Cost-Sharing for Blockchain-Enabled Collaborative Governance of Fruit Tree Residues Based on a System Dynamics Approach

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Abstract： Agricultural waste governance is long-term and requires multi-actor collaboration. Information asymmetry and lack of trust hinder the stable expansion of the collection–treatment–reuse chain of fruit tree residual branches. Blockchain can enhance traceability, accountability, and process transparency, yet its high implementation cost impedes adoption. Using the Pinggu "Eco-Bridge" project in Beijing as the case, this study develops a system dynamics model based on the PSR framework and stock–flow modeling, identifies key feedback structures, and compares two cost-sharing mechanisms: a government-led model and a government–enterprise cooperative model. Simulation results show that blockchain improves polycentric governance effectiveness and enterprise profitability with time lags; the government-led model performs better in the early stage, while the cooperative model dominates in the long run; government prefers cooperation under a fixed budget, whereas enterprises may hesitate due to investment risks. Phased support, investment oversight, and a platform revenue reinvestment mechanism are needed to sustain a sound blockchain-enabled governance system.

Keywords: blockchain technology; resource utilization of fruit tree residual branches; cost-sharing mechanisms; system dynamics; feedback analysis, simulation

1.Introduction

Agricultural wastes such as fruit tree pruning residues are generated in large quantities. Improper disposal may lead to environmental pollution and safety risks, making their resource utilization a critical component of green transformation. At present, the management of fruit tree residues is largely government-led and involves multiple stakeholders and processes, including government regulation and subsidies, collection and resource utilization by third-party environmental governance enterprises, and collection and delivery by farmers. However, information asymmetry and limited traceability throughout the process constrain collaborative efficiency. Specifically, governments face difficulties in accurate verification and effective supervision; enterprises encounter challenges in demonstrating processing standards and quality; and farmers are unable to assess governance quality and product value. These issues, in turn, weaken participation willingness and reduce enterprises' incentives to invest.

Blockchain technology, characterized by immutability and traceability, can provide trustworthy records for key stages such as "generation–collection–transportation–processing–conversion–subsidy." Combined with smart contracts, it enables the automatic execution of predefined rules, thereby enhancing information transparency and accountability while reducing coordination frictions. However, the construction and operation of blockchain platforms entail substantial reinvestment costs. Different cost-sharing mechanisms may alter stakeholder incentives and governance performance, highlighting the need to evaluate their effects from a dynamic evolutionary perspective.

To address this issue, this study develops two blockchain adoption scenarios: a government-led model and a government–enterprise cooperative model. A system dynamics approach is employed to characterize the feedback structure and time-delay effects in the collaborative governance of fruit tree residues. Comparative simulations are conducted from two dimensions: waste reduction and enterprise profitability. Under the Pressure–State–Response (PSR) framework, a stock–flow basic structure is constructed, incorporating three subsystems: traditional governance, enterprise investment and returns, and blockchain empowerment. Key feedback mechanisms are identified, and policy implications are proposed regarding phased government support, investment pacing, and platform operation and maintenance. The overall research framework is illustrated in Figure 1.

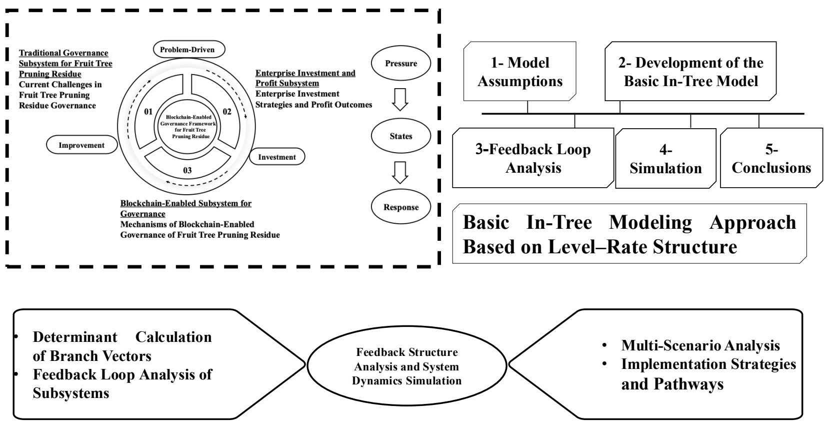


Figure 1 Research Framework

2. Literature Review

2.1 The Value of Blockchain-Enabled Waste Governance

Blockchain technology can record the entire lifecycle of waste—from generation, collection, and transportation to treatment—forming an immutable and traceable database. This enhances data transparency and strengthens full-process control as well as regulatory accountability (Keskin et al., 2025; Yao et al., 2025). Through multi-source information integration and sharing, blockchain enables enterprises to optimize disposal planning and governance network configuration. Its decentralized architecture further improves the efficiency of collection and treatment processes, reduces coordination costs and decision biases, and mitigates errors arising from information opacity, thereby supporting strategic decision-making in the circular economy (Lou et al., 2025).In addition, Li et al. (2024) argue that blockchain, through its tamper-proof mechanism, provides a trustworthy foundation for multi-stakeholder collaboration. This reduces transaction uncertainty, alleviates information asymmetry, and enhances the overall efficiency of the supply chain.

2.2 Blockchain Adoption Costs and Cost-Sharing Mechanisms

High adoption costs constitute a primary constraint on the diffusion of blockchain technology. Liu et al. (2024) argue that adoption occurs only when costs fall within an acceptable range, making cost-sharing among multiple stakeholders a crucial mechanism to facilitate implementation. However, due to divergent interests and risk considerations, some participants may resist adoption because of concerns over information leakage, weakened bargaining power, and technological uncertainty (Li C et al., 2025). Although cost-sharing mechanisms may enhance system-level performance, consumer surplus, and social welfare (Che et al., 2024), they do not necessarily benefit individual participants (Huo et al., 2023). Moreover, variations in supply chain structures can alter the value of blockchain and lead to uncertain outcomes of cost-sharing mechanisms. The advantages of blockchain can only be fully realized and generate synergistic benefits under specific conditions (Cui Y et al., 2023).

Existing studies primarily focus on three types of cost-sharing arrangements:

(1) Cost-sharing among upstream and downstream enterprises:

Most studies employ game-theoretic approaches to analyze adoption strategies and equilibrium outcomes, with a focus on profits, welfare, costs, competition, and blockchain adoption preferences. For instance, in contract farming, only two equilibria—“enterprise-only adoption” and “enterprise–farmer joint adoption”—are feasible, while farmer-only adoption cannot be sustained (Wang et al., 2024). Manufacturers may choose among independent adoption, joining a consortium blockchain, or leading a consortium, with decisions influenced by consumer concerns and perceived brand value; notably, they consistently exhibit incentives to adopt consortium blockchain solutions (Chen et al., 2025). Other studies examine adoption decisions from perspectives such as product freshness and supplier profitability (Yan et al., 2025), as well as the impact of competitive relationships on cost-sharing modes (Hong et al., 2025).

(2) Government-involved cost-sharing:

This stream of research investigates the role of government participation in bearing construction and maintenance costs or providing financial support and subsidies, and its effects on multi-stakeholder decision-making and governance performance. For example, some studies analyze government–enterprise–bank interactions using evolutionary game models under local government cost-bearing scenarios (Li S et al., 2024), while others consider financial support from central governments (Ma et al., 2023). Subsidies are also identified as an important policy instrument (Liang et al., 2025), with dynamic subsidy schemes shown to promote recycling and enhance traceability levels (Wang Y et al., 2024).

(3) Platform-based cost-sharing:

In this arrangement, blockchain platforms are typically invested in by a central entity, while other participants share costs or pay for usage. For instance, online platforms may invest in blockchain infrastructure with suppliers bearing part of the costs (Wan et al., 2025). Alternatively, governments may establish public platforms, share costs with suppliers, and allow third-party governance enterprises to access the platform through paid services, with implications for supplier profitability (Gopalakrishnan, 2021).

2.3 System Dynamics Studies on Blockchain

System dynamics can be employed to simulate the dynamic evolution before and after the introduction of blockchain technology and to evaluate its comprehensive impacts. The use of distributed ledgers facilitates consensus formation, enhances alliance resilience, and may reduce enterprise costs (Elo et al., 2021; Vu et al., 2024), while also improving resource allocation efficiency. For instance, Xu et al. (2022) use Vensim to simulate the effects of blockchain investment and promotional or educational subsidies on environmental benefits associated with resource utilization. Zhao et al. (2021) construct a system dynamics model for the transformation of resource-based cities, comparing scenarios with and without blockchain adoption. By integrating system dynamics with evolutionary game theory, Lin et al. (2024) demonstrate that blockchain can improve the efficiency of construction waste recycling while coordinating the interests of multiple stakeholders.

In addition, system dynamics has been widely applied to the evaluation of technology diffusion processes (Roozkhosh et al., 2023). For example, both government support and organizational factors have been shown to significantly influence adoption decisions (Yan et al., 2024).

2.4 Literature Review and Research Gaps

In summary, three key insights can be drawn from the existing literature. First, prior studies generally acknowledge the necessity and feasibility of applying blockchain technology in waste governance, highlighting its potential to enhance transparency and traceability. However, the adoption of blockchain does not necessarily generate positive returns for all participating stakeholders. Second, current research on cost-sharing mechanisms primarily focuses on governments and enterprises, often within the context of two-tier supply chains (e.g., supplier–retailer structures), while relatively limited attention has been paid to incorporating third-party environmental governance enterprises into a unified analytical framework. Third, methodologically, most studies rely on game-theoretic approaches to characterize strategic equilibria or partial economic outcomes, which makes it difficult to capture multi-variable dynamic feedback, time-delay effects, and long-term nonlinear impacts.

Based on these limitations, this study introduces a system dynamics approach to examine the dynamic evolution of blockchain-enabled collaborative governance of fruit tree pruning residues under different cost-sharing mechanisms. It further compares policy implications across alternative blockchain cost-sharing scenarios.

3. Problem Description and Model Development

Agricultural waste in China is diverse in type; however, the utilization rate of fruit tree pruning residues remains significantly lower than that of crop straw. Taking Beijing as an example, the annual generation of fallen branches and leaves exceeds 3 million tons, while the resource utilization rate is only about 10%. In contrast, the comprehensive utilization rate of crop straw nationwide reached 84.7% during the same period. Similarly, in Shaanxi Province—one of China's major fruit-producing regions—approximately 7 million tons of fruit tree residues are generated annually, yet the effective utilization rate remains below 5%. The improper disposal of such residues exerts pressure on the resource–environment system (Pressure), leading to changes in environmental conditions (States).

Nevertheless, fruit tree residues are rich in minerals and play a significant role in improving soil fertility and promoting tree growth. Therefore, enhancing their resource utilization has become an urgent priority to respond (Response) to changes in the resource–environment system.

Since 2017, Pinggu District in Beijing has implemented the "Ecological Bridge" project, which converts fruit tree pruning residues into organic fertilizer for reuse. This initiative has established a relatively complete governance chain and a solid practical foundation. Meanwhile, the Beijing municipal government has proposed promoting blockchain-enabled agricultural governance, providing a policy basis for the design of blockchain adoption scenarios. Against this background, this study takes the fruit tree residue management project in Pinggu District as a case and develops a system dynamics model.

3.1 A Blockchain-Enabled Collaborative Governance Framework for Fruit Tree Residues

(1) Existing Mechanisms and Challenges

Based on the literature and field interviews, the current governance mechanism in Pinggu District operates as follows: fruit growers deliver pruning residues to third-party environmental governance enterprises, which process them into organic fertilizer, while farmers are incentivized to participate through a "residue-for-fertilizer exchange" scheme. However, several challenges remain. First, the government simultaneously undertakes multiple roles—including promotion, regulation, and subsidy provision—resulting in a relatively heavy governance burden. Second, the enterprise collection and processing stages lack effective process recording and quality verification, making government supervision difficult. Third, farmers face challenges in assessing processing quality and the true value of the final products, leading to low levels of trust (He et al., 2023).

Under this traditional model, information asymmetry is pronounced, and the efficiency of multi-stakeholder collaboration remains limited (Shen et al., 2020). Against this background, this study develops a blockchain-enabled collaborative governance framework for fruit tree pruning residues in Pinggu District

(2) Blockchain-Enabled Framework and Smart Contract Mechanisms

With the introduction of blockchain technology, key processes involving farmers, enterprises, and government agencies are recorded on-chain. Specifically, data on residue delivery and exchange transactions are uploaded in real time; enterprise processing activities and quality information are transparently disclosed to enhance credibility and competitiveness; and governments utilize on-chain data for precise supervision and subsidy allocation. These features collectively alleviate information asymmetry, regulatory difficulties, and trust deficits.

Taking smart contracts as an example (He P et al., 2020), the core operational process can be summarized as follows:

(1) **Pre-declaration**: Farmers submit information such as quantity, location, delivery time, and moisture content via mobile applications (e.g., mini-programs or apps) to estimate expected returns. Enterprises allocate labor and equipment in advance based on this information, while governments simultaneously monitor system dynamics. Once confirmed, the data are recorded on-chain.

(2) **Transportation**: The system records GPS trajectories and updates transportation status in real time, with automatic alerts triggered in case of anomalies.

(3) **Arrival registration**: Weighing data are automatically uploaded to the blockchain, and consistency is verified by farmers, enterprises, and government authorities. Moisture content is automatically detected and recorded in an immutable manner. The system calculates exchange quantities based on moisture-adjusted conversion rules and performs automatic settlement, thereby reducing on-site waiting time and manual data entry.

(4) **Processing and exchange**: Enterprises process the residues into organic fertilizer and fulfill the "residue-for-fertilizer exchange" commitment to farmers based on recorded data, while surplus products are supplied to the market.

(5) **Government supervision and subsidies**: Governments allocate subsidies to enterprises based on on-chain exchange data and conduct dynamic supervision.

(6) **Platform revenue generation**: The platform provides services such as data storage, traceability, and smart contract execution, and charges service fees accordingly.

Overall, functions such as pre-declaration, transportation tracking, automated arrival registration, moisture detection, and automated settlement reduce manual intervention and opportunities for fraud, improve governance efficiency, and facilitate the formation of a blockchain-enabled collaborative governance system (Figure 2)

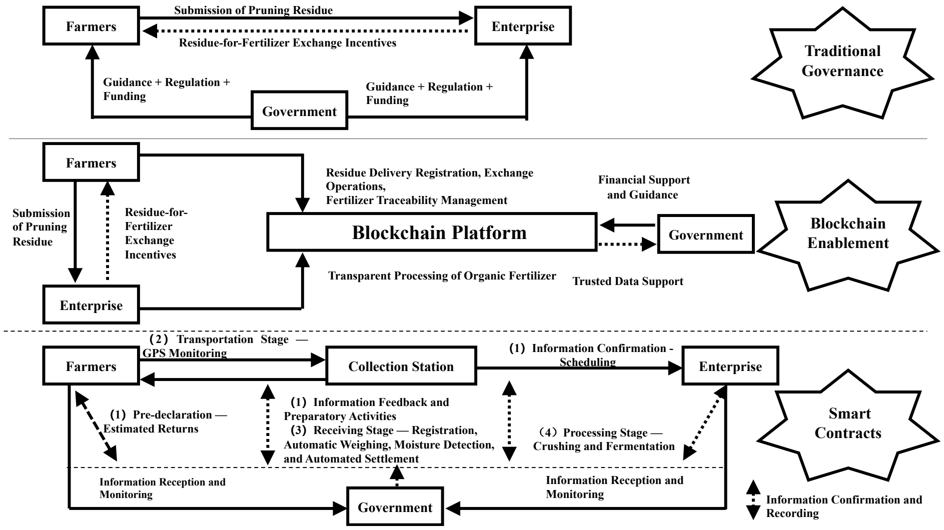


Figure 2 Blockchain-Enabled Governance Framework and Smart Contract Mechanisms for Fruit Tree Pruning Residue

(3) Blockchain Cost-Sharing Models

Based on the above framework, two types of cost-sharing models are considered (Figure 3):

Government-led model: The government bears the cost of platform construction, while enterprises and farmers pay periodic service fees for usage. The platform-generated revenues are retained by the government.

Government–enterprise cooperative model: Enterprises invest in and operate the blockchain platform, while the government provides partial financial support (e.g., subsidies). The platform-generated revenues are retained by the enterprises.

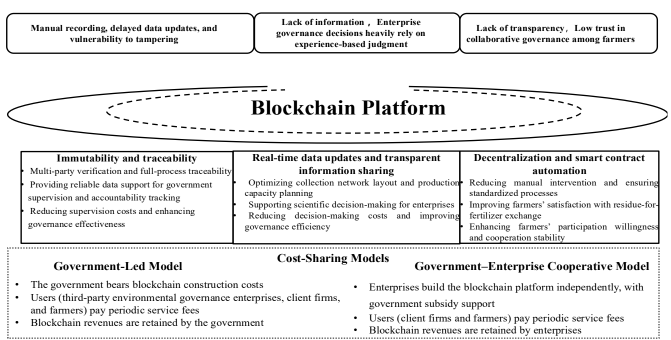


Figure 3 Blockchain Cost-Sharing Models

3.2 Model Assumptions

Assumption 1: To facilitate project implementation, the government provides financial support under two cost-sharing modes: (i) a **government-led model**, in which the government invests in platform construction and entrusts third-party operation, users pay service fees, and revenues are used for operation, maintenance, and reinvestment; and (ii) a **government–enterprise cooperative model**, in which enterprises build the platform, the government provides subsidies, and revenues are retained by the enterprises.

Assumption 2: Enterprises aim to maximize profits. When enterprises build the platform independently, they charge service fees P_1 and P_2 to users (e.g., client firms and farmers), with $P_1>P_2$. Under the government-led model, to promote adoption, service fees are set below market levels and denoted as θP_1 and θP_2, where $0 < \theta < 1$.

Assumption 3: Given the rapid iteration of digital technologies, the platform requires continuous reinvestment to maintain service quality and stability. In line with fiscal support constraints stipulated in relevant policy guidelines, under the government–enterprise cooperative model, government support is provided only once, and subsequent operation, maintenance, and reinvestment are borne by enterprises. Under the government-led model, these costs are covered by platform revenues (i.e., user fees for on-chain services).

Assumption 4: In the agri-food sector, blockchain enhances information transparency and traceability, thereby alleviating information asymmetry and strengthening trust, which in turn expands demand and improves sales performance (Feng et al., 2025; Jing, 2025). Traceable products are associated with higher demand and price premiums.

Assumption 5: Enterprise blockchain investment is positively related to competitiveness. Greater competitiveness leads to higher investment levels, improved technological performance, and increased blockchain-related returns. However, the expansion of user scale and transaction intensity also increases platform maintenance costs.

Assumption 6: Under investment risk constraints, enterprise investment is bounded within upper and lower limits. Blockchain investment occupies a portion of the total investment budget and may crowd out other investments (e.g., increased blockchain investment may reduce investment in collection network infrastructure).

Assumption 7: Blockchain applications are more mature in government services. Under the government-led model, regulatory effectiveness is relatively high, but the level of commercialization is limited, resulting in a weaker contribution to enhancing the traceability value of enterprises' organic fertilizer products.

3.3 Stock–Flow Model Based on System Dynamics

Based on the case of Pinggu District, this study develops a system dynamics model for the resource utilization of fruit tree pruning residues, with third-party environmental governance enterprises as the core actors. The model aims to evaluate both economic and environmental performance and consists of three subsystems: (i) the traditional governance subsystem, (ii) the enterprise investment decision and return subsystem, and (iii) the blockchain-enabled governance subsystem. Together, these subsystems constitute a collaborative governance system for fruit tree residues empowered by blockchain technology.

The traditional governance subsystem describes the processes of residue generation, collection, enterprise recycling, collection network expansion, and farmer income. The government promotes enterprise investment in equipment, technological development, and the establishment of collection stations through administrative regulation, policy guidance, and financial support, thereby gradually forming a collection network. Farmers collect pruning residues and transport them to nearby collection points, while enterprises convert the residues into organic fertilizer and incentivize farmer participation through a residue-for-fertilizer exchange mechanism.

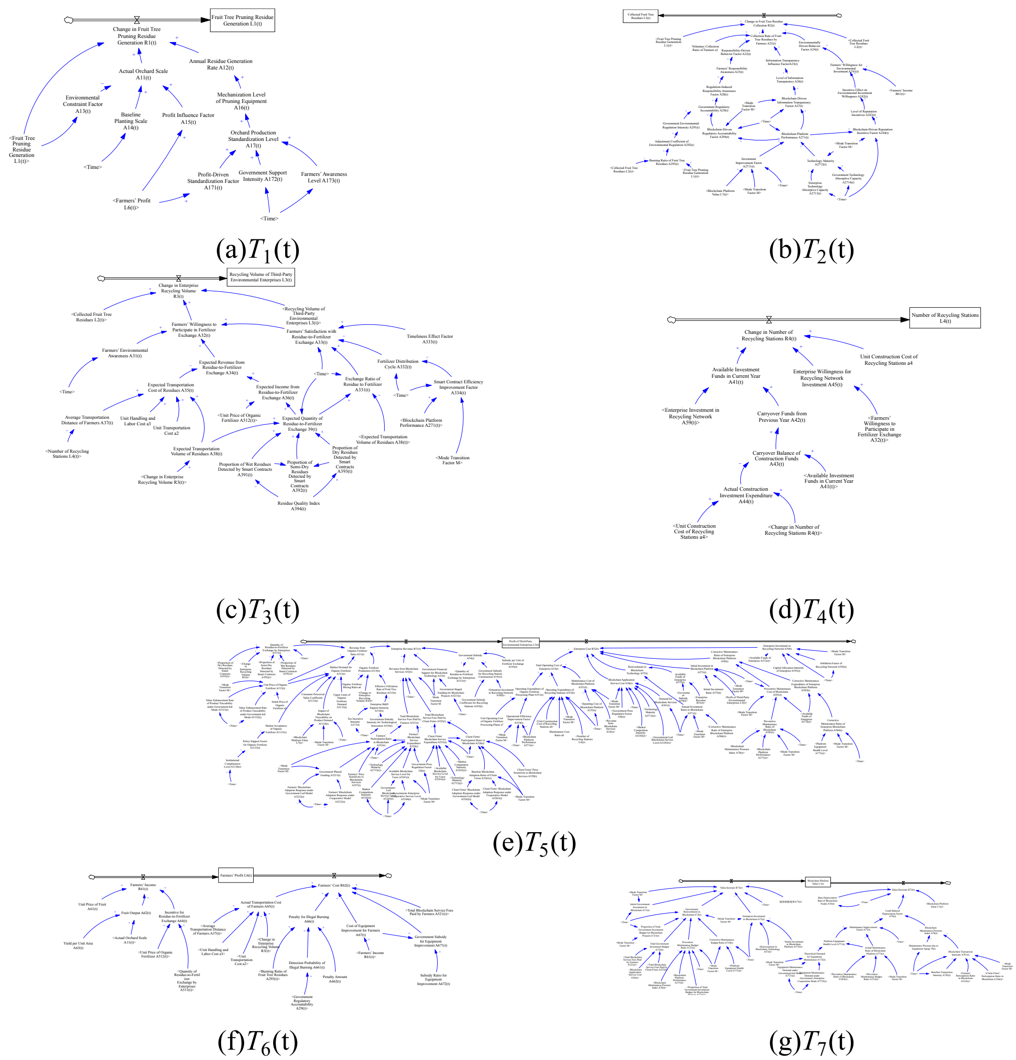
The enterprise investment decision and return subsystem captures changes in enterprise and farmer benefits following the introduction of blockchain. It incorporates investment and cost components such as platform construction and operation, as well as the expansion of the collection network, and analyzes how investment decisions influence overall system performance. Farmer income includes both operational revenue and incentives for participating in governance activities, while costs include transportation, technology usage, and penalties for open burning. The government influences both enterprise and farmer behavior through reward and penalty mechanisms, thereby affecting governance outcomes.

The blockchain-enabled subsystem characterizes the evolution of platform value and the enabling effects of blockchain technology within the system.

Following the fundamental stock–flow modeling approach (Jia et al., 1998, 2005), seven pairs of stock and flow variables are identified to define the basic system structure (see Table 1). Based on these, the relationships among stock variables, flow variables, and auxiliary variables are established, leading to the construction of the system dynamics stock–flow model (see Figure 4).

Table 1 Level–Rate Variables of the Collaborative Governance System for Fruit Tree Pruning Residue

Level Variables	**Rate Variables**	**Unit**
Fruit Tree Pruning Residue Generation L_1(t)	Change in Fruit Tree Pruning Residue Generation R_1(t)	ton
Collected Fruit Tree Residue L_2(t)	Change in Fruit Tree Residue Collection R_2(t)	ton
Recycling Volume of Third-Party Environmental Governance Enterprises L_3(t)	Change in Enterprise Recycling Volume R_3(t)	ton
Number of Recycling Stations L_4(t)	Change in Number of Collection Stations R_4(t)	Unit
Profit of Third-Party Environmental Governance Enterprises L_5(t)	Enterprise Revenue R_{51}(t) 、Enterprise Cost R_{52}(t)	CNY
Farmers' Profit L_6(t)	Farmers' Income R_{61}(t) 、 Farmers' Cost R_{62}(t)	CNY
Blockchain Platform Value L_7(t)	Value Increase R_{71}(t) 、 Value Decrease R_{72}(t)	CNY



(a)T_1(t) (b)T_2(t) (c)T_3(t) (d)T_4(t) (e)T_5(t) (f)T_6(t) (g)T_7(t)

Figure 4 Basic Flow-Rate In-Tree Model of the Blockchain-Enabled Collaborative Governance System for Fruit Tree Residues

4.Feedback Loop Analysis and Policy Implications of Blockchain-Enabled Fruit Tree Residue Resource Utilization Systems

4.1 System Feedback Loop Analysis

Based on the stock–flow model, the control relationships between stock variables and their corresponding flow variables are identified, allowing the derivation of first-order feedback loops within the system structure. Following the principles of the branch vector determinant method for feedback loop calculation (Zhu et al., 2015; Jia et al., 2005, 2018), a branch vector determinant corresponding to the fundamental stock–flow model is constructed. The results show that the system contains a total of 113 feedback loops (see Appendix for details)

$$|A| = \begin{vmatrix} 1 & 0 & 0 & 0 & 0 & A_{16} & 0 \\ A_{21} & 1 & 0 & 0 & 0 & A_{26} & A_{27} \\ 0 & A_{32} & 1 & A_{34} & 0 & 0 & A_{37} \\ 0 & 0 & A_{43} & 1 & A_{45} & 0 & A_{47} \\ 0 & 0 & A_{53} & A_{54} & 1 & 0 & A_{57} \\ A_{61} & A_{62} & A_{63} & A_{64} & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & A_{75} & 0 & 1 \end{vmatrix}$$

$A_{16}=(R_1,+,A_{11},L_6)+(R_1,+,A_{12},L_6)$,$\mathrm{A}_{21}=(R_2,+,L_1)+(R_2,+,A_{22},L_1)$,

$A_{26}=(R_2,+,R_{61})$,$A_{27}=3(R_2,+,L_7)$,$A_{32}=(R_3,+,L_2)$,$A_{34}=(R_3,+,L_4)$,$A_{37}=(R_3,+,L_7)$,

$A_{43}=(R_4,-,R_3)+(R_4,+,R_3)$,$A_{45}=(R_4,+,R_{51})$,$A_{47}=(R_4,+,A_{33},L_7)$,$A_{54}=(R_{52},+,L_4)$,

$A_{53}=(R_{51},-,A_{511},R_3)+(R_{51},+,A_{514},R_3)+(R_{51},+,A_{54},R_3)$,$A_{64}=(R_{62},-,L_4)$

$A_{57}=(R_{51},+,A_{513},L_7)+2(R_{52},-,A_{55},L_7)+(R_{52},+,A_{57},L_7)+(R_{52},+,A_{581},L_7)+(R_{52},-,A_{581},L_7)$,

$A_{61}=(R_{61},-,L_1)+2(R_{62},+,L_1)$,$A_{63}=(R_{61},+,R_3)+(R_{62},+,R_3)$,

$A_{62}=2(R_{62},-,L_2)$,$A_{75}=(R_{71},+,L_5)+(R_{71},+,R_{51})$

To better understand system behavior and identify effective managerial leverage points, the feedback loops are analyzed across three subsystems: (i) the traditional governance subsystem, (ii) the enterprise investment decision and return subsystem, and (iii) the blockchain-enabled governance subsystem.

4.2 Feedback Loop Structure Analysis of the Traditional Governance Subsystem

4.2.1 Major Feedback Loops

In the traditional governance model, the key stock variables include fruit tree residue generation L1(t), collection volume L2(t), enterprise recycling volume L3(t), the number of collection stations L4(t), and farmers' profit L6(t). The main feedback loops of this subsystem are illustrated in Figure 5.

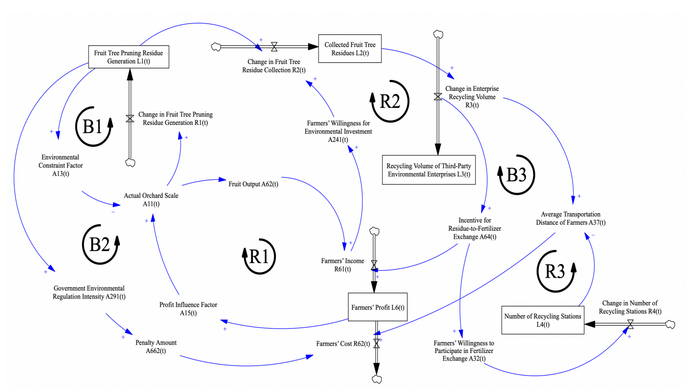


Figure 5 Feedback Structure of the Traditional Governance Subsystem for Fruit Tree Residue

(1) Limits to Growth Archetype (R1–B1):

This structure consists of both reinforcing and balancing feedback loops. Based on the feedback structure, L1(t) and L6(t) form a reinforcing loop R1 (expansion of orchard scale → increase in residue generation rate growth in accumulated residues → further expansion of orchard scale). However, the accumulation of residues leads to environmental deterioration, which in turn constrains orchard expansion and income growth, forming a balancing loop B1 (increase in accumulated residues → strengthening of environmental constraint factors → restriction and contraction of orchard scale → decrease in residue generation rate → reduction in accumulated residues).

(2) Government Regulation Balancing Loop (B2):

When residue-related pollution intensifies, it exerts pressure on the environment and alters environmental conditions. To mitigate these adverse effects, the government responds by strengthening regulatory measures, such as increasing penalties for burning or improper disposal. This raises farmers' costs and induces behavioral adjustments, forming a second-order balancing loop B2 (increase in accumulated residues → rise in environmental impact factors → strengthening of government regulation → higher penalty levels → increased farmer costs → reduced farmer profits → constrained orchard expansion → decreased residue generation rate → reduction in accumulated residues). This loop helps reduce open burning and alleviate environmental pressure.

(3) Residue-for-Fertilizer Incentive Reinforcing Loop (R2):

Regulation alone is insufficient for long-term stability. Incentive mechanisms, such as the "residue-for-fertilizer exchange," jointly promoted by government and enterprises, enhance farmers' willingness to participate, forming a reinforcing loop R2 centered on incentives (increase in farmer profits → stronger willingness to invest and participate → increase in residue collection rate → growth in accumulated collected residues → increase in enterprise recycling rate → higher recycling volume by third-party enterprises → increased farmer income → further increase in farmer profits).

(4) Transportation Cost Constraint Balancing Loop (B3):

Participation in the exchange mechanism is subject to constraints. Longer transportation distances increase farmers' self-transport costs and reduce net returns, thereby suppressing participation. This forms a balancing loop B3 (increase in enterprise recycling volume → strengthening of dispersion-related constraints → increase in transportation costs → rise in total farmer costs → decline in farmer profits → reduced willingness to participate in exchange → decrease in accumulated collected residues → reduction in enterprise recycling volume).

(5) Recycling Network–Participation–Benefit Reinforcing Loop (R3):

Enhanced participation increases recycling scale and enterprise returns, encouraging enterprises to expand the collection network. This shortens transportation distances and further stimulates participation, forming a higher-order reinforcing loop R3 (increase in farmers' willingness to participate → increase in the rate of collection station expansion → growth in the number of collection stations → weakening of dispersion constraints → reduction in transportation costs → decrease in total farmer costs → increase in farmer profits → further enhancement of participation willingness). However, when farm sizes are small, exchange costs are high, and trust is insufficient, this loop is difficult to initiate, and the system may fall into a vicious cycle of "low participation–low recycling–insufficient stations–high costs–weak participation incentives."

4.2.2 Management Implications

First, orchard scaling should be pursued alongside effective control of environmental burdens. According to the limits-to-growth archetype, priority should be given to alleviating the constraining factor—namely, residue-induced environmental pressure—by promoting source reduction and enhancing processing capacity, thereby preventing environmental constraints from becoming a bottleneck to expansion.

Second, a balanced approach of “rewards and penalties” can reduce regulatory pressure. The balancing loop B2 indicates that punitive measures are effective; however, relying solely on regulation is costly. In contrast, the reinforcing loop R2 suggests that appropriate incentives (e.g., point-based rewards, in-kind exchange, and recognition mechanisms) can enhance farmers’ participation and generate a virtuous cycle.

Finally, improving farmers’ net income should be placed at the core of governance design. The reinforcing loop R3 shows that insufficient participation weakens enterprise investment and network expansion, leading to a persistent reliance on government-led governance. Therefore, increasing farmers’ net income and reducing participation costs—particularly transportation-related constraints—are essential to break this lock-in and achieve sustainable system development.

4.3 Feedback Loop Structure Analysis of the Enterprise Investment Decision and Return Subsystem

4.3.1 Feedback Loop Analysis

The enterprise investment decision and return subsystem primarily captures the changes in enterprise returns following the introduction of blockchain, as well as the feedback effects of investments in the collection network and blockchain platform on recycling scale, forming a typical feedback structure (Figure 6).

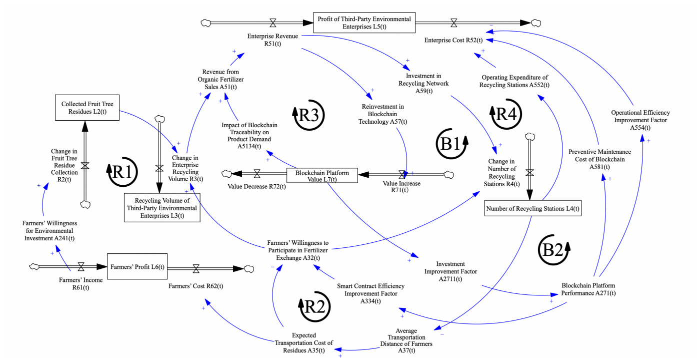


Figure 6 Feedback Loop Structure of the Enterprise Investment Decision and Revenue Subsystem

(1) Reinforcing Loop of Collection Network Expansion (R1):

Reinforcing loop R1 (increase in accumulated residue collection → increase in enterprise recycling rate → increase in recycling volume by third-party enterprises → stronger incentives for collection station expansion → increase in the rate of station construction → growth in the number of collection stations → reduction in farmers’ transportation costs → decrease in total farmer costs → increase in farmer profits → stronger willingness to invest and participate → increase in residue collection rate → further growth in accumulated residue collection).

This loop indicates that the expansion of recycling scale promotes the development of the collection network, which reduces transportation costs, enhances farmers' profitability, and strengthens their collection efforts, thereby further expanding the recycling scale.

(2) Self-Reinforcing Loop of Enterprise Recycling Scale (R2):

Reinforcing loop R2 (increase in enterprise recycling volume → stronger incentives for station expansion → increase in the rate of station construction → growth in the number of collection stations → further increase in enterprise recycling volume).

This loop reflects a self-reinforcing mechanism between recycling scale and network expansion.

(3) Blockchain Revenue-Driven Reinforcing Loop (R3):

Reinforcing loop R3 (increase in blockchain platform value → increase in enterprise revenue → increase in enterprise profits → stronger willingness to invest in blockchain → increase in total blockchain investment → further enhancement of platform value).

This loop shows that improvements in platform value can enhance enterprise revenue and profitability, which in turn stimulate further investment, forming a reinforcing process of "value–revenue–reinvestment–value."

(4) Blockchain Cost-Reduction-Driven Reinforcing Loop (R4):

Reinforcing loop R4 (increase in total blockchain investment → enhancement of platform value → reduction in farmers' transportation costs → decrease in total farmer costs → increase in farmer profits → stronger willingness to participate in exchange → increase in accumulated residue collection → increase in enterprise recycling volume → increase in enterprise revenue → increase in enterprise profits → further increase in total blockchain investment).

This loop highlights that blockchain investment reduces coordination frictions (represented by transportation costs), thereby expanding participation and recycling scale, which feeds back into enterprise returns and further strengthens investment.

(5) Balancing Loop of Collection Network Expansion Cost (B1):

Balancing loop B1 (increase in the number of collection stations → increase in enterprise costs → decrease in enterprise profits → weakened incentives for station expansion → decrease in the rate of station construction → constrained growth in the number of collection stations).

This loop indicates that network expansion raises operational and management costs, thereby constraining further expansion.

(6) Balancing Loop of Blockchain Operation and Maintenance Costs (B2):

Balancing loop B2 (increase in total blockchain investment → rise in platform operation and maintenance pressure (O&M costs) → increase in enterprise costs → decrease in enterprise profits → weakened willingness to invest in blockchain → constrained growth in blockchain investment).

This loop shows that although blockchain investment may generate enabling benefits, its ongoing operation and reinvestment costs can suppress further investment and profit growth from the cost side.

4.3.2 Management Implications

First, the alignment between blockchain solutions and operational processes should be enhanced. The automation of key steps—such as registration, inspection, exchange, and settlement—can reduce coordination frictions, shorten processing cycles, and improve both the user experience of residue-for-fertilizer exchange and overall governance efficiency.

Second, the timing and structure of investments in blockchain platforms and collection networks should be carefully managed. Under resource constraints, a phased investment strategy is recommended, taking into account participation willingness, cost pressures associated with expansion, and cash flow risks, in order to avoid overexpansion.

Finally, platform performance should be maintained within an appropriate range. While self-built platforms can expand revenue streams and service capabilities, they also entail long-term operation and maintenance costs. Therefore, investment decisions should strike a dynamic balance between revenue growth and cost constraints.

4.4 Feedback Loop Structure Analysis of the Blockchain-Enabled Governance Subsystem

4.4.1 Feedback Loop Analysis

The main feedback loops of the blockchain-enabled subsystem are illustrated in Figure 7.

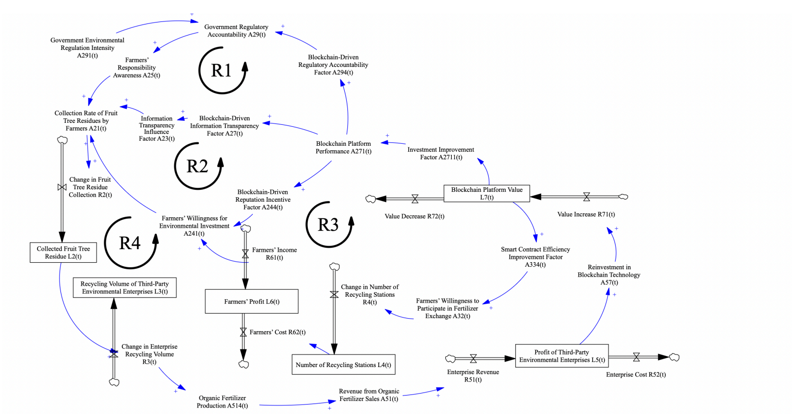


Figure 7 Feedback Loop Structure of the Blockchain-Enabled Governance Subsystem

(1) Regulatory Accountability Reinforcing Loop (R1):

Reinforcing loop R1 (increase in blockchain platform value → improvement in government regulatory capacity → enhancement of violation detection and accountability → increase in the cost of non-compliance for farmers → stronger willingness of farmers to comply and participate → increase in residue collection → improvement in the completeness and usability of on-chain data → further enhancement of blockchain platform value).

This loop reflects that improvements in platform value strengthen regulatory effectiveness, raise the cost of non-compliant behavior, promote farmer participation, and enhance data accumulation, thereby further reinforcing platform value.

(2) Transparency–Trust Reinforcing Loop (R2):

Reinforcing loop R2 (increase in blockchain platform value → higher level of information transparency → stronger guarantees of traceability and immutability → increased trust among multiple stakeholders → stronger willingness of farmers to participate → increase in residue collection → greater accumulation of on-chain data → further enhancement of blockchain platform value).

This loop indicates that improved transparency and traceability enhance trust, which in turn promotes participation and strengthens the value of the blockchain platform.

(3) Efficiency–Revenue Reinforcing Loop (R3):

Reinforcing loop R3 (increase in blockchain platform value → improvement in recycling coordination and operational efficiency → increase in recycling volume by third-party enterprises → growth in enterprise operating revenue → increase in blockchain reinvestment intensity → further enhancement of blockchain platform value).

This loop shows that enhanced platform value improves operational efficiency, which increases enterprise revenue and supports further investment, forming a reinforcing cycle.

(4) Traceability Value-Added Reinforcing Loop (R4):

Reinforcing loop R4 (increase in blockchain platform value → enhancement of traceability-driven value added for organic fertilizer products → improvement in product market competitiveness → increase in enterprise sales revenue → growth in enterprise operating income → expansion of blockchain investment → further enhancement of blockchain platform value).

This loop demonstrates that traceability-enabled value creation enhances product competitiveness and enterprise revenue, which in turn stimulates further investment and strengthens platform value.

4.4.2 Management Implications

First, blockchain should be leveraged as a systemic tool for both reducing regulatory costs and enhancing trust-based incentives. By ensuring data credibility and process transparency, it can promote win–win outcomes among stakeholders and facilitate the market-oriented evolution of governance mechanisms.

Meanwhile, a “renewal–maintenance” mechanism for the platform should be established. Given the rapid pace of technological iteration and the increasing intensity of transactions, system wear and maintenance demands are likely to rise. Therefore, regular system upgrades and maintenance are essential to sustain the enabling effects of blockchain.

5 Simulation Analysis of the Blockchain-Enabled Collaborative Governance System for Fruit Tree Residues

To capture the dynamic effects of blockchain-enabled governance, this study takes the “Ecological Bridge” project in Pinggu District, Beijing, as a case and employs system simulation to evaluate the effects of blockchain empowerment from the perspectives of waste reduction and enterprise profit maximization.

5.1 Overview of the "Ecological Bridge" Project in Pinggu District

Pinggu District generates more than 200,000 tons of fruit tree branches and other agroforestry residues annually, and improper disposal can impose significant ecological burdens. In January 2017, the "Ecological Bridge" project was launched on a pilot basis in Liujiadian Town. It has since developed into a "four-party integrated" model involving government policy support, enterprise-led operations, participation of research institutions, and equity involvement of village-level cooperatives. Specifically, the township government is responsible for policy coordination and supervision; village committees organize publicity, collection, and residue-for-fertilizer exchange; enterprises undertake collection, processing, and sales; and research institutions provide technological updates and quality supervision.

The project has contributed to environmental improvement while promoting green income growth for farmers. Meanwhile, Pinggu District has actively advanced the development of the digital economy, providing a favorable foundation for the introduction of blockchain-based scenarios.

5.2 Model Development and Parameter Setting

The system dynamics model is simulated using Vensim over the period 2017–2035, with a time step of DT = 0.125. Blockchain technology is introduced into the "Ecological Bridge" project in 2024. Based on the literature, statistical yearbooks, research reports, and field investigations, the model equations are constructed and parameter values are assigned as shown inTable 2.

According to the Administrative Measures for Central Budgetary Investment in Energy Conservation and Carbon Reduction (2024), which stipulate that support for demonstration projects in key sectors may reach up to 15% of total verified investment, the government subsidy coefficient for enterprise collection stations is set as A542(t) == RANDOM UNIFORM(0.10, 0.15, 2). In addition, based on local policies in Pinggu District, subsidies for farmers' equipment upgrades are set within the range of 30%–35%, defined as A672(t)= RANDOM UNIFORM (0.30, 0.35, 2)

Table 2 Parameter Settings and Data Sources

Variable	Value and Description	Source
Unit transportation cost a2	2	(Xu X L, 2020)
Unit processing and labor cost a3	6	
Initial amount of organic fertilizer a5	1100	Field survey
Organic fertilizer conversion ratio a6	0.4	Field survey
Price sensitivity factors for blockchain adoption by farmers and client firms A527(t)、A529(t)	Empirical studies suggest that price elasticity ranges from −0.32 to −0.52; the sensitivity factors are set to 0.5	(Obinefo I M, 2025)
Enterprise capital allocation intensity A591(t)	Empirical evidence indicates that the relative risk aversion coefficient of listed companies in China typically ranges from 3.5 to 10.5, with an overall lower risk preference than in developed economies. Based on this, the parameter is set to 0.4 to reflect conservative investment behavior	(Qiao K, 2014)
Unit subsidy for organic fertilizer exchange A542(t)	440	Field survey

5.3 Model Validation and Simulation Analysis

The model is first verified using the "check model" function in Vensim. The equations and dimensional consistency are further examined, and the model passes the dimensional consistency test. Key variables, such as market demand, are tested under extreme values (0 and 1), and the model successfully passes extreme condition tests. In addition, by selectively disconnecting certain causal links, the resulting changes in feedback structure are found to be consistent with real-world expectations, indicating that the model also passes reality checks.

Furthermore, it is assumed that either the government or enterprises begin investing in blockchain platform construction from 2024 onward. Two cost-sharing scenarios are designed accordingly, with specific parameter settings presented in Table 3.

Table 3 Parameter Settings for Scenario Analysis

Government-Led Model					
Parameter	A71(t)	A53(t)	A524(t)	A721(t)	A528(t)
Value	3000000	0	0.5	(0,0.07]	0.8
Government–Enterprise Cooperative Model					
Parameter	A71(t)	A53(t)	A524(t)	A571(t)	A528(t)
Value	0	3000000	0.3	0.1	1

(1) **Government-led model**:

The initial government investment in the blockchain platform is set at A71(t) = 3 million RMB, allocated in stages for platform infrastructure and system development. After the platform becomes operational, enterprises, client firms, and farmers pay annual fees for on-chain services, with additional charges incurred when node capacity is insufficient. Referring to Huawei Cloud pricing, the annual on-chain service fees are set at 100,000 RMB for enterprises and 50,000 RMB for farmers. The government-regulated pricing factor is defined as A528(t) = 0.8, reflecting prices below market levels. For regulatory purposes, the initial participation rate of farmers on-chain is set at A524(t) = 0.5.

Following Gopalakrishnan (2021), continuous operation, maintenance, and reinvestment are required for platform sustainability. Considering fiscal constraints, a portion of service revenues is allocated to operation and reinvestment, with A721(t) capped at 0.7 to ensure long-term viability.

(2) **Government–enterprise cooperative model**:

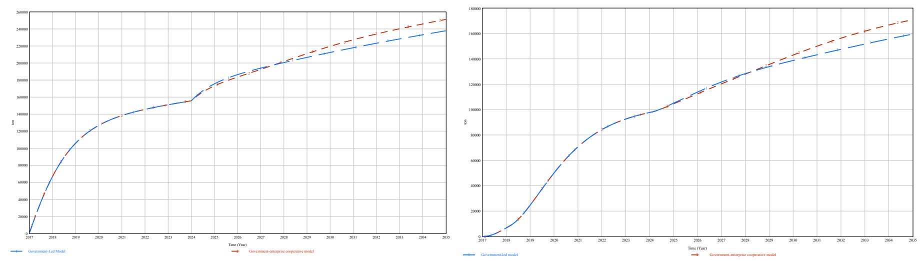
In this scenario, enterprises build and operate the platform, while the government provides a one-time financial subsidy. For comparability, the subsidy amount is also set at 3 million RMB. Enterprises, after meeting their own operational needs, provide on-chain services to other stakeholders at market prices, thereby promoting market-oriented platform operation. The enterprise reinvestment ratio is set at A571(t) = 0.1.

The simulation results are presented in Figure 8. Since 2017, both residue collection and enterprise recycling volumes have shown an overall upward trend. However, enterprise recycling remains consistently lower than total collection, indicating that some farmers do not participate in the residue-for-fertilizer exchange, thereby constraining recycling capacity. The growth rate is relatively rapid during 2017–2020 but slows down during 2020–2023, reflecting diminishing marginal effects of incentives and increasing transportation cost constraints.

After the introduction of blockchain in 2024, the growth rates of both collection and recycling volumes increase significantly. This suggests that blockchain enhances participation willingness and system efficiency through improved information transparency, regulatory capacity, and trust mechanisms.

Comparative analysis of the two scenarios shows that the government-led model performs better in the initial stage of blockchain investment. However, this advantage is surpassed by the government–enterprise cooperative model after 2028, indicating diminishing regulatory dividends and the limited sustainability of purely constraint-based approaches. In contrast, the cooperative model continuously improves transparency, accountability, and trust-based incentives through more efficient resource allocation and process optimization, thereby achieving higher governance performance.

To avoid a loss of momentum in the later stages, it is necessary to strengthen environmental awareness campaigns and promote participation based on income-enhancing incentives (e.g., reputation points and recognition mechanisms). At the same time, transportation constraints in the residue-for-fertilizer exchange should be reduced through measures such as expanding the collection network and organizing group-based logistics. In addition, more blockchain-based applications should be developed around governance needs to further enhance the enabling effects of the platform.



(a) Collected Amount of Fruit Tree Pruning Residue

(b) Enterprise Recycling Volume

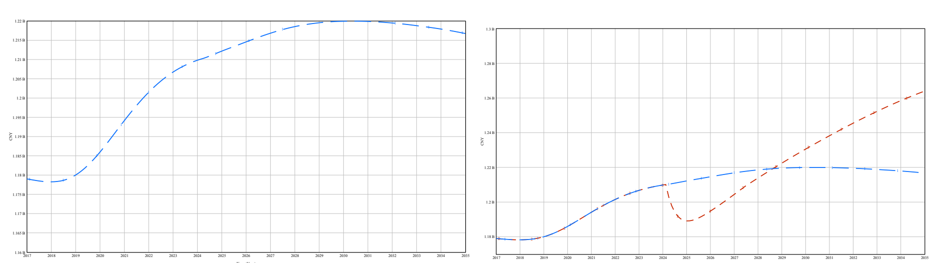
Figure 8：Trends in Fruit Tree Pruning Residue Collection and Enterprise Recycling Volume

A comparison of enterprise profit trajectories under the two scenarios (see Figure 9) reveals that, under the government-led model, the profit curve exhibits three distinct turning points (Figure 9a). In the initial stage, profits decline due to high costs associated with station construction and equipment investment, as well as a low level of cooperation. As policies are implemented and collaboration improves, profits gradually recover. However, after 2023, profit growth slows due to increasing operating costs and insufficient participation.

Following the introduction of blockchain in 2024, enterprises are required to bear relatively high application costs, resulting in a further slowdown in profit growth during 2024–2025. From 2025 to 2026, the enabling effects of blockchain begin to materialize, leading to a rebound in growth and reflecting a time-lag effect. Nevertheless, under the government-led model, the commercial benefits of blockchain remain limited, and revenues in later stages are insufficient to offset the continuously rising application costs. As a result, profit growth slows again after 2026 and begins to decline after 2030.

In contrast, under the government–enterprise cooperative model, enterprises bear the initial investment, reinvestment, and operation and maintenance costs of the platform. Consequently, profits remain lower than those under the government-led model before 2029 due to cash flow pressure and a longer payback period. However, after 2029, profits surpass those of the government-led model and continue to grow steadily.

These findings suggest that reliance on a single product and subsidies is insufficient to sustain long-term profit growth. Enterprises need to develop higher value-added products and services. In addition, given the time-lag effect of blockchain adoption, a long-term perspective and appropriate financial planning are essential. Although enterprise-led platform development yields superior outcomes in the long run, it also requires stronger financial reserves and more rigorous investment management.



(a) Scenario 1

(b) Scenario 2

Figure 9. Enterprise Profit Trends

In summary, the government-led model achieves faster governance improvements in the early stage but suffers from insufficient momentum in the long run, accompanied by a decline in enterprise profits. In contrast, the government–enterprise cooperative model delivers superior governance performance and long-term benefits; however, it requires substantial investment and involves a longer payback period, exposing enterprises to higher risks. Consequently, while governments tend to favor cooperative arrangements, enterprises may remain cautious in adopting such models.

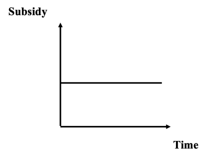
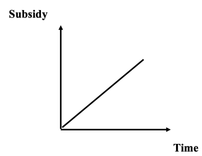
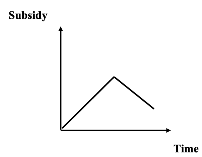
5.4 Implementation Pathways and Strategic Analysis of the Government–Enterprise Cooperative Model

Although the government–enterprise cooperative model demonstrates superior performance, enterprises' willingness to invest is constrained by high costs and risk aversion. To mitigate the misalignment between government objectives and enterprise incentives, this study proposes implementation conditions from both the government and enterprise perspectives.

(1) Optimization of government support strategies

Under an identical total subsidy budget, three scenarios are designed: uniform allocation, linearly increasing support, and two-stage subsidies (Yu L et al., 2023), as shown in Table 4. Simulation results indicate that the two-stage subsidy scheme yields the greatest improvement in enterprise profits, followed by the uniform allocation scheme, while the linear growth scheme performs the worst. This suggests that, under a fixed budget, front-loading government support is more effective in enhancing enterprise profitability (see Figure 10).

Table 4. Design of Government Subsidy Schemes under Different Scenarios

Scenario	Illustration	Functional Form
Uniform Subsidy Allocation		With lookup (Time, ([(2017,0)- (2035,2e+06)], (2017,0),(2023.875,0),(2024,187500),(2024.125,187500),(2024.25,187500),(2024.375,187500),(2024.5,187500), (2024.625,187500),(2024.75,187500),(2024.875,187500),(2025,187500),(2025.125,187500),(2025.25,187500),(2025.375,187500),(2025.5,187500),(2025.625,187500),(2025.75,187500),(2025.875,187500),(2026,0),(2035,0)))
Linearly Increasing Subsidy		With lookup (Time, ([(2017,0)-(2035,2e+06)], (2017,0),(2023.875,0),(2024,0),(2024.125,25000),(2024. 25,50000),(2024.375,75000),(2024.5,100000),(2024.625 ,125000),(2024.75,150000),(2024.875,175000),(2025,20 0000),(2025.125,225000),(2025.25,250000),(2025.375,2 75000),(2025.5,300000),(2025.625,325000),(2025.75,35 0000),(2025.875,375000), (2026,0),(2035,0)));
Two-Stage Subsidy		With lookup (Time,([(2017,0)-(2035,2e+06)], (2017,0),(2023.875,0),(2024,150000),(2024.125,171429),(2024.25,192857),(2024.375,214286),(2024.5,235714), (2024.625,257143),(2024.75,278571),(2024.875,300000),(2025,200000),(2025.125,185714),(2025.25,171429),(2025.375,157143),(2025.5,142857),(2025.625,128571),(2025.75,114286),(2025.875,100000),(2026,0),(2035,0)))

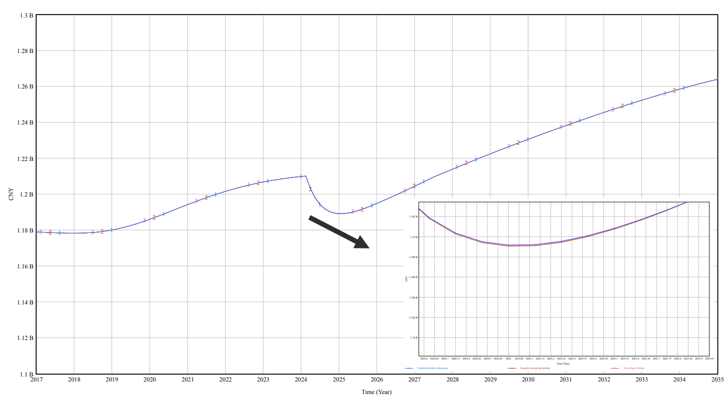


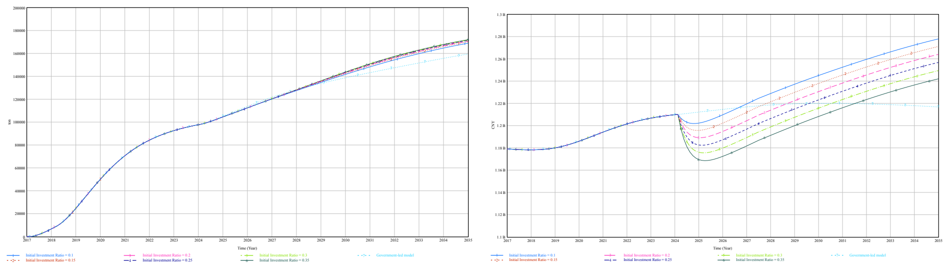
Figure 10. Enterprise Profit Dynamics under Different Government Subsidy Scenarios

(2) Regulation of enterprise investment and profit space

① Adjustment 1: Initial investment ratio

The initial investment ratio A574(t) is set at 0.10, 0.15, 0.20, 0.25, 0.30, and 0.35, and compared with the government-led model (see Figure 11). The results show that reducing the investment ratio weakens the enabling effect of blockchain and decreases recycling volume; however, in the later stage, recycling volume remains higher than that under the government-led model. At the same time, a lower investment ratio shortens the payback period.

The promotion effect on recycling exhibits diminishing marginal returns: once the investment ratio exceeds a certain threshold, the incremental increase in recycling becomes limited. Moreover, even small changes in the investment ratio have a significant impact on the payback period. Considering both recycling performance and profitability, an investment ratio of 0.15 is found to be optimal, as enterprise profits can surpass those of the government-led model by 2027, while further increases in the ratio contribute only marginally to recycling expansion.



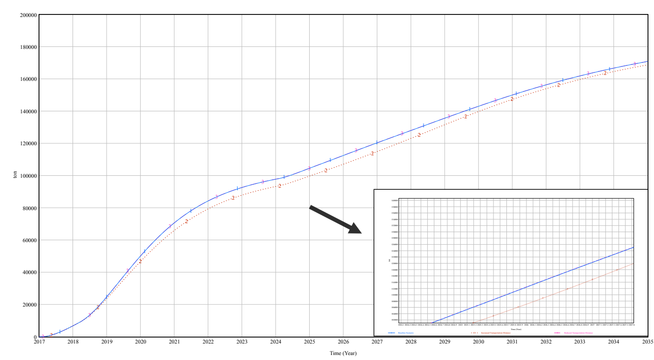
(a) Enterprise Recycling Volume (b) Enterprise Profit

Figure 11. Simulation Results under Adjustment 1

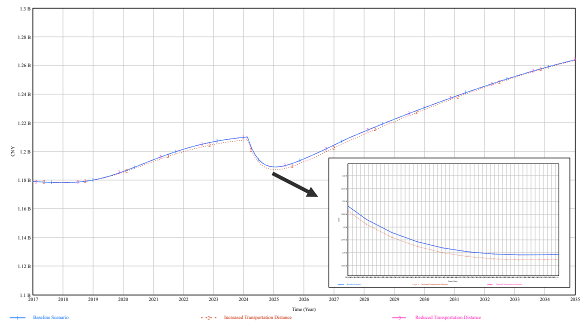
② Adjustment 2: Enhancing farmers' willingness to participate in residue-for-fertilizer exchange (transportation constraints)

Scenarios of increased and decreased transportation distances are compared with the baseline case (see Figure 12). The results show that an increase in transportation distance significantly suppresses farmers' willingness to participate and reduces recycling volume. Moreover, the negative impact of increased distance is stronger than the positive incentive effect of distance reduction, indicating an asymmetric effect. This also leads to a simultaneous decline in enterprise profits.

Therefore, improving the collection network, reducing transportation distances, and lowering transportation costs are critical for enhancing governance performance and overall system efficiency.



(a) Enterprise Recycling Volume



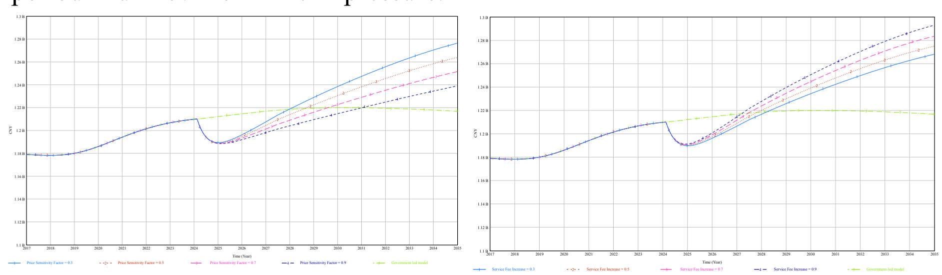
(b) Enterprise Profit

Figure 12. Simulation Results under Adjustment 2

③Adjustment 3: Enhancing blockchain service revenues

Price sensitivity factors for farmers and client firms, denoted as A527(t) and A529(t), are introduced to characterize the trade-off between service price and platform performance in shaping adoption willingness. These parameters are set at 0.3, 0.5, 0.7, and 0.9 for both groups (see **Figure** 13). The results show that lower sensitivity values (i.e., lower price sensitivity) are associated with higher enterprise profits.

Accordingly, enterprises should strengthen value communication to mitigate the inhibitory effect of price on adoption willingness. In addition, service fees can be moderately adjusted upward to shorten the payback period and alleviate financial pressure.



(a) Enterprise Profit -Blockchain Adoption Incentives

(b) Enterprise Profit -Increased Service Fees

Figure 13. Simulation Results under Adjustment 3

④ Adjustment 4: Regulating enterprise investment intensity

Scheme A: Adjustment of collection network investment intensity

The investment intensity in the collection network is set at 0.2, 0.4, 0.5, 0.6, 0.8, and 1.0 (see Figure 14). The results show that when the allocation intensity reaches 1.0, enterprise profits decline significantly in the later stage. This indicates that excessive investment increases long-term operating costs and constrains profit growth. Therefore, enterprises should maintain a balanced investment portfolio and carefully manage the timing of investments.

Scheme B: Adjustment of the reinvestment ratio

The reinvestment ratio is set at 0.05, 0.10, 0.15, 0.20, and 0.25 (see Figure 15). Lowering the reinvestment ratio shortens the payback period. When the ratio is set at 0.05, profitability improves significantly in the later stage, and enterprise profits surpass those under the government-led model by 2028. This suggests that blockchain reinvestment should be maintained within a reasonable range, as excessive investment may lead to rapidly increasing operation and maintenance costs and constrain profit growth.

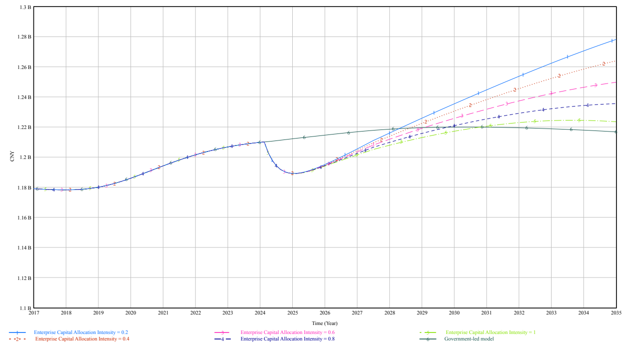
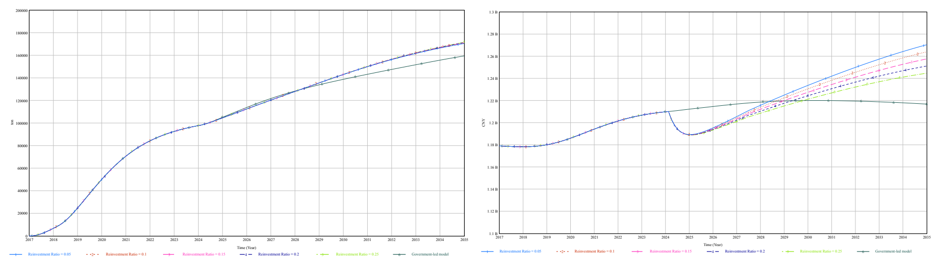


Figure 14. Simulation Results of Adjustment 4 (Scheme A)



Enterprise Recycling Volume　　　　Enterprise Profit

Figure 15. Simulation Results of Adjustment 4 (Scheme B)

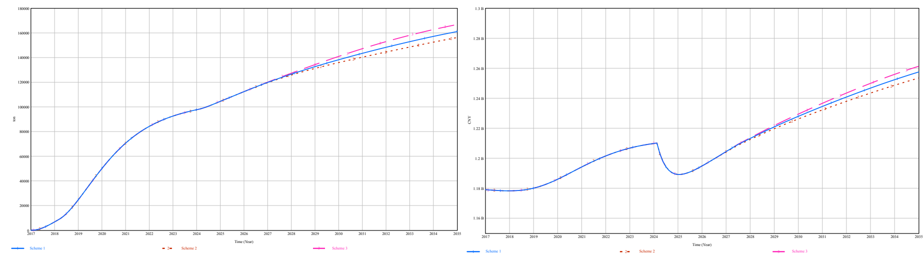
(3) Enterprise blockchain functional strategy selection

Under the dual objectives of regulatory compliance and commercialization, a platform function allocation coefficient F is introduced, where a higher value of F indicates a stronger regulatory orientation, and 1 - F represents a greater emphasis on commercial traceability. Three scenarios are designed (see Table 5): Scheme 1 (0.5/0.5), Scheme 2 (0.2/0.8), and Scheme 3 (0.8/0.2).

Table 5. Blockchain Function Allocation Schemes

Scheme	Description	Regulatory Function Weight	Commercial Traceability Weight
Scheme 1	Balanced (0.5 / 0.5)	0.5	0.5
Scheme 2	Commercial-oriented (0.2 / 0.8)	0.2	0.8
Scheme 3	Regulation-oriented (0.8 / 0.2)	0.8	0.2

The simulation results (see Figure 16) indicate that, under the combined objective of waste reduction and profit maximization, overall performance ranks as follows: Scenario 3 > Scenario 2 > Scenario 1. This suggests that platform functionality should place greater emphasis on regulatory orientation in order to achieve superior long-term governance and economic performance.



(a) Enterprise Recycling Volume (b) Enterprise Profit

Figure 16. Governance Effects under Different Blockchain Platform Function Orientations

6 Conclusions and Implications

This study develops a system dynamics model to examine the collaborative governance of fruit tree pruning residue utilization under blockchain application scenarios. Two blockchain adoption modes—government-led and government–enterprise cooperative—are constructed, and the dynamic evolution of governance performance and stakeholder benefits is evaluated through feedback structure analysis and simulation. The results indicate that residue governance is driven by the interaction of multiple factors, including government regulation, reward–penalty mechanisms, farmer participation, and enterprise investment in recycling networks. The system exhibits a typical limits-to-growth pattern characterized by "reinforcing-driven expansion and balancing constraints." In the early stage, appropriate incentives can effectively suppress open burning and promote collaborative governance; however, over time, diminishing marginal effects of incentives and the emergence of constraints such as transportation costs slow down recycling growth. This suggests that reliance on a single reward–penalty mechanism is insufficient to sustain long-term governance performance, and that continuous improvements in farmers' net income and participation convenience are essential to maintain stable engagement.

Further feedback analysis and simulation results show that the introduction of blockchain enhances information transparency and traceability, strengthens regulatory accountability, and builds trust among stakeholders. These effects reduce coordination frictions and increase participation willingness, thereby simultaneously improving recycling scale, farmer income, and enterprise performance. Although both adoption modes provide new momentum for circular utilization, they exhibit distinct stage-dependent characteristics. The government-led model emphasizes information disclosure and regulatory enforcement in the early stage, resulting in faster short-term improvements in recycling volume and governance outcomes. However, its advantages diminish over time due to declining regulatory dividends, increasing platform-related costs borne by enterprises, and limited value-added from commercialization, leading to slower profit growth and even decline. In contrast, the government–enterprise cooperative model faces higher initial investment costs, reinvestment requirements, and cash flow pressure, resulting in a longer payback period and lower profits in the early stage. Nevertheless, in the long run, enterprises can continuously optimize resource allocation and operational processes, enhance platform functionality, and improve governance efficiency through transparency, accountability, and trust-based incentives. As a result, this model performs better in terms of residue reduction and enterprise profitability. These findings highlight that, under a fixed level of government investment, governments tend to prioritize long-term governance performance, whereas enterprises are more sensitive to initial financial pressure and payback periods, leading to potential misalignment in preferences.

To address the practical constraints of implementing the government–enterprise cooperative model, several policy and managerial implications are proposed. Governments can reduce enterprise risks and cost burdens through tax incentives, financing support, and optimized subsidy structures. Enterprises should optimize investment timing and capital allocation, maintaining a dynamic balance between blockchain investment and collection network expansion to prevent excessive operation and maintenance costs. They should also enhance market-oriented profitability by developing higher value-added products and services to shorten the payback period. Farmers, in turn, can reduce unit transportation costs through cooperative logistics (e.g., group-based delivery) and improve efficiency and returns through policy support and equipment upgrades.

By integrating system dynamics with scenario-based simulation, this study identifies the feedback mechanisms underlying different blockchain cost-sharing modes and quantitatively evaluates their performance differences, providing a basis for optimizing policy support structures in agricultural waste governance

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Appendix

(1) Second-order feedback loops (n = 17):

$(R_{71},+,R_{51})(R_{51},+,A_{513},L_7)$, $2(R_{52},-,A_{55},L_7)(R_{71},+,R_{51})$, $(R_{52},+,A_{57},L_7)(R_{71},+,R_{51})$,
$(R_{52},+,A_{581},L_7)(R_{71},+,R_{51})$, $(R_{52},-,A_{581},L_7)(R_{71},+,R_{51})$, $(R_{52},+,L_4)(R_4,+,R_{51})$,
$(R_3,+,L_4)(R_4,-,R_3)$, $(R_3,+,L_4)(R_4,+,R_3)$, $2(R_{62},-,L_2)(R_2,+,R_{61})$, $(R_1,+,A_{11},L_6)(R_{61},-,L_1)$,
$(R_1,+,A_{11},L_6)2(-R_{62},+,L_1)$, $(R_1,+,A_{12},L_6)(R_{61},-,L_1)$, $(R_1,+,A_{12},L_6)2(-R_{62},+,L_1)$,

(2) Third-order feedback loops (n = 16):

$(R_{71},+,R_{51})(R_{51},-,A_{511},R_3)(R_3,+,L_7)$, $(R_{71},+,R_{51})(R_{51},+,A_{514},R_3)(R_3,+,L_7)$,
$(R_{71},+,R_{51})(R_{51},+,A_{54},R_3)(R_3,+,L_7)$, $(R_{52},+,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})$,
$(R_3,+,L_4)(R_4,+,R_{51})(R_{51},-,A_{511},R_3)$, $(R_3,+,L_4)(R_4,+,R_{51})(R_{51},+,A_{514},R_3)$,
$(R_3,+,L_4)(R_4,+,R_{51})(R_{51},+,A_{54},R_3)$, $(R_{62},+,R_3)(R_3,+,L_2)(R_2,+,R_{61})$,
$(R_2,+,R_{61})(R_{61},+,R_3)(R_3,+,L_2)$, $(R_1,+,A_{11},L_6)2(-R_{62},-,L_2)(R_2,+,L_1)$,

$(R_1,+,A_{11},L_6)2(-R_{62},-,L_2)(R_2,+,A_{22},L_1)$, $(R_1,+,A_{12},L_6)2(-R_{62},-,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{12},L_6)2(-R_{62},-,L_2)(R_2,+,A_{22},L_1)$,
(3) **Fourth-order feedback loops (n = 24):**
$(R_{71},+,R_{51})(R_{51},-,A_{511},R_3)(R_3,+,L_4)(R_4,+,A_{33},L_7)$,
$(R_{71},+,R_{51})(R_{51},+,A_{514},R_3)(R_3,+,L_4)(R_4,+,A_{33},L_7)$,
$(R_{71},+,R_{51})(R_{51},+,A_{54},R_3)(R_3,+,L_4)(R_4,+,A_{33},L_7)$,
$(R_{71},+,R_{51})(R_{51},-,A_{511},R_3)(R_3,+,L_2)3(R_2,+,L_7)$,
$(R_{71},+,R_{51})(R_{51},+,A_{514},R_3)(R_3,+,L_2)3(R_2,+,L_7)$,
$(R_{71},+,R_{51})(R_{51},+,A_{54},R_3)(R_3,+,L_2)3(R_2,+,L_7)$,
$(R_{52},+,L_4)(R_4,-,R_3)(R_3,+,L_7)(R_{71},+,R_{51})$,
$(R_{52},+,L_4)(R_4,+,R_3)(R_3,+,L_7)(R_{71},+,R_{51})$,
$(R_{62},-,L_4)(R_4,-,R_3)(R_3,+,L_2)(R_2,+,R_{61})$,
$(R_{62},-,L_4)(R_4,+,R_3)(R_3,+,L_2)(R_2,+,R_{61})$,
$(R_1,+,A_{11},L_6)(R_{61},+,R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{11},L_6)(R_{61},+,R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},+,R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},+,R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{12},L_6)(R_{61},+,R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{12},L_6)(R_{61},+,R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},+,R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},+,R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
(4) **Fifth-order feedback loops (n = 17):**
$(R_{52},+,L_4)(R_4,-,R_3)(R_3,+,L_2)3(R_2,+,L_7)(R_{71},+,R_{51})$,
$(R_{52},+,L_4)(R_4,+,R_3)(R_3,+,L_2)3(R_2,+,L_7)(R_{71},+,R_{51})$,
$(R_{62},-,L_4)(R_4,+,R_{51})(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,R_{61})$,
$(R_{62},-,L_4)(R_4,+,R_{51})(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,R_{61})$,
$(R_{62},-,L_4)(R_4,+,R_{51})(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,R_{61})$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,-,R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,-,R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,-,R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,-,R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
(5) **Sixth-order feedback loops (n = 15):**
$(R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,R_{61})$,
$(R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,R_{61})$,
$(R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,R_{61})$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,R_{51})(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,R_{51})(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,R_{51})(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,R_{51})(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,R_{51})(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,R_{51})(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,R_{51})(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,L_1)$,

$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,R_{51})(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,R_{51})(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,R_{51})(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,R_{51})(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,R_{51})(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,

(6) **Seventh-order feedback loops (n = 15):**

$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,L_5)(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,L_5)(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,L_5)(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,L_5)(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,L_5)(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,L_5)(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{11},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,L_5)(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,L_5)(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,L_5)(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,L_5)(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,L_5)(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,L_5)(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},-,A_{511},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},+,A_{514},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,L_1)$,
$(R_1,+,A_{12},L_6)(-R_{62},-,L_4)(R_4,+,A_{33},L_7)(R_{71},+,R_{51})(R_{51},+,A_{54},R_3)(R_3,+,L_2)(R_2,+,A_{22},L_1)$,