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Blockchain technology adoption decision and coordination contract in green supply chain

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A B S T R A C T

Chronic information asymmetries in green markets erode consumer trust, creating dual impediments to sustainable consumption and supply chain efficiency. Blockchain addresses these challenges by leveraging its unique technical features. This research analyzes a two-stage green supply chain comprising a manufacturer and retailer, developing three models with key parameters: green preference levels, trust coefficients, and blockchain traceability costs. These models, which include a baseline non-blockchain model, blockchain-enabled decentralized decision-making and blockchain-integrated centralized decision-making frameworks, are designed to explore blockchain adoption strategies and coordination mechanisms. This research elucidates several critical insights: (1) The optimal level of green production investment correlates positively with consumer green preferences regardless of blockchain implementation. Blockchain incentivizes the manufacturer to boost green investments, stimulating demand, improving retailer profits and Consumer Surplus. (2) Beyond blockchain operational costs, consumer trust levels act as pivotal determinants in decisions regarding blockchain adoption. The manufacturer tends to be more inclined to adopt blockchain technology only when consumer trust levels and the fixed costs of blockchain implementation are both below specific thresholds. (3) Compared with the decentralized decision-making model, the centralized decision-making model exhibits elevated levels of green production investment, significantly higher overall supply chain profits, and an augmented Consumer Surplus. The design of a two-part tariff contract with fixed remuneration enables supply chain coordination. Within a defined threshold range, fixed remuneration can achieve Pareto improvement in profits for both manufacturer and retailer. (4) The asymmetric Nash bargaining equilibrium enables the efficient allocation of post-coordination surplus gains. This research offers theoretical support for blockchain adoption choices in green supply chains, promoting green, efficient, and sustainable supply chain development.

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1. Introduction

The intensifying global climate crises have made green development a common imperative in international policymaking. On April 12, the State Council Executive Meeting endorsed the “2024-2025 Energy Conservation and Carbon Reduction Action Plan” and the “Work Plan for Accelerating the Establishment of a Carbon Emission Dual Control System”. These frameworks foster green low-carbon consumption patterns aimed at optimising synergistic benefits across economic development, social progress, and ecological preservation. This policy-driven transition has spurred sustained growth in green product demand, which has led to environmentally conscious consumption patterns gaining significant consumer traction (Li et al., 2020; Long et al., 2022). Nevertheless, persistent information asymmetry and transparency gaps have continued to undermine consumer confidence in green products (Wu & Zhao, 2024; Ma et al., 2024). Blockchain technology, as an innovative information

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technology, enhances supply chain transparency by implementing immutable data recording and decentralized consensus mechanisms, which in turn bolsters product traceability. Blockchain delivers auditable data access to stakeholders by cryptographically securing the recording of supply chain activities such as material sourcing, production monitoring, logistics tracking, and retail verification. This capacity significantly mitigates information asymmetries that cause green market inefficiencies. A prime example is TextileGenesis' blockchain-based traceability platform for textile supply chains, which tracks sustainable features like natural fiber sourcing, recycled materials, and ethical manufacturing standards throughout the production process. Through the implementation of distributed ledger technology, all supply chain participants can obtain real-time access to verifiable data pertaining to ecological certifications and social responsibility compliance. This technological innovation safeguards environmental integrity at each production stage while accelerating the industry's shift towards circular economy practices and supply chain digitization. However, the conflicting factors between the multi-party benefits of blockchain and its development and maintenance costs have reduced members' willingness to adopt blockchain. To address these challenges, supply chain members need to establish contractual agreements that balance short-term costs with long-term benefits. This approach will encourage proactive involvement in blockchain application and development. Consequently, this strategy will drive digital transformation and promote efficiency across the supply chain ecosystem. Contractual support mechanisms introduced by global retailers like Li & Fung and Walmart have offset upstream manufacturers' operational costs, spurred green technological innovation, and achieved supply chain efficiency optimization (Dai et al., 2017; Xu et al., 2020; Du & Li, 2024). Consequently, under conditions of consumer green preference and trust shortfalls, research on blockchain implementation strategies and coordination mechanisms holds substantial implications for optimizing supply chain operations and facilitating digital transition. Building upon the aforementioned analysis, this study constructs a two-stage green supply chain considering consumer green trust levels to examine manufacturer's blockchain technology adoption decisions and green supply chain coordination issues. By developing models without blockchain technology adoption, as well as decentralized and centralized decision-making models under blockchain implementation, the research primarily examines:

(1) Within a two-stage green supply chain where the manufacturer adopts blockchain technology, how do different members arrive at optimal operational decisions? What are the conditions under which the manufacturer can achieve profitability through blockchain technology adoption? Additionally, what specific values does blockchain technology deliver to the green supply chain?

(2) How do market factors, such as consumer trust in green products, preference intensity, and blockchain adoption costs, impact the manufacturer's green investment levels, the economic profits of supply chain members, Consumer Surplus, and Social Welfare? What are the magnitude characteristics of these impacts?

(3) How do blockchain-enabled decentralized and centralized structures influence product greenness, supply chain members' economic profits, and Consumer Surplus? Additionally, what contractual mechanisms can effectively coordinate the blockchain-enabled green supply chain? How should surplus earnings be distributed?

The structure of this paper is organized as follows: Section 2 systematically reviews scholarly advances in blockchain applications for supply chains and influence factors of green supply chains. Section 3 formalizes the model description and foundational assumptions. Section 4 establishes the models and derives optimal solutions under three scenarios accompanied by sensitivity analyses. Section 5 conducts numerical simulations to validate theoretical propositions. Section 6 synthesizes key theoretical contributions, elucidates managerial implications, and identifies promising avenues for future research in blockchain-enabled green supply chain systems.

2. Literature review

In recent years, blockchain technology adoption in supply chain management has attracted significant academic interest. Researchers worldwide have conducted extensive research spanning multiple sectors, including e-commerce, food production, healthcare systems, financial services, logistics networks, and government operations. Zhang et al. (2022) developed a retailer competition model, which indicates that blockchain adoption is not universally beneficial for retailers in all scenarios. It is only adopted when two critical conditions are met: minimal consumer privacy concerns and significant improvements in information transparency. Choi et al. (2020) constructed a duopoly competition model to analyze blockchain-enabled information disclosure strategies in rental service platforms. Xu and Choi (2021) examined the impact of cross-channel effects, sales model selection, and commission rates on blockchain adoption in dual-channel supply chains that operate through both offline retail channels and online platforms within carbon trading systems. Ma and Hu (2022) introduced a digital closed-loop supply chain framework to evaluate blockchain deployment in recycling processes and its subsequent effects on operational performance. Cui et al. (2024) comprehensively assessed the timing and architectural design of blockchain adoption, revealing that its profitability depends on whether manufacturers have sufficient production capacity. Li et al. (n.d.) examined blockchain adoption in two-stage supply chains based on rational agent theory that incorporates reference-dependent preferences, proposing contract coordination mechanisms that mitigate information leakage risks in blockchain systems. Wang and Zhang (2024) conducted a comprehensive analysis of optimal strategies for the introduction of blockchain traceability

technology in contract farming supply chain systems, revealing that the cost-effectiveness of blockchain investment is the dominant factor influencing technology adoption decisions among supply chain members. Wu et al. (2023) showed in fresh product supply chain contexts that blockchain application is not always optimal, as its feasibility depends on consumer acceptance of conventional products, product spoilage rates, and cost-sharing ratios for traceability systems. Gao et al. (2023) created a dynamic game-theoretic model that combines blockchain with AI in vaccine supply chains, quantifying how this integration improved coordination and operational efficiency during the pandemic response. Dong et al. (2021) applied game-theoretic frameworks to examine operational strategies for asset-backed securitization within supply chain finance contexts. Lou et al. (2022) approached blockchain's impact on financing market efficiency and stakeholders' spontaneous choices through tripartite and dynamic evolutionary game models, from the dual perspective of bank-enterprise financing efficiency optimization. Zhong et al. (2021) provided strategic guidance to the container shipping sector for developing pricing strategies in blockchain-mediated markets. Du and Li (n.d.) positioned regulators as consensus nodes within blockchain architectures, creating a "big boss" game-theoretic framework to analyze the regulatory intensity and node threshold conditions in international trade logistics. Turning to policy implications, Zhang et al. (2023) investigated how blockchain adoption influences government subsidy allocations within low-carbon supply chains. While existing studies have identified key determinants such as privacy concerns, transparency levels, cross-channel effects, production capacities, and implementation costs, they collectively overlook the pivotal role of consumer trust. Additionally, limited research has integrated supply chain contracts with technological adoption to optimize supply chain performance.

Academic exploration remains limited regarding blockchain applications in green supply chains, but emerging studies have begun revealing its potential. Xia et al. (2021) analyzed the influence of cross-shareholding mechanisms across power structures on decision-making, showing that implementation results in carbon emission reductions among supply chain members. Li et al. (2021) analyzed various contract strategies and found that increasing product greenness benefits companies regardless of whether retailers' marketing efforts are highly effective or not. Gao et al. (2023) investigated the incentive effects of platform certification fees and government subsidies on green supply chains from the dual perspectives of online trading platforms and government low-carbon subsidies. The results demonstrate that the introduction of online trading platforms enables governments to achieve higher emission reduction levels with reduced low-carbon subsidy investment. Ma et al. examined the impact of information advantage, green optimism, and power structure, pertaining to consumers' green preferences, on green supply chain decisions and performance. Li et al. (2024) demonstrated how channel competition affects the overall greenness and economic performance of green supply chains through its impact on manufacturers' sales model choices and green investment decisions.

Emerging research indicates a growing interest in exploring blockchain technology's influence within green supply chain contexts. Yi et al. (2024) constructed a tripartite closed-loop green supply chain model that includes manufacturers, e-commerce platforms, and recyclers, demonstrating how CSR commitments enhance product greenness, stimulate recycling rates, and expand market demand. The aforementioned literature examines various conventional market factors influencing green supply chains but does not address whether blockchain technology adoption can improve operational decisions and overall performance in green supply chains. To address this research gap, Lu et al. (2024) explored the effects of different blockchain implementation modes in green supply chains on product greenness and traceability information levels. Their findings show that when manufacturers are involved in traceability-level decision-making, blockchain adoption significantly enhances product greenness. Moreover, the highest traceability is achieved when both parties implement mutual self-implementation modes. Liu et al. (2023) developed a competition model between manufacturers of green and non-green products, demonstrating that blockchain technology can shift the competitive dynamics between these product types by increasing consumer trust in green product information. Shen and Dai (n.d.) examined the operational and blockchain adoption decisions of green manufacturers and e-commerce platforms in platform supply chains. The study reveals that both parties exhibit adoption willingness for blockchain technology only when the unit implementation cost is low and consumer green preference is high, across both reselling and agency selling models. Blockchain technology's positive role in enhancing transparency, traceability, and consumer trust in green supply chains has been demonstrated by these studies. However, they fall short in exploring how to design effective coordination mechanisms after blockchain application to optimize overall supply chain performance and eliminate the double marginalization effect. Liu et al. (2020) examined the credibility of agricultural product greenness, studied investment decisions in big data and blockchain-based information services within green agricultural supply chains, and proposed cost-sharing and revenue-sharing contracts to coordinate the supply chain. However, their research was restricted to a preliminary framework of cost and revenue sharing, and failed to examine how to address the surplus benefit distribution problem arising from coordination.

Based on the aforementioned analysis, this study identifies limitations in previous research: 1) Prior research has extensively examined blockchain applications and factors influencing green supply chain operational decisions, yet limited studies have investigated the impact of consumer trust on technology adoption decisions in blockchain-enabled green supply chains and post-implementation supply chain coordination. 2) While some studies utilize blockchain-integrated big data to enhance information transparency and design coordination contracts, they fall short in addressing the surplus benefit distribution issue stemming from coordination mechanisms. Accordingly, we integrate three key parameters - consumer green trust, degree of green preference, and blockchain unit traceability cost - to establish a two-stage green supply chain led by the manufacturer and followed by the retailer. We design three models: non-blockchain adoption, blockchain-enabled decentralized decision-

making, and centralized decision-making, to examine the blockchain technology adoption decisions of green supply chain members. Building on the centralized decision-making model's equilibrium and the supply chain system's optimal profit, we design a two-part tariff contract to coordinate the supply chain profit under decentralized decision-making. Moreover, we use asymmetric Nash bargaining equilibrium to allocate the surplus benefits generated after contractual coordination.

3. Model description and assumptions

3.1. Model description

This study examines a manufacturer-led green supply chain comprising a single green manufacturer and a single retailer. In this system, the manufacturer first determines the effort level s of the green product input and the wholesale price w, after which the retailer sets the retail price p based on these decisions. Due to issues such as untimely, inaccurate, incomplete, and unreliable disclosure of green product information, the current green market is plagued by chaos and rampant greenwashing. To address consumer trust issues caused by information asymmetry and enhance purchase willingness, the manufacturer introduces blockchain technology. The study establishes two operational models based on blockchain adoption status: non-blockchain and blockchain-integrated scenarios. The model parameters and their definitions are summarized in Table 1.

Table 1
Symbolic description of model parameters

model parameter	meaning
w	wholesale price per unit product
p	retail price per unit product
a	the maximum potential market demand
D	market demand
η	consumers' green trust coefficient
θ	consumers' preference for green products
s	the efforts of manufacturers to produce green products, i.e. product greenness
ϕ	manufacturer's green effort cost coefficient
c	the unit production cost of green products produced by manufacturers
F	one-time fixed payment cost required to introduce blockchain technology
f	the unit traceability cost that the retailer needs to pay to the manufacturer after adopting the blockchain technology

3.2. Hypothesis

(a) According to the reference (Zhang et al., 2023), market demand is determined by product retail price, manufacturer's green effort, consumer green preference, and green trust level. Without blockchain technology, the market demand is $D^N = a - p + \eta\theta s$ with a green trust coefficient $0 < \eta < 1$. With blockchain adoption, consumers access complete green information of products through blockchain traceability, resulting in full green trust $\eta = 1$, and the market demand updates to $D = a - p + \theta s$.

(b) The Manufacturer's production, retailer's order quantity and market demand are identical.

(c) $C(S) = \frac{1}{2}\phi s^2$ denotes the cost of effort invested by the manufacturer in producing green products, where ϕ represents the green effort cost coefficient, and s indicates the effort level invested by the manufacturer.

(d) The implementation of blockchain technology incurs associated costs. According to reference (Liang & Xiao, 2023), we define f as the per-unit traceability fee transferred from retailer to manufacturer following blockchain adoption, while F denotes the fixed implementation cost associated with blockchain deployment.

(e) Social Welfare (SW) constitutes the aggregate of supply chain participants' profits and Consumer Surplus (CS), where CS measures the disparity between consumers' reservation price for green products and their actual expenditure, derivable through demand function. Following the definition by Panda et al. (2017), the Consumer Surplus is $CS = \int_p^{\bar{p}} D dp = \frac{D^2}{2}$.

4. Model construction and solution

Decentralised decision-making model without blockchain technology (Model N)

We first examine the scenario without blockchain technology implementation as the benchmark model. In this structure, the green manufacturer and the retailer follow a two-stage Stackelberg game: initially, the green manufacturer decides the wholesale price w and the green effort s; subsequently, the retailer decides the retail price p of the product. The model is established as follows:

$$D^N = a - p^N + \eta\theta s^N \tag{1}$$

$$\pi_m^N = (w^N - c)D^N - \frac{\phi s^{N2}}{2} \tag{2}$$

$$\pi_{\mathrm{r}}^N = (p^N - w^N)D^N \tag{3}$$

Based on the above decision-making process, applying the backward induction method yields Theorem 1.

Theorem 1. When $\eta^2\theta^2 - 4\phi < 0$, the optimal wholesale price w^{N*}, green effort s^{N*}, retail price p^{N*}, market demand D^{N*}, Consumer Surplus, optimal profit and optimal total Social Welfare under this model are shown in Eqs. (4)-(12):

$$w^{N*} = \frac{c\eta^2\theta^2 - 2(a+c)\phi}{\eta^2\theta^2 - 4\phi} \tag{4}$$

$$s^{N*} = \frac{(-a+c)\eta\theta}{\eta^2\theta^2 - 4\phi} \tag{5}$$

$$p^{N*} = \frac{c\eta^2\theta^2 - (3a+c)\phi}{\eta^2\theta^2 - 4\phi} \tag{6}$$

$$D^{N*} = \frac{(-a+c)\phi}{\eta^2\theta^2 - 4\phi} \tag{7}$$

$$CS^{N*} = \frac{(a-c)^2\phi^2}{2(\eta^2\theta^2 - 4\phi)^2} \tag{8}$$

$$\pi_m^{N*} = -\frac{(a-c)^2\phi}{2\eta^2\theta^2 - 8\phi} \tag{9}$$

$$\pi_{\mathrm{r}}^{N*} = \frac{(a-c)^2\phi^2}{(\eta^2\theta^2 - 4\phi)^2} \tag{10}$$

$$\pi_s^{N*} = -\frac{\phi(a-c)^2(\eta^2\theta^2 - 6\phi)}{2(\eta^2\theta^2 - 4\phi)^2} \tag{11}$$

$$SW^{N*} = -\frac{\phi(a-c)^2(\eta^2\theta^2 - 7\phi)}{2(\eta^2\theta^2 - 4\phi)^2} \tag{12}$$

Proof. See Appendix A.

Proposition 1. When blockchain technology is not adopted,

(1) $\frac{\partial w^{N*}}{\partial \eta} > 0$, $\frac{\partial s^{N*}}{\partial \eta} > 0$, $\frac{\partial p^{N*}}{\partial \eta} > 0$, $\frac{\partial D^{N*}}{\partial \eta} > 0$, $\frac{\partial \pi_m^{N*}}{\partial \eta} > 0$, $\frac{\partial \pi_r^{N*}}{\partial \eta} > 0$, $\frac{\partial CS^{N*}}{\partial \eta} > 0$, $\frac{\partial SW^{N*}}{\partial \eta} > 0$;

(2) $\frac{\partial w^{N*}}{\partial \theta} > 0$, $\frac{\partial s^{N*}}{\partial \theta} > 0$, $\frac{\partial p^{N*}}{\partial \theta} > 0$, $\frac{\partial D^{N*}}{\partial \theta} > 0$, $\frac{\partial \pi_m^{N*}}{\partial \theta} > 0$, $\frac{\partial \pi_r^{N*}}{\partial \theta} > 0$, $\frac{\partial CS^{N*}}{\partial \theta} > 0$, $\frac{\partial SW^{N*}}{\partial \theta} > 0$;

(3) $\frac{\partial w^{N*}}{\partial \phi} < 0$, $\frac{\partial s^{N*}}{\partial \phi} < 0$, $\frac{\partial p^{N*}}{\partial \phi} < 0$, $\frac{\partial D^{N*}}{\partial \phi} < 0$, $\frac{\partial \pi_m^{N*}}{\partial \phi} < 0$, $\frac{\partial \pi_r^{N*}}{\partial \phi} < 0$, $\frac{\partial CS^{N*}}{\partial \phi} < 0$, $\frac{\partial SW^{N*}}{\partial \phi} < 0$.

Proof. See Appendix B.

Proposition 1 establishes that in non-blockchain green supply chains, the following variables exhibit positive correlations with consumer green trust and preference: wholesale prices, green production efforts, retail prices, market demand, manufacturer and retailer's profits, Consumer Surplus, and Social Welfare. The proliferation of low-carbon awareness drives consumer preferences toward eco-efficient products characterized by environmental friendliness and resource efficiency. Strengthened consumer trust amplifies premium price acceptance, directly stimulating market demand expansion. This virtuous cycle subsequently enhances the manufacturer and retailer profitability and aggregate societal welfare. Furthermore, Proposition 1 demonstrates inverse relationships between the green effort cost coefficient and decision variables, profits, Consumer Surplus, and Social Welfare. Counterintuitively, manufacturers implement price reductions to absorb cost pressures instead of passing them to consumers, thereby preserving sales stability and market share.

Decentralised decision-making model with blockchain technology (Model Y)

For green products, consumers are increasingly concerned about the authenticity of their environmental friendliness. Blockchain delivers detailed and tamper-proof product histories, thus the manufacturer strategically adopts this technology to authenticate green attributes and build consumer trust. In Model Y, the manufacturer possesses both the technological capability and operational resources to implement blockchain technology. This strategic adoption is driven by compelling incentives to pursue supply chain innovation and facilitate systemic optimization. Because the manufacturer's dominant governance position within the green supply chain structure creates direct economic incentives for technology implementation.

In this structure, the green manufacturer and the retailer follow a two-stage Stackelberg game: initially, the green manufacturer decides the wholesale price w and the green effort level s; subsequently, the retailer decides the retail price p of the product. The model is established as follows :

$$D^Y = a - p^Y + \theta s^Y \tag{13}$$

$$\pi_{\mathrm{m}}^Y = (w^Y - c + f)D^Y - \frac{\phi s^{Y2}}{2} - F \tag{14}$$

$$\pi_r^Y = (p^Y - w^Y - f)D^Y \tag{15}$$

Based on the above decision-making process, applying the backward induction method yields Theorem 2.

Theorem 2. When $\theta^2 - 4\phi < 0$, the optimal wholesale price w^{Y*}, green effort s^{Y*}, retail price p^{Y*}, market demand D^{Y*}, Consumer Surplus, optimal profit and optimal total Social Welfare under this model are shown in Eqs. (16)-(24):

$$w^{Y*} = \frac{(c-f)\theta^2 - 2(a+c-2f)\phi}{\theta^2 - 4\phi} \tag{16}$$

$$s^{Y*} = \frac{(-a+c)\theta}{\theta^2 - 4\phi} \tag{17}$$

$$p^{Y*} = \frac{c\theta^2 - (3a+c)\phi}{\theta^2 - 4\phi} \tag{18}$$

$$D^{Y*} = \frac{(-a+c)\phi}{\theta^2 - 4\phi} \tag{19}$$

$$CS^{Y*} = \frac{(a-c)^2\phi^2}{2(\theta^2 - 4\phi)^2} \tag{20}$$

$$\pi_{\mathrm{m}}^{Y*} = -F - \frac{(a-c)^2\phi}{2(\theta^2 - 4\phi)} \tag{21}$$

$$\pi_r^{Y*} = \frac{(a-c)^2 \phi^2}{\left(\theta^2 - 4\phi\right)^2} \tag{22}$$

$$\pi_s^{Y*} = -\frac{\phi(a-c)^2\left(\theta^2 - 6\phi\right)}{2\left(\theta^2 - 4\phi\right)^2} - F \tag{23}$$

$$SW^{Y*} = -\frac{\phi(a-c)^2\left(\theta^2 - 7\phi\right)}{2\left(\theta^2 - 4\phi\right)^2} - F \tag{24}$$

Proof. See Appendix C.

Proposition 2. When a manufacturer adopts blockchain technology,

(1) $\frac{\partial w^{Y*}}{\partial f} < 0$, $\frac{\partial s^{Y*}}{\partial f} = \frac{\partial p^{Y*}}{\partial f} = \frac{\partial D^{Y*}}{\partial f} = \frac{\partial \pi_m^{Y*}}{\partial f} = \frac{\partial \pi_r^{Y*}}{\partial f} = \frac{\partial CS^{Y*}}{\partial f} = \frac{\partial SW^{Y*}}{\partial f} = 0$;

(2) $\frac{\partial \pi_m^{Y*}}{\partial F} < 0$, $\frac{\partial SW^{Y*}}{\partial F} < 0$, $\frac{\partial w^{Y*}}{\partial F} = \frac{\partial s^{Y*}}{\partial F} = \frac{\partial p^{Y*}}{\partial F} = \frac{\partial D^{Y*}}{\partial f} = \frac{\partial \pi_r^{Y*}}{\partial F} = \frac{\partial CS^{Y*}}{\partial f} = 0$.

Proof. See Appendix D.

Proposition 2 demonstrates that after the manufacturer adopts blockchain technology, the wholesale price exhibits negative correlations with the unit traceability fee, while the following variables remain unaffected by unit traceability fees: the green production effort level, retail price, market demand, profits of both manufacturer and retailer, Consumer Surplus, and total Social Welfare. Fixed blockchain costs negatively impact manufacturer profits and Social Welfare, while leaving unaffected: the wholesale price, green production effort level, retail price, market demand, retailer's profit, and Consumer Surplus. The conclusions of Proposition 2 align with Liang and Xiao's (2023) analysis of blockchain adoption costs, revealing that fixed blockchain implementation costs have no impact on retailer profits but negatively affect manufacturer profits, while unit traceability fees do not influence supply chain members' profits.

Proposition 3. When a manufacturer adopts blockchain technology,

(1) $\frac{\partial w^{Y*}}{\partial \theta} > 0$, $\frac{\partial s^{Y*}}{\partial \theta} > 0$, $\frac{\partial p^{Y*}}{\partial \theta} > 0$, $\frac{\partial D^{Y*}}{\partial \theta} > 0$, $\frac{\partial \pi_m^{Y*}}{\partial \theta} > 0$, $\frac{\partial \pi_r^{Y*}}{\partial \theta} > 0$, $\frac{\partial CS^{Y*}}{\partial \theta} > 0$, $\frac{\partial SW^{Y*}}{\partial \theta} > 0$;

(2) $\frac{\partial w^{Y*}}{\partial \phi} < 0$, $\frac{\partial s^{Y*}}{\partial \phi} < 0$, $\frac{\partial p^{Y*}}{\partial \phi} < 0$, $\frac{\partial D^{Y*}}{\partial \phi} < 0$, $\frac{\partial \pi_m^{Y*}}{\partial \phi} < 0$, $\frac{\partial \pi_r^{Y*}}{\partial \phi} < 0$, $\frac{\partial CS^{Y*}}{\partial \phi} < 0$, $\frac{\partial SW^{Y*}}{\partial \phi} < 0$.

Proof. See Appendix E.

Proposition 3 establishes that in the blockchain-enabled green supply chain, the wholesale price, manufacturer's effort level in green product production, retail price, market demand, profits of both manufacturer and retailer, Consumer Surplus, and total Social Welfare all maintain positive correlations with consumers' environmental preference while showing inverse relationships with the green effort cost coefficient.

Proposition 4. (1) $s^{Y*} > s^{N*}, p^{Y*} > p^{N*}, D^{Y*} > D^{N*}$; (2) $w^{Y*} > w^{N*}$ if and only if $f < f_1$, where $f_1 = \frac{2\left(\eta^2 - 1\right)\theta^2\phi(a-c)}{\left(\theta^2 - 4\phi\right)\left(\eta^2\theta^2 - 4\phi\right)}$.

Proof. See Appendix F.

Proposition 4 establishes that in decentralized systems, blockchain adoption yields enhanced green efforts, elevated retail

prices, and expanded market demand relative to non-blockchain scenarios. This phenomenon arises from blockchain's capacity to establish transparent information sharing and immutable product traceability. This mechanism not only stimulates manufacturers to enhance their green efforts but also activates consumers' premium payment willingness for environmentally friendly products. Consequently, demand expansion enables retailers to leverage price premiums and capture increased profit margins. Furthermore, when unit traceability fees fall below a critical threshold, blockchain adoption in Model Y leads to significantly higher wholesale prices than those observed in Model N.

Proposition 5. (1) $\pi_{\mathrm{r}}^{Y*} > \pi_{\mathrm{r}}^{N*}$; (2) $\pi_{\mathrm{m}}^{Y*} > \pi_{\mathrm{m}}^{N*}$ if and only if $\eta < \eta_1$ and $F < F_1$, where $\eta_1 = \sqrt{\dfrac{\phi\left\{\theta^2\left[(a-c)^2+8F\right]-32F\phi\right\}}{\theta^2\left[\phi(a-c)^2+2F\left(\theta^2-4\phi\right)\right]}}$ and $F_1 = \dfrac{(a-c)^2\theta^2}{8\left(4\phi-\theta^2\right)}$; (3) $CS^{Y*} > CS^{N*}$; (4) $SW^{Y*} > SW^{N*}$ if and only if $F < F_2$, where $F_2 = -\dfrac{\left(\eta^2-1\right)\theta^2\phi(a-c)^2\left[\eta^2\theta^4-7\left(\eta^2+1\right)\theta^2\phi+40\phi^2\right]}{2\left(\theta^2-4\phi\right)^2\left(\eta^2\theta^2-4\phi\right)^2}$.

Proof. See Appendix G.

Proposition 5 reveals that the retailer's profit is consistently enhanced following the manufacturer's adoption of blockchain technology. Diverging from Shen and Dai's (2024) research, which found that the unit cost of the blockchain and consumers' green preferences influence supply chain members' decision-making, this research identifies consumer trust level as a novel influence driver. Manufacturer demonstrates blockchain adoption incentives only when both fixed costs and consumer trust levels fall below determinative thresholds, thereby creating a profitability advantage for post-adoption scenarios over pre-adoption outcomes. Specifically, blockchain technology's decentralised, tamper-proof and highly transparent features can successfully restore consumer confidence and increase product sales in a trust-deficient environment, which will boost manufacturer profitability. While enhancing consumer trust, excessive adoption costs may erode the manufacturer's profit, the manufacturer should only invest in blockchain technology strategies in markets with low customer trust and cheap adoption costs. Proposition 5 further establishes that blockchain adoption significantly enhances total Social Welfare under low fixed-cost conditions.

Centralised decision-making model with blockchain technology (Model C)

Under the centralized decision-making model, the manufacturer and retailer act as a unified entity to maximize supply chain profits. The profit function of the green supply chain system is:

$$\pi^C = (p^C - c)(a - p^C + \theta s^C) - \frac{\phi s^{C2}}{2} - F \tag{25}$$

It follows from (25) that π^C is a strictly concave function for p^C and s^C when $\theta^2 - 2\phi < 0$. The optimal decision variables under centralised decision-making can be obtained through the simultaneous equations $\dfrac{\partial \pi^C}{\partial p^C} = 0$ and $\dfrac{\partial \pi^C}{\partial s^C} = 0$. The optimal demand, Consumer Surplus, optimal system profit and optimal Social Welfare can then be obtained as shown in Eqs. (26)-(31):

$$s^{C*} = \frac{\theta(c-a)}{\theta^2 - 2\phi} \tag{26}$$

$$p^{C*} = \frac{c\theta^2 - \phi(a+c)}{\theta^2 - 2\phi} \tag{27}$$

$$D^{C*} = \frac{\phi(c-a)}{\theta^2 - 2\phi} \tag{28}$$

$$CS^{C*} = \frac{\phi^2(a-c)^2}{2\left(\theta^2 - 2\phi\right)^2} \tag{29}$$

$$\pi_s^{C*} = \frac{\phi(a-c)^2}{2\left(2\phi - \theta^2\right)} - F \tag{30}$$

$$SW^{C*} = -\frac{\phi(a-c)^2\left(\theta^2 - 3\phi\right)}{2\left(\theta^2 - 2\phi\right)^2} - F \tag{31}$$

Proposition 6. (1) $s^{C*} > s^{Y*}$, $D^{C*} > D^{Y*}$; (2) $p^{C*} > p^{Y*}$ if and only if $\theta > \sqrt{\phi}$; (3) $\pi_s^{C*} > \pi_s^{Y*}$, $CS^{C*} > CS^{Y*}$,

$SW^{C*} > SW^{Y*}$.

Proof. See Appendix H.

Proposition 6 demonstrates that blockchain adoption induces significantly higher green effort investments by the manufacturer in a centralized model than in a decentralized framework. These heightened green efforts stimulate market demand. Elevated consumer environmental preferences enable centralized supply chain systems to command premium pricing strategies, thereby increasing the overall profit of the green supply chain. Therefore, under decentralized decision-making, the manufacturer and retailer's pursuit of individual profit maximization in a green supply chain can lead to double marginalization, thus reducing the supply chain's total profit. Conversely, centralized coordination enables complete mitigation of double marginalization, synergistically optimizing resource allocation while amplifying both performance and Social Welfare.

Coordination mechanism： two-part tariff contract

Coordination model based on a two-part tariff contract (Model H)

To enhance supply chain profitability and collaborative development while achieving benchmarks for centralized decision-making, effective contract mechanisms must be designed to coordinate pricing strategies between supply chain members and optimize profit distribution. This approach ensures Pareto improvements across the supply chain. This section develops a two-part tariff contract framework for green supply chain coordination, defined by strategic parameters (w^H, T). The contractual protocol initiates with the manufacturer determining wholesale price w^H and the product's greenness s^H to replicate centralized optimization, while the retailer provides fixed remuneration T compensating for green investment costs and blockchain implementation, subsequently setting retail price p^H. Therefore, the model is established as follows:

$$D^H = a - p^H + \theta s^H \tag{32}$$

$$\pi_{\mathrm{m}}^H = (w^H - c + f)D^H - \frac{\phi s^{H2}}{2} - F + T \tag{33}$$

$$\pi_r^H = (p^H - w^H - f)D^H - T \tag{34}$$

To maximize the overall profit of the supply chain, the optimal decision variables for the manufacturer and retailer under decentralized decision-making must align with those under centralized decision-making, denoted as $s^{H*} = s^{C*}, p^{H*} = p^{C*}$. To ensure the feasibility of the coordination mechanism, the optimal profits of supply chain members after coordination must be no less than those obtained under decentralized decision-making, denoted as $\pi_m^{H*} \geq \pi_m^{Y*}$, $\pi_r^{H*} \geq \pi_r^{Y*}$. Following this rationale, the solution leads to Proposition 7.

Proposition 7. The two-part tariff contract can effectively coordinate the green supply chain when the contract parameters are satisfied both $w^{H*} = c - f$ and $T^* \in \left[T_1^*,\ T_2^*\right]$, where $T_1^* = \dfrac{2\phi^3(a-c)^2}{\left(4\phi-\theta^2\right)\left(\theta^2-2\phi\right)^2}$, $T_2^* = \dfrac{4\left(a-c\right)^2\left(3\phi-\theta^2\right)\phi^3}{\left(\theta^4-6\theta^2\phi+8\phi^2\right)^2}$. The specific value T is determined by the bargaining power of the manufacturer and the retailer.

Proof. See Appendix I.

Proposition 7 establishes that two-part tariff contracts enable effective coordination in blockchain-enabled green supply chains. The product greenness and market equilibrium prices determined under this contract mechanism can both reach the optimal levels of the centralized decision-making model. The profit of each member is greater than that of decentralized decision-making, and the total profit of the system also achieves the optimal state under centralized decision-making.

Asymmetric Nash bargaining of a two-part tariff contract

The equitable distribution of coordination-generated surplus profits constitutes a critical concern in two-part tariff implementations for green supply chain coordination. The asymmetric Nash bargaining model establishes a systematic approach for allocating these gains according to member bargaining positions and relative market influence. This study employs this game-theoretic mechanism to determine surplus apportionment. In this model, where the fixed fee operates as the decision variable in the contractual process, and the objective function is to maximize the returns of the manufacturer and the retailer in the contractual coordination process. The asymmetric Nash bargaining model is:

$$\max_{T_1^* \le T^* \le T_2^*} \pi^{\varepsilon}(T^*) = (\pi_m^{H*} - \pi_m^{Y*})^{\lambda} (\pi_r^{H*} - \pi_r^{Y*})^{1-\lambda} \tag{35}$$

Let λ represents the manufacturer's bargaining power, and $1-\lambda$ represents the retailer's bargaining power, with the condition that $0 < \lambda < 1$. Proposition 8 can be obtained by solving Eq. (35):

Proposition 8. Under the two-part tariff contract, the optimal fixed reward is:

$$T^* = -\frac{2\phi^3 (a-c)^2 \left[\left(\theta^2 - 2\phi \right) \lambda + \theta^2 - 4\phi \right]}{\left(\theta^4 - 6\theta^2 \phi + 8\phi^2 \right)^2} \tag{36}$$

Proof. See Appendix J.

Proposition 8 reveals that the fixed fee T in the two-part tariff contract, transferred from retailer to manufacturer, is governed by the supplier's bargaining power λ. Specifically, as indicated by Eq. (36), λ exerts a positive correlation with T, which means that the retailer will pay the manufacturer a greater fixed compensation if the manufacturer has greater bargaining power. Substituting this parametric relationship into post-coordination profit functions yields the asymmetric Nash bargaining equilibrium outcomes for both parties:

$$\pi_m^{H*} = \pi_m^{Y*} + \lambda\Omega, \quad \pi_r^{H*} = \pi_r^{Y*} + (1-\lambda)\Omega \tag{37}$$

Among them, $\Omega = \pi_m^{H*} + \pi_r^{H*} - \pi_m^{Y*} - \pi_r^{Y*}$, which represents the additional earnings generated by the green supply chain system through the implementation of a two-part tariff coordination contract. Fundamentally, the allocation of these profits between the manufacturer and retailer is directly determined by their relative bargaining power. A party's share proportionally increases with its bargaining power dominance in the negotiation process.

5. Mathematical simulation

5.1. Effect of parameters on model equilibrium

This section utilizes numerical case studies to analyze optimal decision outcomes in the aforementioned scenarios, investigating how consumers' green preferences and trust levels shape supply chain members' strategic decision-making and profit maximization. Suppose $a = 100$, $c = 2.5$, $\phi = 1.7$, $F = 100$, $f = 10$.

Set the consumer trust level $\eta = 0.8$ and the degree of consumer green preference $\theta = 0.7$. Figures 1 to 10 respectively present the variation trends of supply chain members' equilibrium decisions, optimal profits, Consumer Surplus, and optimal Social Welfare with respect to consumers' green preferences and trust levels.

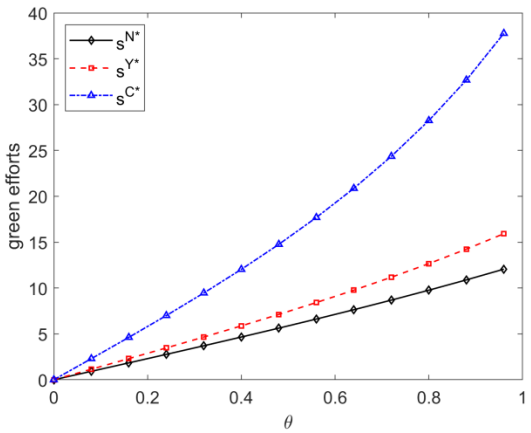


Fig.1. The influence of consumers' green preference levels on green efforts

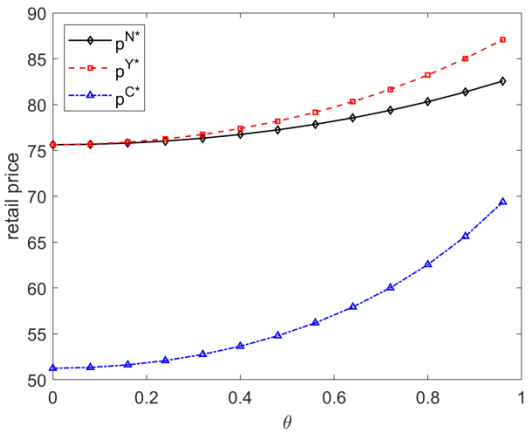


Fig.2. The influence of consumers' green preference levels on retail price

Figs. 1 and 2 illustrate the impact of consumer green preference intensity on equilibrium decisions across three supply chain configurations. The results demonstrate that increasing consumer green preferences drive upward trends in equilibrium green

effort levels and retail prices across all models. Growing consumer preference for green products induces market demand expansion. Consequently, manufacturers amplify green R&D investments to improve product greenness through enhanced production processes. Capitalizing on consumer recognition of green attributes and premium payment willingness, retailers can optimize pricing strategies for profit maximization.

As shown in Fig. 1, the manufacturer's green effort levels under Model C exceed those in Models N and Y. This disparity arises from centralized decision-making's superior coordination capability, which synchronizes green production with marketing strategies to intensify the manufacturer's green investment intensity. Notably, centralized decision-making exhibits heightened sensitivity of optimal green efforts to consumer green preference variations. Fig. 2 reveals that under these parameter settings, the retail price in centralized decision-making is lower than in Models N and Y. This stems from the double marginalization effect inherent to decentralized systems, where manufacturer and retailer independently maximize their profits, whereas centralized coordination enables strategic pricing alignment across supply chain members.

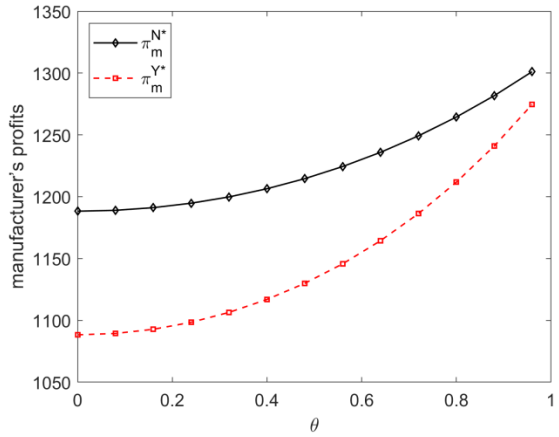


Fig.3. The impact of consumers' green preference levels on the profits of manufacturer

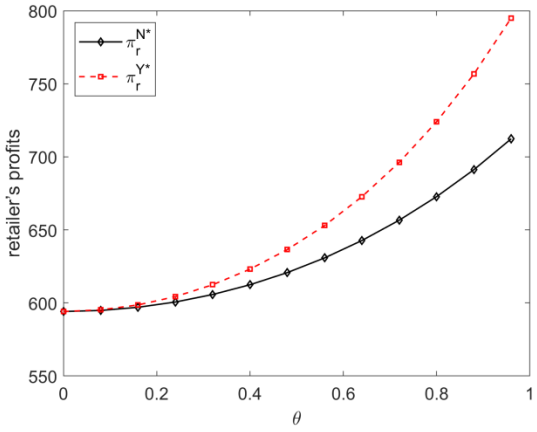


Fig.4. The impact of consumers' green preference levels on the profits of retailer

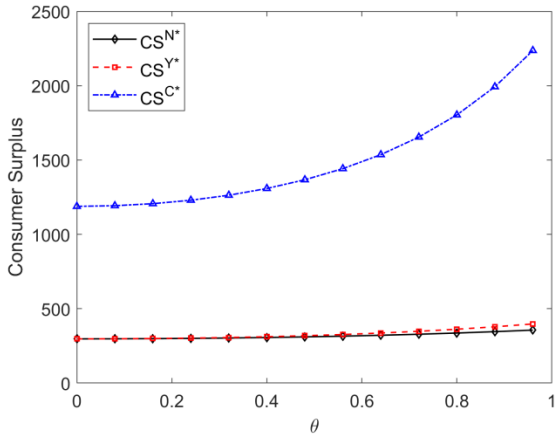


Fig.5. The impact of consumers' green preference levels on Consumer Surplus

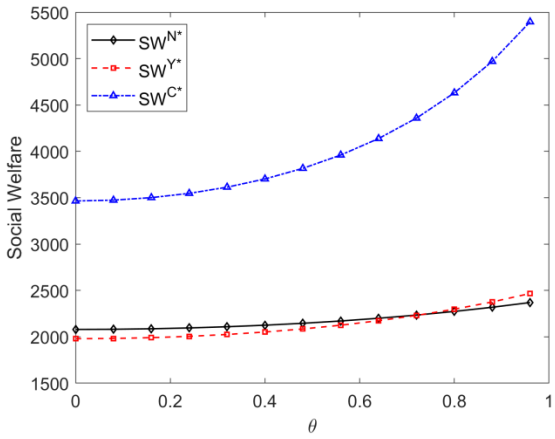
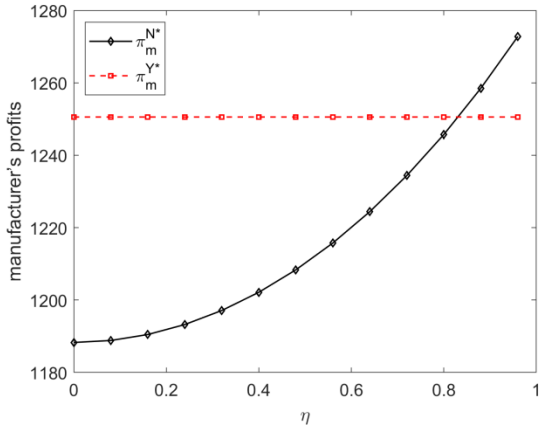
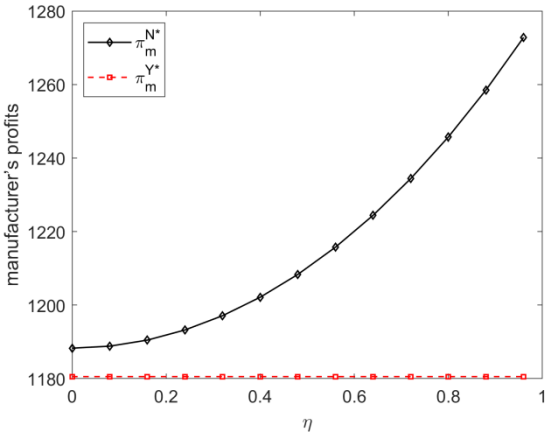


Fig.6. The impact of consumers' green preference levels on Social Welfare

Fig. 3 and Fig. 4 indicate that manufacturer and retailer profits in decentralized decision-making systems grow proportionally with strengthening consumer green preferences. Figs. 5 and 6 reveal Model C's persistent dominance in Consumer Surplus and Social Welfare over Models N and Y, with all metrics exhibiting positive correlations on green preference levels. The intensification of consumer green preferences mirrors rising societal commitments to environmental sustainability. This paradigm shift drives enterprises toward sustainable operations that simultaneously boost profitability and improve Social Welfare. Furthermore, centralized decision-making models demonstrate the superior capacity for achieving optimization of supply chain operations and mitigating double-marginalization effects. These advantages typically result in enhanced Consumer Surplus and Social Welfare levels relative to decentralized models, thus maximizing overall supply chain profits. These findings necessitate proactive responses from governments and supply chain leaders to consumers' evolving green preferences. Through refining policy frameworks, establishing green brand images, and strengthening centralized decision-making with collaborative optimization, they can synergistically advance ecological sustainability while concurrently maximizing systemic profitability and societal welfare.



(a) F =30



(b) F =100

Fig.7. The impact of consumer trust levels on manufacturer's profits, (a) F =30, (b) F =100

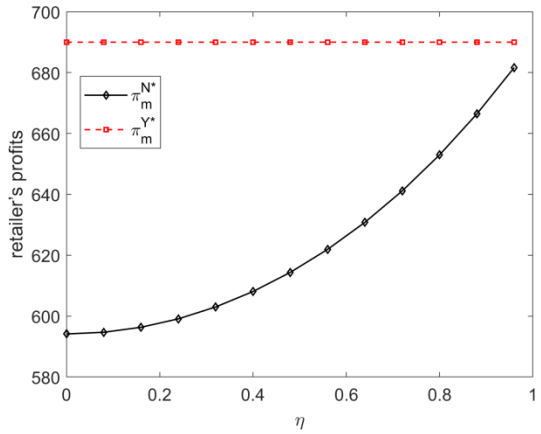


Fig. 8. The impact of consumer trust levels on retailer's profits

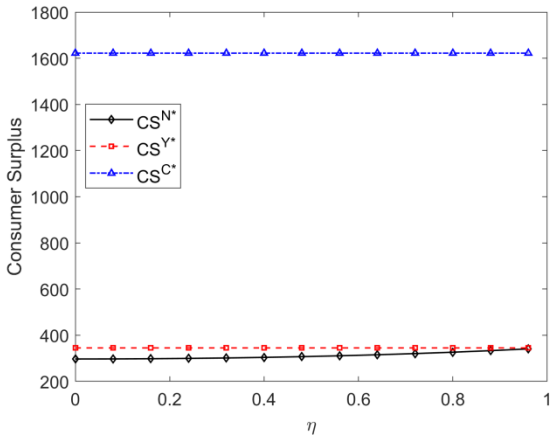


Fig.9. The impact of consumer trust levels on Consumer Surplus.

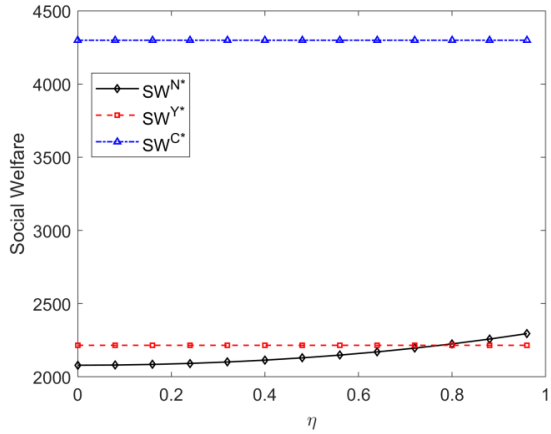


Fig.10. The impact of consumer trust levels on Social Welfare.

As evidenced in Fig. 7 and 8, in Model N, manufacturer and retailer profits show positive correlations with η growth. In Model Y, after blockchain adoption, their profits become independent of this parameter. Specifically, Fig. 7 demonstrates that as blockchain fixed costs increase, manufacturer's post-adoption profits become lower than pre-adoption levels. Consequently, the manufacturer prefers adoption under low consumer trust and blockchain fixed costs, while retailers gain persistent benefits regardless of adoption conditions. These findings align with the theoretical conclusions of Proposition 5. Figs. 9 and 10 demonstrate Model C's consistent superiority in Consumer Surplus and Social Welfare over Models N and Y. Therefore, enterprises should continuously monitor consumer demands and feedback, and promptly adjust and optimize supply chain strategies. Blockchain adoption decisions require holistic evaluation of implementation costs against consumer trust levels. Meanwhile, governments can provide adoption subsidies to lower implementation barriers, incentivize blockchain integration for enhanced transparency, and establish regulatory frameworks to maintain market stability. According to relevant reports, to

accelerate blockchain industry development in Fuzhou, the Fuzhou Municipal Government has implemented three specific measures: offering rent subsidies for enterprises in designated tech parks, providing revenue-based incentives for milestone achievers, and awarding one-time grants to blockchain industry alliances.

5.2. Numerical analysis of supply chain coordination

Substituting the previously set parameter values: $a=100$, $c=2.5$, $\phi=1.7$, $\eta=0.8$ and $\theta=0.7$ into the range of fixed payment $T_1^* \le T^* \le T_2^*$ for the two-part tariff contract, the specific range for the fixed payment can be obtained as: $1748.12 \le T \le 2283.41$. Subsequently, parametric analysis with fixed payment values of 1800, 1900, 2000, 2100, and 2200 are conducted to investigate supply chain coordination under a two-part tariff contract (where the profit values for supply chain members are rounded to two decimal places), we can obtain the numerical results for Table 2.

Table 2
Coordination analysis of a two-part pricing contract

Fixed payment	The two-part tariff contract			Centralised decision-making	Decentralised decision-making		
T	π_m^H	π_r^H	π_s^H	π_s^C	π_m^Y	π_r^Y	π_s^Y
1800	1232.44	1444.30	2676.74	2676.74	1180.56	690.00	1870.56
1900	1332.44	1344.30	2676.74	2676.74	1180.56	690.00	1870.56
2000	1432.44	1244.30	2676.74	2676.74	1180.56	690.00	1870.56
2100	1532.44	1144.30	2676.74	2676.74	1180.56	690.00	1870.56
2200	1632.44	1044.30	2676.74	2676.74	1180.56	690.00	1870.56

Table 2 demonstrates conclusively that under the two-part tariff contract mechanism, the supply chain system's profit equals the profit level under centralized decision-making, i.e., $\pi_m^H + \pi_r^H = \pi_s^C$. Furthermore, both manufacturer and retailer profits exceed their respective levels under decentralized decision-making, i.e., $\pi_m^H > \pi_m^Y$, $\pi_r^H > \pi_r^Y$. Therefore, the two-part tariff contract not only effectively coordinates supply chain operations but also eliminates the "double marginalization effect" caused by decentralized decision-making. This contractual mechanism enables Pareto optimality in both manufacturer and retailer revenues. The numerical experimental results in Table 2 further validate Proposition 7, demonstrating the effectiveness of two-part tariff contracts in green supply chain coordination.

6. Conclusions

This paper has investigated blockchain adoption decisions and coordination mechanisms in the green supply chain. Three analytical models are developed: a non-blockchain adoption model, a blockchain-enabled decentralized decision-making model, and a centralized decision-making model. Key parameters examined include consumer green preference intensity, green trust level, and unit blockchain traceability costs. First, commencing by deriving equilibrium solutions for each model to achieve optimal profits for supply chain members, Consumer Surplus, and Social Welfare. A comparative equilibrium analysis then reveals the manufacturer's optimal blockchain adoption strategies across different scenarios. Second, designing a two-part tariff contract to mitigate the double marginalization effect in decentralized decision-making. This contract is based on the centralized equilibrium and the optimal profit of the supply chain, which enables effective coordination within a decentralized environment. Furthermore, an asymmetric Nash bargaining equilibrium framework is employed to dynamically allocate the surplus benefits arising after coordination. Numerical simulations finally illustrate how parameter changes impact equilibrium solutions, optimal profits, Consumer Surplus, and Social Welfare across all models. The research findings indicate:

(1) Under the decentralized decision-making model, the green supply chain's optimal equilibrium exhibits a positive relationship with consumers' green trust coefficient and green preference, but a negative relationship with the green effort cost coefficient. In the blockchain-enabled decentralized decision-making model, wholesale price shows an inverse relationship with unit traceability cost, whereas manufacturer's profits and Social Welfare are negatively affected by blockchain implementation fixed costs.

(2) In the decentralized decision-making model, blockchain adoption enhances manufacturer's green investments and market demand. Nevertheless, the manufacturer is only motivated to adopt blockchain technology when consumer trust levels and blockchain implementation fixed costs are sufficiently low.

(3) Compared with the decentralized model, the blockchain-enabled centralized decision-making model boosts green efforts, stimulates market demand, increases system profits, and enhances Consumer Surplus and Social Welfare. When consumer green preferences strengthen, centralized decision-making causes higher retail prices; weakened preferences lead to price cuts.

(4) The two-part tariff contract not only effectively eradicates the double marginalization effect inherent in decentralized decision-making supply chains while enabling full coordination. The introduction of an asymmetric Nash bargaining mechanism facilitates the dynamic and flexible allocation of post-coordination surplus benefits. There is a direct proportional relationship between a party's bargaining power and its share of surplus benefits.

Building on these findings, key managerial implications emerge:

(1) When developing strategic approaches, manufacturers should focus on consumer trust and green preferences along with cost control. This improves cost-effectiveness and promotes supply chain efficiency, transparency, and sustainability. When considering blockchain adoption, they must weigh the fixed costs against the potential benefits. Specifically, adopting blockchain is strategically beneficial when consumer trust and its fixed implementation costs are relatively low, as this enhances transparency and trustworthiness.

(2) Retailers should intensify promotional activities during sales periods to heighten consumer awareness of product traceability. They should also adjust retail prices according to supply chain decision-making models and consumer green preferences to attract customers and boost sales. Moreover, improving service quality can strengthen retailers' bargaining power and ensure fair surplus allocation after coordination.

(3) At the supply chain level, the strategic integration of blockchain with coordination mechanisms is crucial for augmenting transparency, efficiency, and operational performance. Supply chain participants should work together to foster consumers' green trust and preferences via educational and marketing initiatives. This not only aids in boosting the demand for green products but is also vital for advancing sustainable supply chain development.

(4) Governments should introduce tax incentives or grants to cut blockchain implementation costs and promote its application through regulatory frameworks for better market governance and orderly competition. Meanwhile, public education campaigns on green consumption can enhance Social Welfare and promote environmental sustainability.

This study primarily focuses on a two-stage supply chain model (single manufacturer-retailer), which can't fully reflect real-world complexities, including multi-echelon structures and coopetition dynamics among multiple stakeholders. Future research should examine more comprehensive supply chain networks with several tiers and participants to enhance the practical relevance of the findings.

Author Contributions Statement

All the authors have contributed to this manuscript. Yuhui Li and Jing Luo provided the idea and wrote the paper. Peiyu Zhao provided the numerical analysis. Lin Tong provided managerial insights.

Competing Interests Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendixes

Appendix A Proof of Theorem 1:

To solve using backward induction, we substitute Eq. (1) into Eq. (3) and take the first-order partial derivative p^N. Setting the first-order partial derivative equal to zero gives us the retailer's reaction function $p^N = \frac{a + w^N + s^N \eta\theta}{2}$. Taking the second-order partial derivative for p^N yields $-2 < 0$ indicates that a maximum value is achieved at this point. The reaction

function is substituted into Eq. (2), and the first-order partial derivatives of w^N and s^N are further obtained respectively. The simultaneous equations are solved to obtain the manufacturer's green effort and wholesale price at this time $w^{N*}=\frac{c\eta^2\theta^2-2(a+c)\phi}{\eta^2\theta^2-4\phi}$, $s^{N*}=\frac{(-a+c)\eta\theta}{\eta^2\theta^2-4\phi}$.

Since the green effort level s^N and the wholesale price w^N are greater than 0 while $a>c$, $4\phi-\eta^2\theta^2>0$ is satisfied.

Based on the Hessian matrix $\begin{pmatrix} -1 & \frac{\eta\theta}{2} \\ \frac{\eta\theta}{2} & -\phi \end{pmatrix}$, we determine that $-1<0$ and $4\phi-\eta^2\theta^2>0$, indicate that a maximum value is achieved at this point. Therefore, the optimal retail price for the retailer is $p^{N*}=\frac{c\eta^2\theta^2-(3a+c)\phi}{\eta^2\theta^2-4\phi}$.

Substituting w^{N*}, s^{N*}, p^{N*} into Eqs. (2)-(3), the maximum profit, system profit, Consumer Surplus and total Social Welfare of retailers and suppliers are obtained as follows:

$$\pi_m^{N*}=-\frac{(a-c)^2\phi}{2\eta^2\theta^2-8\phi} \tag{A.1}$$

$$\pi_{\mathrm{r}}^{N*}=\frac{(a-c)^2\phi^2}{\left(\eta^2\theta^2-4\phi\right)^2} \tag{A.2}$$

$$\pi_s^{N*}=-\frac{\phi(a-c)^2\left(\eta^2\theta^2-6\phi\right)}{2\left(\eta^2\theta^2-4\phi\right)^2} \tag{A.3}$$

$$CS^{N*}=\frac{(a-c)^2\phi^2}{2\left(\eta^2\theta^2-4\phi\right)^2} \tag{A.4}$$

$$SW^{N*}=-\frac{\phi(a-c)^2\left(\eta^2\theta^2-7\phi\right)}{2\left(\eta^2\theta^2-4\phi\right)^2} \tag{A.5}$$

Appendix B Proof of Proposition 1:

According to w^{N*}, s^{N*}, p^{N*}, D^{N*}, π_m^{N*}, π_r^{N*} and SW^{N*} in Theorem 1, the derivatives of η, θ and ϕ can be obtained:

(1) $\frac{\partial w^{N*}}{\partial\eta}=\frac{4(a-c)\eta\theta^2\phi}{\left(\eta^2\theta^2-4\phi\right)^2}>0$, $\frac{\partial s^{N*}}{\partial\eta}=\frac{(a-c)\left(\eta^2\theta^3+4\theta\phi\right)}{\left(\eta^2\theta^2-4\phi\right)^2}>0$, $\frac{\partial p^{N*}}{\partial\eta}=\frac{6(a-c)\eta\theta^2\phi}{\left(\eta^2\theta^2-4\phi\right)^2}>0$,

$\frac{\partial D^{N*}}{\partial\eta}=\frac{2(a-c)\eta\theta^2\phi}{\left(\eta^2\theta^2-4\phi\right)^2}>0$, $\frac{\partial\pi_m^{N*}}{\partial\eta}=\frac{(a-c)^2\eta\theta^2\phi}{\left(\eta^2\theta^2-4\phi\right)^2}>0$, $\frac{\partial\pi_r^{N*}}{\partial\eta}=-\frac{4(a-c)^2\eta\theta^2\phi^2}{\left(\eta^2\theta^2-4\phi\right)^3}>0$,

$\frac{\partial SW^{N*}}{\partial\eta}=\frac{(a-c)^2\eta\theta^2\left(\eta^2\theta^2-10\phi\right)\phi}{\left(\eta^2\theta^2-4\phi\right)^3}>0$;

(2) $\frac{\partial w^{N*}}{\partial\theta}=\frac{4(a-c)\eta^2\theta\phi}{\left(\eta^2\theta^2-4\phi\right)^2}>0$, $\frac{\partial s^{N*}}{\partial\theta}=\frac{(a-c)\left(\eta^3\theta^2+4\eta\phi\right)}{\left(\eta^2\theta^2-4\phi\right)^2}>0$, $\frac{\partial p^{N*}}{\partial\theta}=\frac{6(a-c)\eta^2\theta\phi}{\left(\eta^2\theta^2-4\phi\right)^2}>0$,

$\frac{\partial D^{N*}}{\partial\theta}=\frac{2(a-c)\eta^2\theta\phi}{\left(\eta^2\theta^2-4\phi\right)^2}>0$, $\frac{\partial\pi_m^{N*}}{\partial\theta}=\frac{(a-c)^2\eta^2\theta\phi}{\left(\eta^2\theta^2-4\phi\right)^2}>0$, $\frac{\partial\pi_r^{N*}}{\partial\theta}=-\frac{4(a-c)^2\eta^2\theta\phi^2}{\left(\eta^2\theta^2-4\phi\right)^3}>0$,

$\frac{\partial SW^{N*}}{\partial\theta}=\frac{(a-c)^2\eta^2\theta\left(\eta^2\theta^2-10\phi\right)\phi}{\left(\eta^2\theta^2-4\phi\right)^3}>0$;

(3) $\frac{\partial s^{N*}}{\partial \phi}=\frac{4(-a+c)\eta\theta}{\left(\eta^2\theta^2-4\phi\right)^2}<0$, $\frac{\partial p^{N*}}{\partial \phi}=\frac{3(-a+c)\eta^2\theta^2}{\left(\eta^2\theta^2-4\phi\right)^2}<0$, $\frac{\partial D^{N*}}{\partial \phi}=\frac{(-a+c)\eta^2\theta^2}{\left(\eta^2\theta^2-4\phi\right)^2}<0$,

$\frac{\partial \pi_m^{N*}}{\partial \phi}=-\frac{(a-c)^2\eta^2\theta^2}{2\left(\eta^2\theta^2-4\phi\right)^2}<0$, $\frac{\partial \pi_r^{N*}}{\partial \phi}=\frac{2(a-c)^2\eta^2\theta^2\phi}{\left(\eta^2\theta^2-4\phi\right)^3}<0$,

$\frac{\partial SW^{N*}}{\partial \phi}=-\frac{(a-c)^2\eta^2\theta^2\left(\eta^2\theta^2-10\phi\right)}{2\left(\eta^2\theta^2-4\phi\right)^3}<0$.

Appendix C Proof of Theorem 2:

The specific proof method is the same as Theorem 1, which is omitted here.

Appendix D Proof of Proposition 2:

According to w^{Y*}, s^{Y*}, p^{Y*}, D^{Y*}, π_m^{Y*}, π_r^{Y*} and SW^{Y*} in Theorem 2, the derivatives of f and F can be obtained:

(1) $\frac{\partial w^{Y*}}{\partial f}=-1<0$, $\frac{\partial s^{Y*}}{\partial f}=\frac{\partial p^{Y*}}{\partial f}=\frac{\partial D^{Y*}}{\partial f}=\frac{\partial \pi_m^{Y*}}{\partial f}=\frac{\partial \pi_r^{Y*}}{\partial f}=\frac{\partial SW^{Y*}}{\partial f}=0$;

(2) $\frac{\partial \pi_m^{Y*}}{\partial F}=\frac{\partial SW^{Y*}}{\partial F}=-1<0$.

Appendix E Proof of Proposition 3:

According to w^{Y*}, s^{Y*}, p^{Y*}, D^{Y*}, π_m^{Y*}, π_r^{Y*} and SW^{Y*} in Theorem 2, the derivatives of θ and ϕ can be obtained:

(1) $\frac{\partial w^{Y*}}{\partial \theta}=\frac{4(a-c)\theta\phi}{\left(\theta^2-4\phi\right)^2}>0$, $\frac{\partial s^{Y*}}{\partial \theta}=\frac{(a-c)\left(\theta^2+4\phi\right)}{\left(\theta^2-4\phi\right)^2}>0$, $\frac{\partial p^{Y*}}{\partial \theta}=\frac{6(a-c)\theta\phi}{\left(\theta^2-4\phi\right)^2}>0$,

$\frac{\partial D^{Y*}}{\partial \theta}=\frac{2(a-c)\theta\phi}{\left(\theta^2-4\phi\right)^2}>0$, $\frac{\partial \pi_m^{Y*}}{\partial \theta}=\frac{(a-c)^2\theta\phi}{\left(\theta^2-4\phi\right)^2}>0$, $\frac{\partial \pi_r^{Y^*}}{\partial \theta}=-\frac{4(a-c)^2\theta\phi^2}{\left(\theta^2-4\phi\right)^3}>0$,

$\frac{\partial SW^{Y*}}{\partial \theta}=\frac{(a-c)^2\theta\left(\theta^2-10\phi\right)\phi}{\left(\theta^2-4\phi\right)^3}>0$;

(2) $\frac{\partial w^{Y*}}{\partial \phi}=\frac{2(-a+c)\theta^2}{\left(\theta^2-4\phi\right)^2}<0$, $\frac{\partial s^{Y*}}{\partial \phi}=\frac{4(-a+c)\theta}{\left(\theta^2-4\phi\right)^2}<0$, $\frac{\partial p^{Y*}}{\partial \phi}=\frac{3(-a+c)\theta^2}{\left(\theta^2-4\phi\right)^2}<0$,

$\frac{\partial D^{Y*}}{\partial \phi}=\frac{(-a+c)\theta^2}{\left(\theta^2-4\phi\right)^2}<0$, $\frac{\partial \pi_m^{Y*}}{\partial \phi}=-\frac{(a-c)^2\theta^2}{2\left(\theta^2-4\phi\right)^2}<0$, $\frac{\partial \pi_r^{Y*}}{\partial \phi}=\frac{2(a-c)^2\theta^2\phi}{\left(\theta^2-4\phi\right)^3}<0$,

$\frac{\partial SW^{Y*}}{\partial \phi}=-\frac{(a-c)^2\theta^2\left(\theta^2-10\phi\right)}{2\left(\theta^2-4\phi\right)^3}<0$.

Appendix F Proof of Proposition 4:

According to the wholesale price, green effort, retail price and market demand in Theorem 1 and Theorem 2, the comparison can be obtained:

$w^{Y*}-w^{N*}=\frac{2(a-c)\left(1-\eta^2\right)\theta^2\phi}{\left(\theta^2-4\phi\right)\left(\eta^2\theta^2-4\phi\right)}-f$, let $w^{Y*}-w^{N*}>0$, then we can get

$f<\frac{2\left(1-\eta^2\right)\theta^2\phi(a-c)}{\left(\theta^2-4\phi\right)\left(\eta^2\theta^2-4\phi\right)}$;

$$s^{Y*}-s^{N*}=(-a+c)\theta\left(\frac{1}{\theta^2-4\phi}+\frac{\eta}{-\eta^2\theta^2+4\phi}\right)>0;$$

$$p^{Y*}-p^{N*}=-\frac{3(a-c)\left(-1+\eta^2\right)\theta^2\phi}{\left(\theta^2-4\phi\right)\left(\eta^2\theta^2-4\phi\right)}>0;$$

$$D^{Y*}-D^{N*}=(-a+c)\phi\left(\frac{1}{\theta^2-4\phi}+\frac{1}{-\eta^2\theta^2+4\phi}\right)>0.$$

Appendix G Proof of Proposition 5:

$\pi_r^{Y*}-\pi_r^{N*}=(a-c)^2\left(\frac{1}{\left(\theta^2-4\phi\right)^2}-\frac{1}{\left(\eta^2\theta^2-4\phi\right)^2}\right)\phi^2>0$ permanent establishment;

$\pi_m^{Y*}-\pi_m^{N*}=-F-\frac{(a-c)^2\left(-1+\eta^2\right)\theta^2\phi}{2\left(\theta^2-4\phi\right)\left(\eta^2\theta^2-4\phi\right)}$, let $\pi_m^{Y*}-\pi_m^{N*}>0$, then we can get $F<\frac{(a-c)^2\theta^2}{8\left(4\phi-\theta^2\right)}$ and

$\eta<\sqrt{\frac{\phi\left\{\theta^2\left[(a-c)^2+8F\right]-32F\phi\right\}}{\theta^2\left[\phi(a-c)^2+2F\left(\theta^2-4\phi\right)\right]}}$;

$SW^{Y*}-SW^{N*}=\frac{1}{2}\left(-2F-\frac{(a-c)^2\left(\theta^2-7\phi\right)\phi}{\left(\theta^2-4\phi\right)^2}+\frac{(a-c)^2\left(\eta^2\theta^2-7\phi\right)\phi}{\left(\eta^2\theta^2-4\phi\right)^2}\right)$, let

$SW^{Y*}-SW^{N*}>0$, then we can get $F<\frac{\left(1-\eta^2\right)\theta^2\phi(a-c)^2\left[\eta^2\theta^4-7\left(\eta^2+1\right)\theta^2\phi+40\phi^2\right]}{2\left(\theta^2-4\phi\right)^2\left(\eta^2\theta^2-4\phi\right)^2}$.

Appendix H Proof of Proposition 6:

$s^{C*}-s^{Y*}=\frac{2(a-c)\theta\phi}{\theta^4-6\theta^2\phi+8\phi^2}>0$,

$D^{C*}-D^{Y*}=\frac{2(a-c)\phi^2}{\theta^4-6\theta^2\phi+8\phi^2}>0$

$p^{C*}-p^{Y*}=\frac{2(a-c)\left(\theta^2-\phi\right)\phi}{\theta^4-6\theta^2\phi+8\phi^2}$, let $p^{C*}-p^{Y*}>0$, then we can get $\theta>\sqrt{\phi}$,

$\pi_s^{C*}-\pi_s^{Y*}=-\frac{2(a-c)^2\phi^3}{\left(\theta^2-4\phi\right)^2\left(\theta^2-2\phi\right)}>0$

$SW^{C*}-SW^{Y*}=-\frac{2(a-c)^2\left(2\theta^2-5\phi\right)\phi^3}{\left(\theta^4-6\theta^2\phi+8\phi^2\right)^2}>0$

Appendix I Proof of Proposition 7:

To coordinate the decentralized supply chain system, it is necessary to meet the following conditions: $s^{H*}=s^{C*}, p^{H*}=p^{C*}$. Therefore, the optimal wholesale price in the two-part tariff contract can be obtained as $w^{H*}=c-f$;

Substituting p^{H*}, w^{H*}, s^{H*} into Eqs (33)-(34), the profits of the manufacturer and the retailer in the contract can be obtained as follows: $\pi_m^{H*}=-F+T-\frac{(a-c)^2\theta^2\phi}{2\left(\theta^2-2\phi\right)^2}$, $\pi_r^{H*}=\frac{-T\left(\theta^2-2\phi\right)^2+(a-c)^2\phi^2}{\left(\theta^2-2\phi\right)^2}$. To ensure the implementation of the contract, it is necessary to ensure that the profits of the manufacturer and the retailer under the coordination situation are not lower than those under the decentralized decision-making situation, that is, $\pi_m^{H*}\geq\pi_m^{Y*}$, $\pi_r^{H*}\geq\pi_r^{Y*}$, and the conditions for a simultaneous solution are obtained:

$$\frac{2\phi^3(a-c)^2}{\left(4\phi-\theta^2\right)\left(\theta^2-2\phi\right)^2}<T<\frac{4(a-c)^2\left(3\phi-\theta^2\right)\phi^3}{\left(\theta^4-6\theta^2\phi+8\phi^2\right)^2}.$$

Appendix J Proof of Proposition 8:

The logarithm of Eq. (35) can be obtained by:

$$\ln \max_{T_1^* \le T^* \le T_2^*} \pi^{\varepsilon}(T^*) = \lambda \ln \left[T + \frac{2(a-c)^2 \phi^3}{\left(\theta^2 - 4\phi\right)\left(\theta^2 - 2\phi\right)^2} \right] + (1-\lambda) \ln \left[-T - \frac{4(a-c)^2 \left(\theta^2 - 3\phi\right)\phi^3}{\left(\theta^4 - 6\theta^2\phi + 8\phi^2\right)^2} \right]$$

The Nash bargaining solution can be obtained from the first-order condition: $T^* = -\frac{2\phi^3 (a-c)^2 \left[\theta^2(\lambda+1) - 2(\lambda+2)\phi\right]}{\left(\theta^4 - 6\theta^2\phi + 8\phi^2\right)^2}$.

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