatives were designed as instruments for the redistribution of forest resource access to local communities (Malik & Mawaddah, 2019). This framework was further expanded in 2008 with the enactment of MoFor Regulation No. 49/2008, which established the Village Forests (*Hutan Desa*) scheme. Despite this regulatory development, the implementation of social forestry permits between 2007 and 2014 remained limited, covering only 449,104.23 hectares. This low level of implementation indicates a lack of a strong policy drive during this period.

A significant shift occurred in 2015 when President Joko Widodo elevated social forestry to a national priority agenda under the Nawacita program, setting an ambitious target of legalizing community access to 12.7 million hectares of forest area by 2019. To streamline implementation, the Ministry of Environment and Forestry (MoEF) issued Regulation No. 83/2016, which defined five schemes under social forestry: Customary Forest (*Hutan Adat*), Village Forest (*Hutan Desa*), Community/People Plantation Forest (*Hutan Tanaman Rakyat*), Community Forestry (*Hutan Kemasyarakatan*), and Forestry Partnership (*Kemitraan Kehutanan*). Subsequent policies were enacted to accelerate the program's progress, including MoEF Regulations No. 39/2017, No. 9/2021, No. 4/2023, and Presidential Regulation (Perpres) No. 28/2023. These efforts substantially expanded social forestry allocation, with the MoEF reporting by May 2023 that 7.08 million hectares of state forest area had been granted under the social forestry scheme. The program's priority status has been reaffirmed under the administration of President Prabowo Subianto in 2024, which has signaled its intent to increase the quantitative target for the total area under social forestry permits to 15 million hectares (Kompas, 2025).

Forest management contributes directly to the implementation of the Sustainable Development Goals (SDGs; De Jong et al., 2018; Madjid et al., 2025). In particular, social forestry is designed to enhance employment opportunities and strengthen household economies through agroforestry practices and livelihood diversification (Goals 1 & 8; Gunawan et al., 2022; Rakatama & Pandit, 2020; Stoian et al., 2019). The integration of agroforestry within social forestry schemes also offers opportunities to improve local food security (Goal 2: Zero Hunger; Octavia et al., 2022). Furthermore, in line with MoEF Regulation No. 31/2017, social forestry requires the participation of women's groups in forest management activities (Goal 5: Gender Equality). Such participation is expected to go beyond "nominal" involvement, instead becoming "transformative" through active roles in formulating solutions to community challenges (Anugrah et al., 2022). Devolving management rights to local communities helps to reduce injustices and inequalities, particularly among marginalized groups living adjacent to forests (Goal 10: Reduced Inequalities; Race & Sumirat, 2015).

The implementation of social forestry in Indonesia has emerged as a significant subject of research for both domestic and international scholars. There are previous studies on preparatory actions (Maring, 2022; Putraditama et al., 2021; Wulandari et al., 2021), implementation (Iriyani et al., 2020; Wulandari & Inoue, 2018; Rahayu et al., 2024; Ramadhan et al., 2023), and the impact of social forestry (Situmorang & Yen, 2022; Wahyu et al., 2024). However, despite the growing body of literature, there remains a notable absence of studies that systematically synthesize research trends in this field. A comprehensive understanding of evolving research dynamics is essential for stakeholders to identify emerging themes and shifts in scholarly focus (Chen, 2006). Consequently, this study aims to address this gap by mapping the trajectory of social forestry research in Indonesia, thereby providing a foundation for future scholars to identify underexplored areas and contribute to a more holistic body of knowledge.

Scientometric analysis provides a systematic approach to identify structural patterns and delineate the boundaries of a research field based on databases of scientific publications. This methodology yields insights into past and present scholarly output while also forecasting future knowledge development (Olawumi & Chan, 2018). One of the key instruments in this approach is CiteSpace, a bibliometric visualization tool developed by Chaomei Chen to map research trends, collaborative networks, and conceptual transformations within a scientific domain. CiteSpace has been widely employed to assess publication trends across diverse fields, including tourism and climate change (Fang et al., 2018), forest carbon sequestration (Huang et al., 2020), sustainable tourism (Geng et al., 2024), forest hydrology (Farooqi et al., 2024), forest ecology (Singh & Borthakur, 2018), forest health and disease (Pautasso, 2016), and monitoring of forest fires (Zhang et al., 2025). Despite its extensive application across these disciplines, no study has yet employed a bibliometric approach or utilized CiteSpace to conduct a comprehensive analysis of social forestry research in Indonesia. This gap presents a significant opportunity for novel contributions to the social forestry literature.

This study employs a scientometric analysis to examine the topic of social forestry in Indonesia, utilizing CiteSpace for data visualization. Specifically, this research aims to (i) examine the publication landscape to present the actual condition of scholarly output on social forestry; (ii) map patterns of collaboration to capture the relationships among researchers and institutions; (iii) identify fundamental and pioneering studies; and (iv) trace the evolution, hotspots, and emerging research trends. The findings are expected to contribute to the future development of social forestry research by providing a comprehensive overview of current scholarly trajectories. Furthermore, by highlighting influential researchers and institutions, this study seeks to facilitate enhanced collaboration and knowledge exchange among stakeholders, thereby strengthening the scientific foundation of social forestry practice and policy.

2. Materials and Methods

2.1. Data Collection

This study employs a scientometric analysis approach to synthesize and map publications on social forestry in Indonesia, encompassing contributions from universities, research institutions, government agencies, and NGOs. Scientometric analysis is defined as a quantitative method used to examine patterns in the distribution of scientific literature, thereby providing insights into research trends (Chen et al., 2012). The study relies on secondary data obtained from the Web of Science (WoS) Core Collection, which is widely recognized as a reliable source of scholarly information. Moreover, WoS offers high data integrity, extensive temporal coverage, and comprehensive search features, ensuring both the accuracy and relevance of the findings (Geng et al., 2024).

To ensure accuracy and precision, several criteria were established for document selection:

(1) The search query in the "Topic" field included "social forestry OR community forest OR customary forest OR community plantation forest OR village forest", combined with "Indonesia" in the "All Fields" column.
(2) Only documents categorized as "Articles" were included.
(3) The geographic focus was limited to Indonesia.
(4) Only publications in English were considered.
(5) The publication period was restricted to January 1st, 2007–December 31st, 2024.

Based on these criteria, data collection was conducted on July 25th, 2025, resulting in 1,662 articles. All selected records were then downloaded and further processed using the CiteSpace application. Some doubts which readers may raise are explained as follows.

(1) Why we select "topic" rather than "title" or "abstract" as a search query: Researchers want to obtain information related to research topics on a broader scale. Meanwhile, when testing using title and abstract options, the number of publications obtained is smaller, raising concerns that it does not adequately represent the distribution of existing articles.

(2) Why we only select "articles" document: Researchers believe that articles undergo a more comprehensive review process than proceedings, so researchers consider the information presented to be more relevant and reliable.
(3) Why we select "Indonesia" as geographic focus: The geographic location is limited to Indonesia to increase the relevance of the filtered articles to the research topic, which focuses specifically on social forestry in Indonesia.
(4) Why we select "English": English is the language used by researchers around the world. Documents written in English can be understood by many readers, allowing the information they contain to be understood and utilized in a wider context. Moreover, the analysis results would be more relevant if the same language were chosen in the data file.
(5) Why we select this time publication period: Although the research was conducted in mid-2025, researchers considered that adding publication data from 2025 would be inappropriate, given that many articles may be published during the course of this research.

2.2. Data Analysis

The research data were analyzed using CiteSpace software version 6.4.2R2 (64-bit) Advanced. CiteSpace was developed to address inherent biases in traditional literature analysis methods, which often reflect the perspectives of specific disciplinary specializations and may not align with viewpoints from other fields (Chen, 2016). This necessitates an analytical tool capable of supporting multidisciplinary integration. CiteSpace was selected due to its distinct advantages over other bibliometric tools such as VOSViewer, HistCite, and SATI. Its key strengths include: (i) multidimensional analysis, enabling researchers to perform various analyses within a single platform, including cluster analysis, co-citation networks, and keyword evolution; and (ii) visualization capacity, which allows correlations, evolutions, and structural relationships among research articles to be easily identified (Geng & Maimaituerxun, 2022; Zhang et al., 2025).

The configuration of parameters in CiteSpace plays a critical role in determining the quality and scope of scientometric analysis. Accordingly, this study applied the following criteria:

(1) The time slicing was set from 2007 to 2024, with a one-year interval (years per slice = 1).
(2) Node types analyzed included authors, institutions, keywords, journal sources, and categories.
(3) Selection criteria were configured as follows: LRF = 3.0, L/N = 10, LBY = 5, and E = 1.0.

The analysis outputs were visualized in the form of "Science Knowledge Maps," which illustrate the location and size of nodes within the knowledge network (Shao et al., 2021; Wang et al., 2020). Detailed parameter information is presented in each knowledge map. In cluster graphs, silhouette values were used to measure network homogeneity, where values approaching 1 indicate higher homogeneity, and clusters are generally considered acceptable when ≥ 0.5. Meanwhile, variations in node color and size represent differences in publication years and citation frequencies of individual articles within the network (Lin et al., 2025; Wang et al., 2020).

3. Results

3.1. Research Overview

3.1.1. Analysis of Annual Publication

The publication trend on social forestry has shown a general increase from 2007 to 2024, despite intermittent declines in certain years (2012–2013; 2017–2018; 2020–2021; 2022–2023). Since 2017, the annual number of publications on social forestry has consistently exceeded 100 articles per year. This pattern reflects the growing enthusiasm of researchers to engage in social forestry studies in Indonesia.

Based on the dynamics of literature development (see Figure 1), research on social forestry in Indonesia can be divided into three phases: (i) the start-up phase (2007–2011), characterized by relatively slow growth in publications, with an average of 29 articles per year; (ii) the early development phase (2012–2016), during which the number of publications increased, with an average annual output of 57 articles. Although there was a temporary decline in 2013 (34 articles), publication numbers rebounded and more than doubled by 2015 (71 articles); and (iii) the rapid growth phase (2017–2024), marked by a significant surge in scientific productivity, with an average of 137 articles per year, approximately 2.4 times higher than in the previous phase.

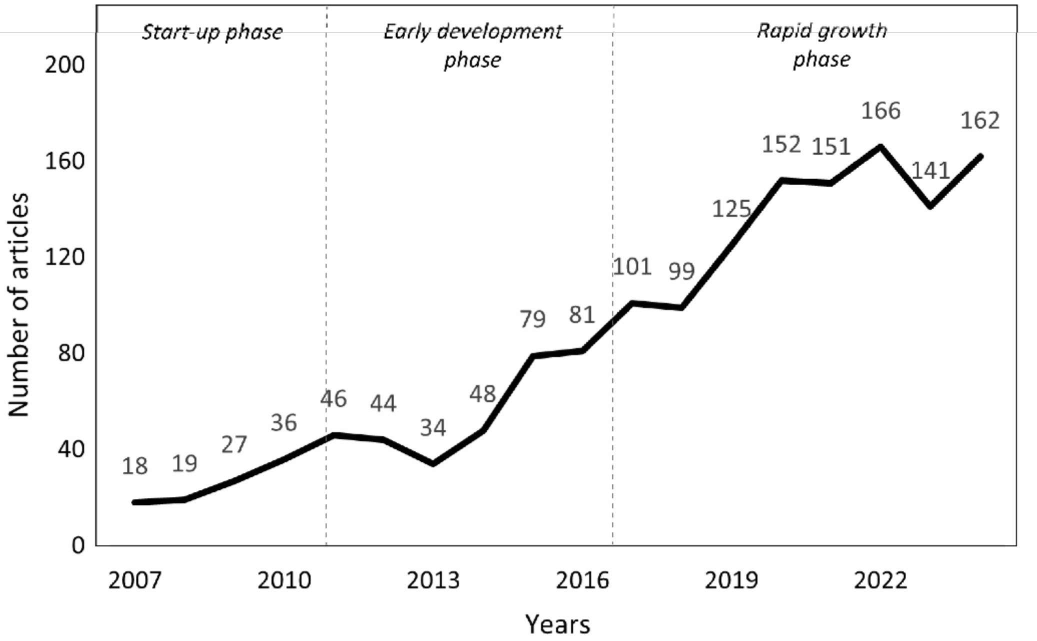

Figure 1. Trend of annual publication.

The dynamics of annual scientific publication volume on social forestry in Indonesia demonstrate a strong correlation with the evolution of national policy directions. The findings of this study indicate that during the period of 2007–2014, publication output remained relatively low, averaging fewer than 50 publications per year. This aligns with the limited realization of social forestry permits issued by the government during the same period, reflecting that social forestry had yet to emerge as a strategic issue in national forest governance. The trend shifted significantly after 2015, marked by a consistent rise in annual publications following the designation of social forestry as a national strategic agenda by President Joko Widodo. This policy transformation spurred growing attention from multiple actors, including research institutions, government agencies, and international organizations, toward social forestry issues in Indonesia. Such a phenomenon underscores the substantial leverage of public policy in shaping both the direction and intensity of scientific publication output.

3.1.2. Analysis of Research Areas

Table 1 presents the top 10 categories for the classification of scientific articles in the field of social forestry in Indonesia. The key findings can be summarized as follows: (i) The majority of research falls within a closely related thematic scope. Research is predominantly situated in the natural sciences, represented by fields such as forestry, environmental sciences, ecology, environmental studies, biodiversity conservation, and plant sciences. In addition, several fields extend beyond the natural sciences, including economics and green sustainable technology, as well as multidisciplinary sciences, which encompass broader research topics. (ii) The distribution of research fields is concentrated in specific categories. Forestry ranks first with 511 articles, followed by environmental sciences (307 articles) and ecology (293 articles). The ‘forestry’ category holds the highest proportion, accounting for nearly one-third of the total publications on social forestry.

Table 1. Top 10 research areas by number of articles.

Rank	Research Areas	Number of Articles	%
1	Forestry	511	30.75
2	Environmental Sciences	307	18.47
3	Ecology	293	17.63
4	Environmental Studies	292	17.57
5	Biodiversity Conservation	147	8.84
6	Multidisciplinary Sciences	92	5.54
7	Economics	91	5.48
8	Green Sustainable Technology	66	3.97
9	Plant Sciences	40	2.41
10	Biology	36	2.19

3.1.3. Analysis of Published Journals

Table 2 presents the top ten journals that have published research articles on social forestry in Indonesia. The findings can be summarized as follows: (i) All journals are linked to environmental issues, with a strong emphasis on forestry, as evidenced by six journals explicitly including the term forest in their titles. (ii) The number of publications varies considerably across journals. *Jurnal Manajemen Hutan Tropika* ranks first with 109 articles on the subject, followed by Forest and Society (70 articles) and Forest Policy and Economics (62 articles). Journals ranked 4th to 10th each published fewer than 50 articles on the topic. (iii) Thirty percent of the journals originate from Indonesia. Among the top ten, three are published by Indonesian institutions: Jurnal Manajemen Hutan Tropika (IPB University), Forest and Society (Hasanuddin University), and Indonesian Journal of Forestry Research (Forestry Research and Development Agency/FORDA, Ministry of Forestry Indonesia). (iv) Journal impact factors (IF) do not appear to influence publication volume. The top ten journals publishing on social forestry in Indonesia have IF values ranging from 0.75 to 6.992, yet these figures do not determine the ranking in terms of publication output.

Table 2. Top 10 journals by number of articles.

Rank	Journal	Articles	%	IF 2024
1	Jurnal Manajemen Hutan Tropika	109	6.56	0.808
2	Forest and Society	70	4.21	2.127
3	Forest Policy and Economics	62	3.73	4.627
4	Forests	47	2.83	2.793
5	International Forestry Review	47	2.83	1.15
6	Land Use Policy	34	2.05	6.992
7	PLOS One	31	1.87	2.824
8	Sustainability	30	1.81	4.320
9	Indonesian Journal of Forestry Research	29	1.74	0.75
10	Land	23	1.38	3.617

3.2. Partnerships

3.2.1. Analysis of Institutional Collaboration

Information on institutional collaboration within the top ten institutions in the field of social forestry is presented in Table 3. The key points can be summarized as follows: (i) Collaboration intensity, shown in the count column, indicates that CIFOR recorded the highest level of collaboration (335), followed by Bogor Agricultural University (225) and Universitas Gadjah Mada (148), respectively. (ii) Centrality values reflect the strength of institutional linkages. The three institutions with the most significant roles in the collaboration structure are CIFOR, Bogor Agricultural University, and Universitas Gadjah Mada, with centrality scores of 0.42, 0.22, and 0.16, respectively. (iii) Collaboration among the top ten institutions began during the start-up phase (2007–2011), in line with early publication trends. To date, these institutions continue to engage in social forestry research collaboration, as evidenced by their count and centrality values. A visualization of these institutional networks is provided in Figure 2.

Table 3. Top 10 analysis of institutional cooperation.

Rank	Count	Centrality	Starting year	Institution
1	335	0.42	2007	Center for International Forestry Research (CIFOR)
2	225	0.22	2007	Bogor Agricultural University
3	148	0.16	2014	Universitas Gadjah Mada
4	84	0.04	2022	BRIN
5	75	0.09	2008	Gottingen University
6	44	0.01	2017	Universitas Indonesia
7	41	0.1	2014	Ministry Environment & Forestry
8	41	0.04	2017	James Cook University
9	38	0.03	2017	University British Columbia
10	34	0.06	2013	Indonesian Institute Science

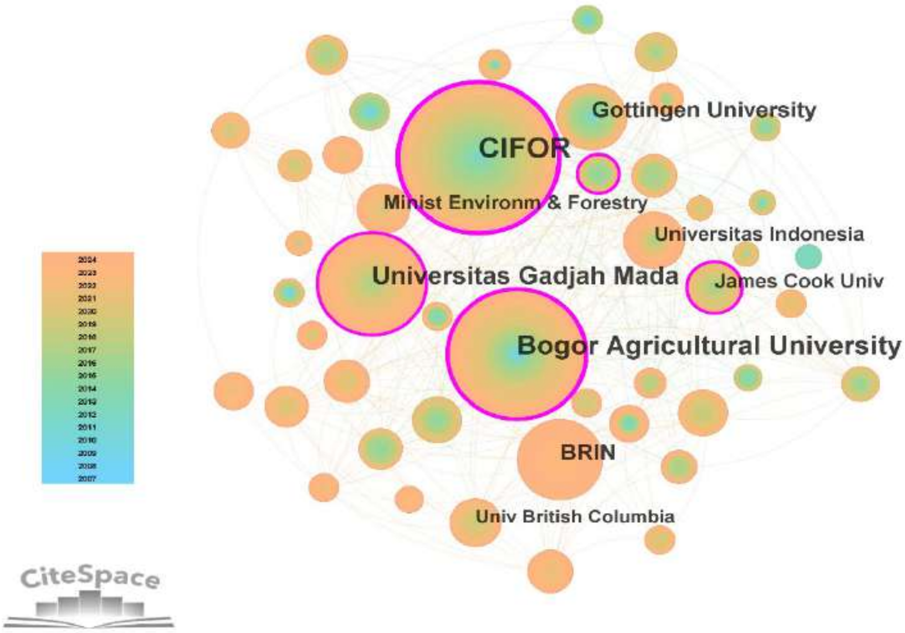

Figure 2. Knowledge map of institutional collaboration.

CIFOR and Bogor Agricultural University are two institutions that rank highest in collaboration on social forestry research in Indonesia. Collaboration between CIFOR and Bogor Agricultural University began in 1997 with a focus on contributing to the development of science in Indonesia (CIFOR, 2017). This collaboration continues, as evidenced by a cooperation contract that is renewed every five years.

3.2.2. Analysis of Country Collaboration

The results of the country-level collaboration analysis (Figure 3) show that Indonesia ranks the highest in producing publications on the selected topic. This is expected, given that the research focus is on social forestry in Indonesia. Nevertheless, several other Asian countries, such as Malaysia and Japan, also demonstrate an interest in conducting research on this topic. In addition, several countries are represented by relatively large nodes, such as England, the USA, Australia, and Germany, indicating a high intensity of publications and collaborative activities. This pattern highlights that Indonesian researchers have the potential to collaborate extensively with scholars from other countries, thereby expanding their networks and producing more comprehensive research outcomes.

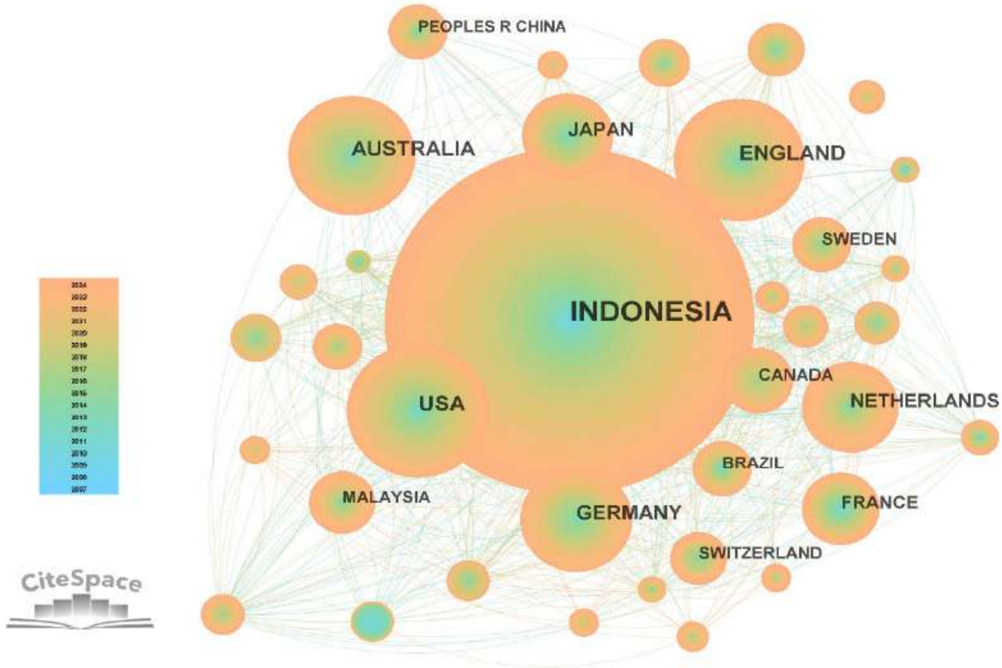

Figure 3. Knowledge map of country collaboration

3.2.3. Analysis of Author Collaboration

Table 4 presents the top 10 authors with the highest number of publications on the topic under study. Ahmad Maryudi, a Professor at the Faculty of Forestry, Universitas Gadjah Mada, Indonesia, ranks first in research on social forestry in Indonesia. His studies primarily focus on the role of actors, institutions, and social forestry policies in the country. Ahmad Maryudi began collaborative research on social forestry policy in 2016 by examining decentralization policies as a strategy for recentralization, continued with a study on customary forest schemes as a prior option for social forestry implementation, and further explored the development of social forestry policy in Indonesia along with its local-level implementation (Myers et al., 2017; Sahide et al., 2016; Sahide et al., 2020). Furthermore, Douglas Sheil, a Professor of Forest Ecology and Forest Management at Wageningen University and Research, the Netherlands, also stands out among the most productive authors. His research in 2007 focused on local conservation practices to maintain tropical forest landscape cover (Padmanaba & Sheil, 2007). Although not originally from Indonesia, Douglas Sheil has demonstrated a strong interest in the topic of social forestry in Indonesia, as evidenced by his 36 published articles on the subject.

Table 4. Top 10 authors collaboration analysis.

Rank	Count	Centrality	Year	Author	Institution
1	43	0.19	2016	Maryudi, Ahmad	Universitas Gadjah Mada
2	36	0.26	2007	Sheil, Douglas	Wageningen University and Research
3	26	0.17	2017	Sunderland, Terry	University of British Columbia
4	24	0.02	2015	Baral, Himlal	Center for International Forestry Research
5	22	0.04	2012	Meijaard, Erik	University of Kent
6	18	0.04	2012	Brockhaus, Maria	University of Helsinki
7	15	0.09	2020	Fisher, Micah R.	University of Hawaii
8	14	0.04	2009	Nasi, Robert	CIFOR
9	14	0.03	2010	Buchori, Damayanti	Bogor Agricultural University
10	14	0.00	2015	Giessen, Lukas	Dresden University of Technology

In the author collaboration network, each node represents an individual author. The size of the node corresponds to the number of articles published by that author, while the connecting lines between nodes indicate collaborative relationships between authors (Wang et al., 2020). The author collaboration analysis revealed a network comprising 196 nodes and 200 connections (Figure 4). A larger node size signifies a greater number of publications by the researcher in the field of social forestry in Indonesia, whereas the connecting lines represent co-authorship relationships between researchers. The visualization presented in Figure 4 indicates that several authors, including Ahmad Maryudi, Douglas Sheil, and Terry Sunderland, have engaged in extensive collaboration with other researchers.

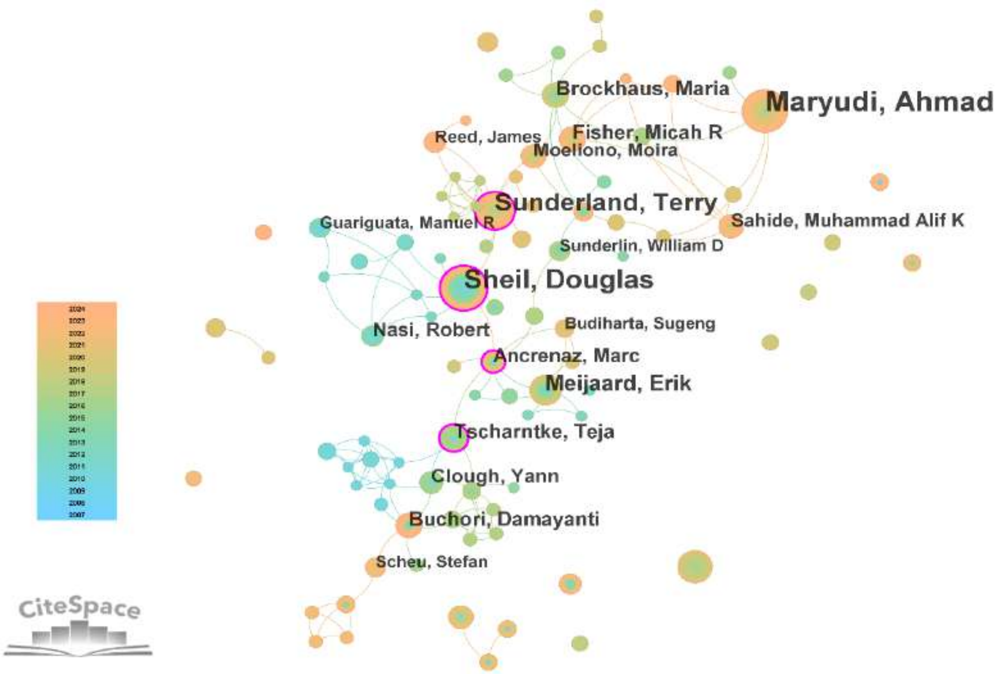

Figure 4. Collaborative authorship mapping in the social forestry topic.

3.3. Co-Citation Analysis

3.3.1. Author Co-Citation Analysis

This analysis illustrates the condition in which documents authored by different writers are cited within the same publication (Sun et al., 2025). The top 10 results of the author co-citation analysis are presented in Table 5. The findings indicate that eight authors received more than 100 citations, with the top three being Ostrom E, Agrawal A, and FAO, with citation frequencies of 141, 139, and 133, respectively. The results further demonstrate that not all highly co-cited entities are individual authors; some, such as FAO, represent institutional or group authors comprising researchers from diverse disciplinary backgrounds.

Table 5. Top 10 author co-citation analysis.

Rank	Count	Year	Author
1	141	2009	Ostrom E.
2	139	2007	Agrawal A.
3	133	2007	FAO
4	115	2016	Sahide M. A. K.
5	112	2014	Maryudi A.
6	111	2008	Sunderlin W. D.
7	111	2009	Larson A. M.
8	108	2010	Angelsen A.
9	96	2015	Margono B. A.
10	86	2013	Peluso N. L.

The researchers ranked in the top 10 in the co-citation analysis produced various studies that played a very important role in the development of social forestry research topics in Indonesia because they provided supporting information for conducting further research. Specifically, Ostrom's (1999) research focuses on forest management as a shared resource utilized by various stakeholders, including how to regulate management activities. Furthermore, Agrawal (2003) focuses on the division of roles and responsibilities between the community and the government in the decentralization of forest management.

The visualization of the author's co-citation analysis on social forestry research in Indonesia is presented in Figure 5, consisting of 174 nodes and 419 links. The varying node sizes indicate that larger nodes represent authors whose works have received higher citation counts. Meanwhile, the connections between authors are represented by links, signifying that in other publications, two or more authors are co-cited to support the development of a new article.

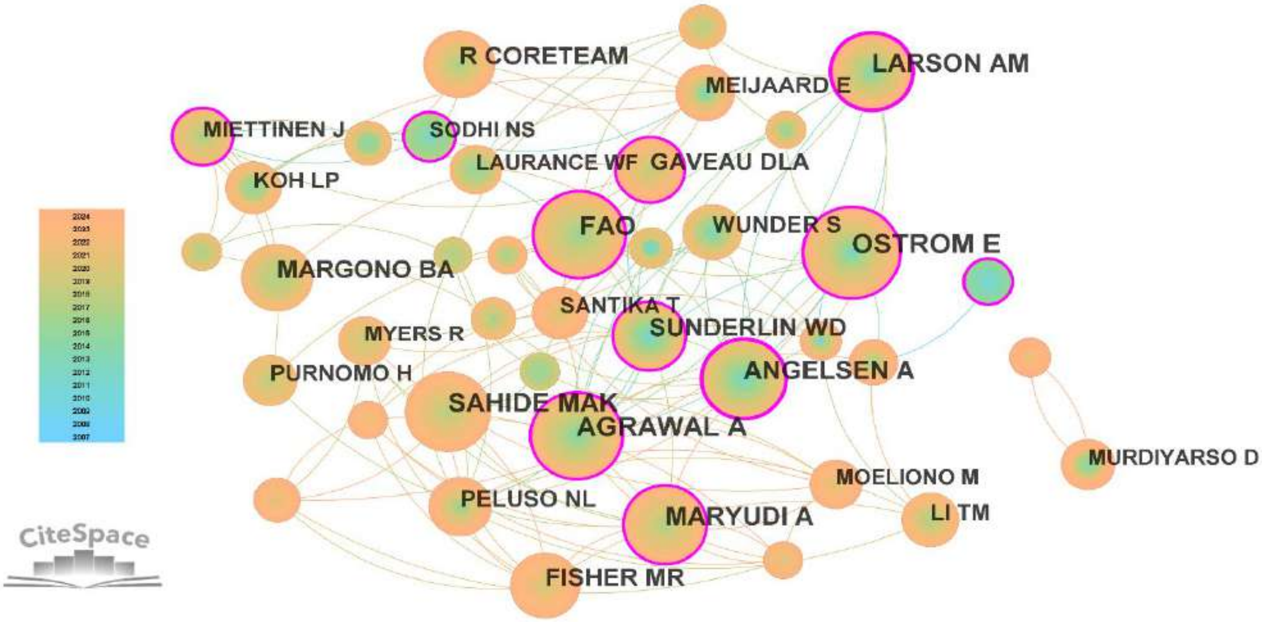

Figure 5. Knowledge map of author co-citation in the social forestry topic.

3.3.2. Journal Co-Citation Analysis

The journal co-citation analysis illustrates how two journals are cited together within a scientific article (Sun et al., 2025), reflecting the extent to which both journals jointly contribute to the development of new research. Table 6 presents the top 10 journals with the highest co-citation frequencies. Research on social forestry is broadly supported by journals in these top 10 rankings, with the three leading journals being Science, Forest Policy and Economics, and PLOS One, which recorded co-citation frequencies of 564, 488, and 482, respectively. The data also indicate that the impact factors of the top 10 journals range from 2.824 to 18.473, underscoring that articles published in these outlets exert a significant influence on advancing knowledge in social forestry as well as in broader forestry research.

Table 6. Top 10 author co-citation analysis.

Rank	Count	IF 2024	Journal
1	564	15.263	Science
2	488	4.627	Forest Policy and Economics
3	482	2.824	PLOS One
4	456	5.724	World Development
5	440	6.992	Land Use Policy
6	425	4.125	Forest Ecology and Management
7	419	4.406	Biological Conservation
8	408	5.573	Conservation Biology
9	400	18.473	Nature
10	391	3.395	Ecology and Society

The visualization of the journal co-citation analysis is presented in Figure 6, limited to journals with at least 200 citations. The co-citation network highlights several leading journals in forestry and ecology, such as Science, World Development, Forests, Ecology and Society, Biological Conservation, and Ecology, which display large node sizes and dense interconnections. This indicates that these journals publish highly influential articles with a broad reach in the field of social forestry in Indonesia. Publications in these outlets integrate social forestry research from both theoretical and practical perspectives, while also elucidating various aspects of its on-the-ground implementation.

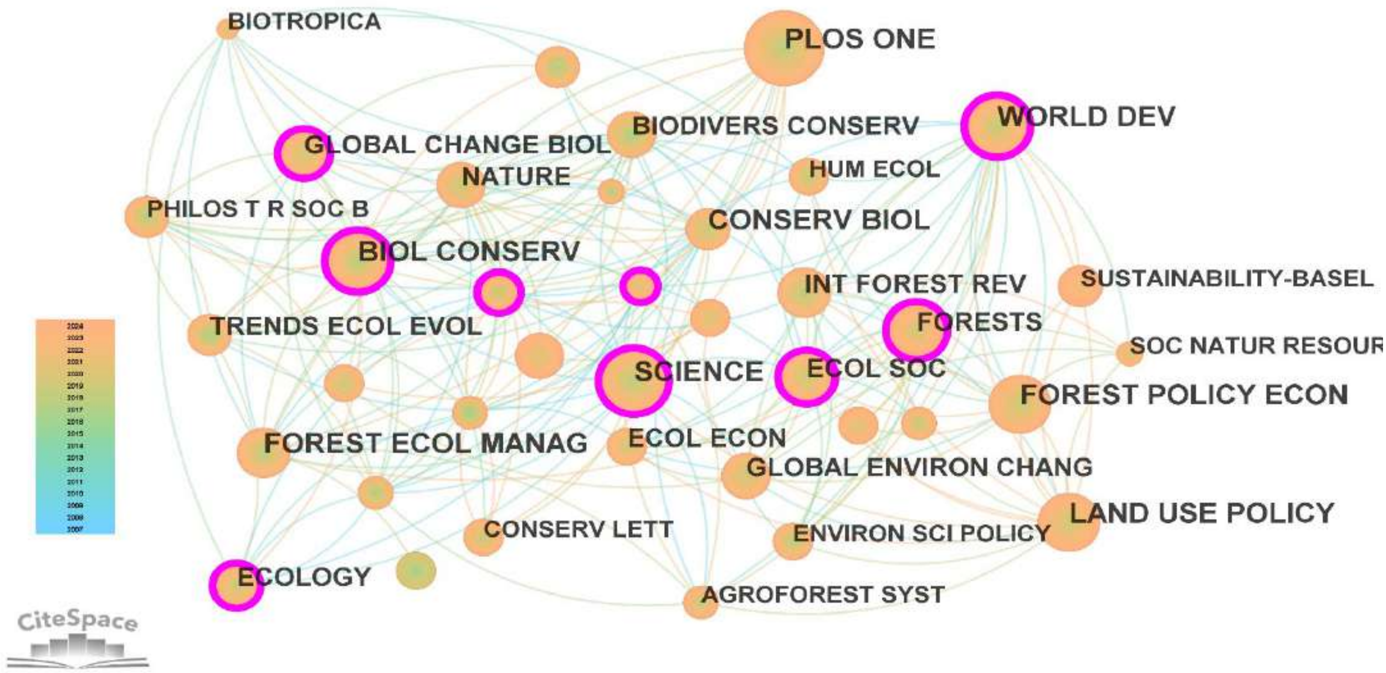

Figure 6. Knowledge map of journal co-citation in the social forestry topic.

3.3.3. Co-Citation Analysis of Literature

Literature co-citation analysis examines how two publications are cited together within a new article. This method helps researchers understand the knowledge structure of a scientific field, identify its research boundaries, and recognize key foundational literature (Sun et al., 2025). The strength of a publication's influence in co-citation analysis is determined by the "strength" value; a higher value indicates a greater influence on the development of subsequent research. Table 7 presents the top 10 publications from the literature co-citation analysis, with strength values ranging from 6.62 to 11.06.

Table 7. Top 10 co-citation analysis of literature.

Rank	Author	Year	Begin	End	Strength	Title
1	Rakatama A.	2020	2022	2024	11.06	Reviewing social forestry schemes in Indonesia: Opportunities and challenges
2	Fisher M. R.	2019	2020	2024	9.1	The politics, economies, and ecologies of Indonesia's third generation of social forestry: An introduction to the special section
3	Sahide M. A. K.	2015	2016	2020	8.92	The fragmented land use administration in Indonesia – Analysing bureaucratic responsibilities influencing tropical rainforest transformation systems
4	Fisher M. R.	2018	2020	2024	8.89	Assessing the new social forestry project in Indonesia: recognition, livelihood, and conservation?
5	Margono B. A.	2014	2018	2019	8.59	Primary forest cover loss in Indonesia over 2000–2012
6	De Royer S.	2018	2020	2024	7.97	Does community-based forest management in Indonesia devolve social justice or social costs?
7	Sahide M. A. K.	2020	2022	2024	7.63	The boom of social forestry policy and the bust of social forests in Indonesia: Developing and applying an access-exclusion framework to assess policy outcomes
8	Sahide M. A. K.	2018	2019	2021	6.96	Deadlock opportunism in contesting conservation areas in Indonesia
9	Fatem S. M.	2018	2019	2022	6.62	Camouflaging economic development agendas with forest conservation narratives: A strategy of lower governments for gaining authority in the re-centralising Indonesia
10	Purnomo H.	2017	2019	2022	6.62	Fire economy and actor network of forest and land fires in Indonesia

The analysis revealed that the top 10 articles were authored by seven different scholars, with Sahide M. A. K. and Fisher M. R. contributing three and two articles, respectively, that ranked within the top 10 co-cited publications. Sahide's three articles focus on policy analysis related to social forestry permits and conservation areas in Indonesia (Sahide & Giessen, 2015; Sahide et al., 2018; Sahide et al., 2020). Meanwhile, Fisher's works examine the implementation of social forestry in Indonesia from political, economic, and ecological perspectives (Fisher et al., 2018; Fisher et al., 2019). Both scholars anchor their research within a social science framework.

In detail, Sahide M. A. K. explains that the management of Indonesia's tropical forests can be directed towards community-based management for plantation forests and agroforestry patterns (Sahide & Giessen, 2015). However, forest management by communities through social forestry needs to be monitored to ensure that community rights and access are in accordance with existing regulations (Sahide et al., 2020). Research conducted by Fisher M. R. emphasizes that the concept of social forestry in Indonesia is based on three main components: a) decentralization of management permits to communities, b) supporting livelihood resources, and c) achieving conservation goals (Fisher et al., 2018).

The literature co-citation analysis also reveals the point in time when articles first began to be cited together in subsequent research, with variations influenced by their respective publication years. Among the top 10 co-cited articles, the earliest co-citation occurrence was in 2016, while the most recent was in 2022. The duration of a literature co-citation is indicated by the interval between the initial and final years in which the articles were cited together. In this analysis, five articles show their co-citation period ending in 2024. However, it is presumed that their co-citation does not actually end in 2024; rather, this is a limitation of the time span applied in the present study, which records 2024 as the terminal year.

3.4. Co-Occurrence Evolution

3.4.1. Co-Occurrence of Keywords

Keywords represent terms selected by authors to describe the main content of an article, thereby facilitating the search process. Co-occurrence keywords refer to terms that frequently appear together and serve to represent the thematic focus of research. The results of the keyword co-occurrence analysis for the top 10 ranked terms are presented in Table 8. According to the table, the keywords "conservation" and "management" emerge most frequently in social forestry publications, with the largest node sizes and frequencies of 248 and 203, respectively. In addition, seven other keywords ("forest," "biodiversity," "community," "diversity," "deforestation," "governance," and "ecosystem services") each occur more than 100 times. Only the keyword "climate change" appears with a frequency below 100.

Table 8. Top 10 author co-citation analysis.

Rank	Count	Year	Centrality	Keyword
1	248	2007	0.2	conservation
2	203	2007	0.15	management
3	193	2007	0.17	forest
4	168	2007	0.1	biodiversity
5	158	2007	0.14	community
6	136	2007	0.14	diversity
7	106	2007	0.07	deforestation
8	106	2014	0.03	governance
9	105	2013	0.05	ecosystem services
10	93	2008	0.07	climate change

The centrality value in Table 8 indicates the relative influence of keywords within the social forestry article network. The keyword "conservation" demonstrates a particularly strong influence, evidenced by its centrality value of 0.20, which is notably higher than other keywords with values ranging from 0.03 to 0.17. This suggests that "conservation" plays a pivotal role within the keyword co-occurrence network, especially in the context of social forestry research in Indonesia. Furthermore, the emergence and top ranking of the keyword "conservation" highlight that research focused on social forestry holds significant importance for forest resource and biodiversity conservation efforts.

3.4.2. Keyword Clustering

Keyword cluster analysis is the process of grouping keywords from various publications that share common themes and relationships into distinct clusters (Sun et al., 2025). The results of this analysis, based on the keywords used for document retrieval in this study, yielded seven cluster labels. A smaller cluster label number indicates a larger number of keywords grouped within it and a higher relevance to the core research topic (Sun et al., 2025). The identified keyword clusters are as follows: #0 social forestry, #1 diversity, #2 tropical forest, #3 oil palm, #4 sustainable development, #5 peatland, and #6 sustainable forest management (Figure 7). These clusters were subsequently categorized by the researchers as follows:

- Forests and ecosystems: "social forestry" and "diversity". This cluster focuses on social forestry permits, their implementation at the local level, and the ecological diversity of forest ecosystems managed by communities through social forestry schemes.
- Land use and land cover: "tropical forests", "oil palm", and "peatland". This cluster highlights the biophysical conditions of land and land cover in the context of social forestry implementation. It indicates that social forestry is not limited to state forests on mineral soils but also extends to peatland areas.
- Technical implementation: "sustainable forest management" and "sustainable development". This cluster centers on the sustainable management of social forestry, aimed at supporting forest management practices that balance ecological, economic, and social dimensions.

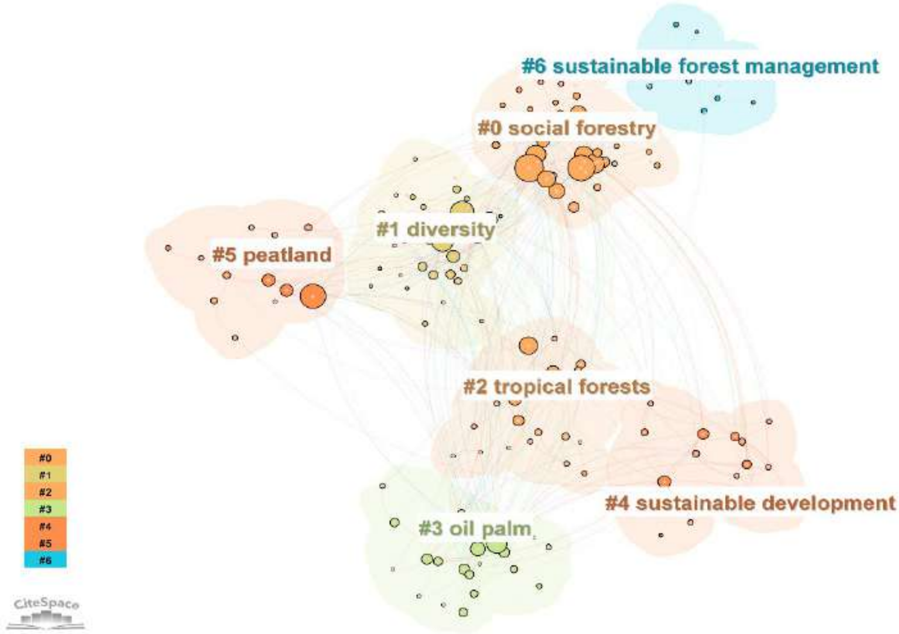

Figure 7. Keyword clustering map.

3.4.3. Analysis of Research Hotspots

Research hotspots represent research topics that have received particular attention from scholars within a specific time span (Li & Chen, 2017). In this study, research hotspots were identified using the burst detection function in CiteSpace 6.4.2R2 (64-bit) Advanced. The selected time interval was 2007–2024, visualized as blue lines, while red lines of larger size indicate the start and end periods of keyword bursts (Huang et al., 2020). Figure 8 provides several pieces of information for readers. The section "Keywords" lists terms according to the timeline of their bursts, with earlier bursts appearing higher in the ranking. "Strength" indicates the magnitude of change associated with each selected keyword (Sun et al., 2025), while "begin" and "end" mark the start and end years of each keyword burst. The greater the difference between "end" and "begin," the longer the burst duration, which signifies that the keyword has served as a research hotspot for a longer period compared to others.

Keywords	Year	Strength	Begin	End	2007 - 2024
biodiversity conservation	2007	4.79	**2007**	2015	
diversity	2007	3.67	**2007**	2010	
tropical forest	2008	5.53	**2008**	2015	
property rights	2011	4.94	**2011**	2014	
non-timber forest products	2011	4.45	**2011**	2012	
tropical forests	2011	4.42	**2011**	2012	
deforestation	2007	6.29	**2012**	2014	
sustainable forest management	2012	4.23	**2012**	2017	
rights	2014	4.23	**2014**	2020	
benefits	2015	3.75	**2015**	2020	
kalimantan	2016	3.93	**2016**	2021	
opportunity	2016	3.9	**2016**	2017	
consequences	2016	3.84	**2016**	2018	
expansion	2016	3.62	**2016**	2019	
redd plus	2017	4.9	**2017**	2020	
oil palm plantations	2017	4.58	**2017**	2019	
social forestry	2008	6.24	**2019**	2024	
restoration	2019	5.85	**2021**	2024	
ecosystem	2021	4.55	**2021**	2024	
power	2017	5.37	**2022**	2024	

Figure 8. Emergent keyword analysis (top 20).

Research hotspots are divided into three distinct timelines. Specifically, during the start-up phase (2007–2011), the emerging keywords included “biodiversity conservation” (first appeared in 2007, identified as a hotspot in 2007–2015), “diversity” (first appeared in 2007, hotspot in 2007–2010), “tropical forest” (first appeared in 2008, hotspot in 2008–2015), “property rights” (first appeared in 2011, hotspot in 2011–2014), “non-timber forest products” (first appeared in 2011, hotspot in 2011–2012), and “tropical forests” (first appeared in 2011, hotspot in 2011–2012). Research in this pioneering phase primarily focused on community rights in forest management activities through state-granted permits under the community-based forest management scheme (Fujiwara et al., 2012; Mulyoutami et al., 2009; Suwarno et al., 2009), with emphasis on the utilization of both timber and non-timber forest products (Barkmann et al., 2010; Siregar et al., 2007).

The early development phase (2012–2016) featured research hotspots consisting of the keywords “deforestation,” “sustainable forest management,” “rights,” “Kalimantan,” “opportunity,” “consequences,” and “expansion.” Research during this phase primarily focused on the application of forest certification as a means to implement sustainable forest management (Harada & Wiyono, 2014). In addition, attention was also directed toward the implementation of community-based forest management programs and the subsequent consequences of their execution (Prasetyo et al., 2012).

Furthermore, the rapid growth phase (2017–2024) revealed bursts in the keywords “REDD+,” “oil palm plantations,” “social forestry,” “restoration,” “ecosystem,” and “power” during the 2017–2024 period. Research in this phase focused on evaluating the implementation of social forestry programs in Indonesia through various existing schemes (such as *hutan desa, hutan adat, hutan kemasyarakatan, hutan tanaman rakyat*, and *kemitraan kehutanan*; Nikmatullah et al., 2024; Rochmayanto et al., 2022; Santika et al., 2017). In addition, research increasingly emphasized the management of community oil palm plantations, which could be addressed within the framework of social forestry schemes (Madjid et al., 2023).

3.5. Knowledge Framework

The findings of this study offer a comprehensive overview of research hotspots within the field of social forestry in Indonesia. Specifically, it elucidates the temporal evolution of research, the contributions of influential authors, the role of journals in knowledge dissemination, collaborative networks among researchers, and frequently occurring keywords in the literature. Based on an analysis of 1,662 documents from the Web of Science, this study constructs a robust theoretical framework that reflects the current state of social forestry research while providing direction for future investigations (Figure 9). These outcomes are fully aligned with the research aims outlined earlier.

Figure 9. Knowledge framework of social forestry research in Indonesia.

3.5.1. Research Aims (1): Present Publication Landscape

Publication trend analysis reveals a consistent annual increase in the number of publications on social forestry in Indonesia. The timeline can be categorized into three distinct phases: a start-up phase (2007–2011), an early development phase (2012–2016), and a rapid growth phase (2017–2024). The most significant expansion occurred during the rapid growth phase, where the annual publication output averaged 100 articles. This surge in scholarly output aligns closely with the accelerated implementation of social forestry policies following the formal definition of its schemes under MoEF Regulation No. 83 of 2016. Across the entire period, Indonesian journals dominate the field, with the top two journals, Jurnal Manajemen Hutan Tropika and Forest and Society, originating from Indonesia, followed by Forest Policy and Economics. Thematic analysis indicates a continued strong emphasis on natural sciences, with the top three research domains being forestry, environmental sciences, and ecology.

3.5.2. Research Aims (2): Collaboration, the Relationship Between Researchers and Institutions

Collaboration analysis reveals distinct dynamics in co-authorship patterns across individual researchers, countries, and institutions. At the individual level, the most prolific authors focusing on social forestry research are Ahmad Maryudi, Douglas Sheil, and Terry Sunderland. The top three countries contributing to collaborative research in this domain are Indonesia, the United States, and the United Kingdom. Furthermore, institutions such as the Center for International Forestry Research (CIFOR), IPB University (Bogor Agricultural University), and Universitas Gadjah Mada demonstrate strong research engagement in Indonesian social forestry, as evidenced by the substantial number of publications contributed by their affiliated authors on this topic.

3.5.3. Research Aims (3): the Fundamental and Pioneering Researches

Co-citation analysis illustrates how a publication by one researcher is intellectually connected to other researchers, journals, and references within the scholarly landscape. This analysis reveals that the work of Ostrom E., Agrawal A., and the Food and Agriculture Organization (FAO) serves as foundational references for subsequent research in the field. Furthermore, the journals Science, Forest Policy and Economics, and PLOS One rank as the top three most frequently co-cited journals, indicating their substantial influence on social forestry research. Additionally, articles published by Rakatama and Pandit (2020), Fisher et al. (2019), and Sahide and Giessen (2015) hold strong positions in the co-citation network, underscoring their role as pivotal references for generating new research within the domain of social forestry.

3.5.4. Research Aims (4): Evolution, Hotspots, and Emerging Research Trends

Co-occurrence analysis serves to identify topics that have attracted significant research attention, as evidenced by the frequency and clustering of keywords. From 2007 to 2024, the keywords “conservation”, “management”, and “forest” ranked as the three most frequently occurring terms. Meanwhile, keywords such as “restoration”, “ecosystem”, and “power” have emerged as prominent and influential themes over the past three years. Keywords related to social forestry in Indonesia were grouped into three major clusters: forest and ecosystem, land use and land cover, and technical implementation.

4. Discussion

4.1. Comparative Discussion

This study adopts a bibliometric approach to examine the development of social forestry research in Indonesia over time, providing readers with information on the distribution of articles, authors, journals, and keywords, especially those with high impact. Similar studies summarizing trends in social forestry research in Indonesia have not been conducted before. However, there are several studies that focus on reviewing the relationship between social forestry and biodiversity conservation (Gunawan et al., 2022), smart agroforestry in social forestry (Octavia et al., 2022), and the opportunities and challenges of implementing social forestry in Indonesia (Rakatama & Pandit, 2020).

This study conducts a comprehensive analysis based on several sources of information, such as publications, collaboration between authors and institutions, co-citation analysis, and co-occurrence analysis. The researchers summarized the available information into a knowledge framework with the aim of providing readers with holistic and comprehensive information on the development of social forestry research in Indonesia. This is in line with the research by Sun et al. (2025), which summarizes the development of forestry education research, with one of its novelties being the existence of a knowledge framework.

In the context of Indonesia’s forestry policy development, the bibliometric results of this study reveal a reciprocal relationship between scientific scholarship and key governance shifts. The early development stage in 2012 aligns with Constitutional Court Decision No. 35/PUU-X/2012, which radically redefined the status of customary forests by removing them from the state forest domain. This ruling marked a foundational shift in Indonesia’s tenure regime and appears to have stimulated the initial wave of academic interest in social forestry (see Sahide & Giessen, 2015). A much sharper rise in publications, the rapid phase beginning in 2016, corresponds with another cluster of significant policy reforms, particularly the issuance of the Ministry of Environment and Forestry Regulation No. 83/2016 that formally established the five social forestry schemes, and the creation of the Directorate General of Social Forestry and Environmental Partnership in 2015. These developments reflect a growing institutional commitment to social forestry and appear to have reinforced the expansion of scientific engagement with the topic. Together, these temporal patterns indicate that policy reforms and scientific inquiry have evolved in mutually reinforcing ways.

In light of the policy–knowledge interactions described above, the bibliometric analysis also reveals the structure of Indonesia’s social forestry knowledge network. Three institutions, CIFOR Bogor Agricultural University, and Universitas Gadjah Mada, consistently emerge as central knowledge producers with substantial contributions to research on social forestry. At the individual level, scholars such as Maryudi A., Sunderland T., Sheil D., Sahide M. A. K., Rakatama A., and Fisher M. dominate the authorship landscape and have been prominent in shaping academic discussions surrounding social forestry. While the bibliometric evidence does not allow direct claims about their influence on policy development, the visibility and concentration of research across these institutions and scholars suggest a close alignment between knowledge production and the policy trajectories observed in Indonesia’s social forestry.

4.2. Future Research Direction

Social forestry policy in Indonesia demonstrates a highly promising trajectory, underscored by its inclusion as a national priority program. Under the current administration of President Prabowo Subianto, over 8.4 million hectares of state forest area have already been incorporated under social forestry schemes, with further expansion anticipated in alignment with the Asta Cita development agenda, particularly in relation to food security and self-sufficiency (MoFor, 2025). This strong policy commitment signals continued institutional and financial support, making social forestry a compelling area for in-depth research aimed at refining implementation frameworks and evaluating impacts. Furthermore, the domestic capacity for scholarly publication has significantly strengthened, as demonstrated by the prominence of Indonesian journals in this field, exemplified by *Jurnal Manajemen Hutan Tropika* and *Forest and Society* in this analysis. This robust local publishing ecosystem facilitates greater accessibility and visibility for Indonesian researchers. The dominance of domestic authors and institutions in collaboration networks further indicates a high level of academic engagement and institutional prioritization of social forestry research within the country. Nevertheless, despite these advancements, several promising niche research areas remain underdeveloped and merit further attention, including:

(1) Expanding Research Collaboration Geographically

This study aligns with the findings of Rakatama and Pandit (2020), which identified a strong geographical concentration of social forestry research in Western Indonesia. A similar western-centric bias is evident in the composition of research leadership: the top affiliated institutions, Bogor Agricultural University, CIFOR, and Universitas Gadjah Mada, are located on Java. However, a promising shift is emerging with the increasing contributions from institutions in Eastern Indonesia, such as Hasanuddin University, which is home to prominent researcher M.A.K. Sahide and hosts the influential journal Forest and Society. Despite this progress, a critical need remains to further expand the inclusion of experts and institutions from Eastern Indonesia. This expansion is strategically imperative, as current national forestry policy is increasingly targeting Eastern Indonesia for development and governance interventions, making localized research expertise essential for effective and contextually relevant implementation.

(2) Gender and Equity Matters

Despite policy mandates for gender inclusion (e.g., PermenLHK 31/2017), women's participation remains under-researched, as evidenced by the absence of prominent keywords related to gender/woman, or authors that focused on gender in the analytical results. Future research should adopt transformative frameworks to analyze how gender equity influences resource access, decision-making, benefit-sharing, and women's leadership in social forestry.

(3) Integrating Landscape Approach

The keyword clustering map, which highlights terms such as "oil palm" and "peatland," along with the emergence of related keywords like "oil palm plantations" and "ecosystem," indicates that social forestry significantly intersects with other land use and land cover systems. Given the fragmented bureaucratic governance and complex ecological conditions, further research is essential to investigate the role of social forestry areas within specific landscape units.

(4) Advancing Socio-Economic and Governance Analyses

The foundational premise of social forestry is its potential to enhance community welfare, making socio-economic improvement a core objective. However, the current research landscape remains predominantly focused on natural science perspectives, as reflected in the prevailing keywords. The emergence of terms such as "power" and the prominence of authors like Ahmad Maryudi, whose work centers on governance and stakeholder interests, signal a positive shift. This indicates a growing recognition that social forestry is not merely a technical or ecological panacea but a complex domain involving multifaceted political and economic interests. Future research should, therefore, prioritize investigating the social and economic sustainability of these initiatives. Studies are needed to critically assess long-term impacts on livelihoods, income diversification, benefit-sharing mechanisms, and the resilience of local economies within social forestry frameworks.

5. Conclusion

This study focused on the development of social forestry research in Indonesia. Within the CiteSpace 6.4.2R2 (64-bit) Advanced, we analyze the comprehensive review of research history, hotspots, and trends. The study found the following:

(1) Publication Trends. Researchers are interested in the topic of social forestry research in Indonesia, as evidenced by an increase in the number of publications during the start-up phase (2007–2011), early development phase (2012–2016), and rapid growth phase (2017–2024). The majority of social forestry research is in the fields of forestry, environmental sciences, and ecology, which are major clusters that encompass forestry. During the period 2007–2024, the journals Jurnal Manajemen Hutan Tropika, Forest and Society, and Forest Policy and Economics ranked in the top three journals with the most publications on social forestry topics.

(2) Collaboration Patterns. There are institutions that frequently conduct research in this field, including CIFOR, Bogor Agricultural University, and Universitas Gadjah Mada. Individually, authors who focus on social forestry research include Ahmad Maryudi, Douglas Sheil, and

Terry Sunderland. Meanwhile, the top three countries that produced research in the social forestry topic were Indonesia, the USA, and England.

(3) Co-citation Analysis. The articles of Ostrom E., Agrawal A., and the Food and Agriculture Organization (FAO) hold a foundational reference for research in the social forestry topic. Furthermore, the top three most frequently co-cited journals were Science, Forest Policy and Economics, and PLOS One, which showed their influence in producing good-quality literature on the social forestry topic. Additionally, the articles published by Rakatama and Pandit (2020), Fisher et al. (2019), and Sahide and Giessen (2015) serve a strong position in the co-citation network. It means that these articles hold a pivotal reference for generating new research on social forestry in Indonesia.

(4) Co-occurrence Analysis. The primary research hotspots in the social forestry include topics such as "conservation," "management," and "forest". The main focus of research is on social forestry, diversity, and tropical forest issues. The keywords of "restoration", "ecosystem", and "power" have emerged as prominent and influential over the past three years. These keywords are predicted as the significant topics of social forestry in the coming years.

These results would help the new researchers quickly understand developments in social forestry research and fill the existing gaps. Moreover, senior researchers and policymakers can use the integrated research trend information to develop adaptive and inclusive social forestry models that provide ecological and economic benefits. Further research on the social forestry topic can be directed towards (i) expanding research collaboration geographically; (ii) investigating the role of women in social forestry management; (iii) investigating the role of social forestry areas within specific landscape units; and (iv) investigating socio-economic and governance conditions.

6. Limitations of the Study

There are some limitations of this study as follows:

(1) Data source: This study only focuses on articles sourced from the Web of Science database, without considering other research database sources such as Scopus. Therefore, it is possible that there are articles that have a high influence on the development of social forestry research in Indonesia but are not recorded in this study.

(2) Language restrictions: This study focuses on articles sourced from English. This bibliometric analysis focuses on English-language publications available in international indexing systems, while a substantial portion of Indonesia's social forestry literature is published in Bahasa Indonesia and stored in national repositories such as SINTA/GARUDA. Because these repositories do not support bulk metadata export in formats compatible with bibliometric tools, their exclusion may result in a partial representation of the national knowledge landscape.

(3) Bibliometric analysis blind spot: This analysis produces information on documents that have a high impact based on the number of documents and citations. However, this analysis cannot capture documents that have a high impact based on significant theoretical innovations but do not yet have a large number of citations. This condition can occur when an article has just been published, and there is not much time difference between its publication and this research analysis.

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Abbreviations

The following abbreviations are used in this manuscript:

CBF	Community-based Forestry

CIFOR	Center for International Forestry Research
FAO	Food and Agriculture Organization of the United Nations
MoEF	Ministry of Environment and Forestry
MoFor	Minister of Forestry
SDGs	Sustainable Development Goals
WoS	Web of Science

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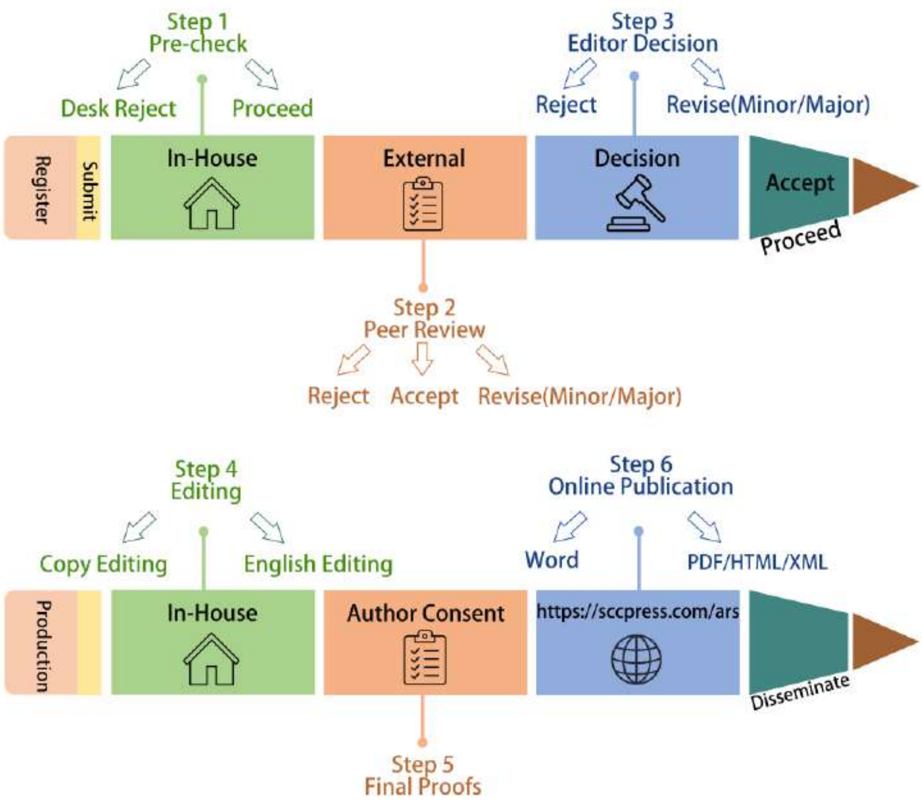

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