Digital Value Traceability of Gardenia jasminoides: An Inclusive Digital Pathway for Smallholder Three-industry Integration Under UN Sustainable Rural Revitalization Initiatives

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Abstract

Under the global agenda of the Sustainable Development Goals, sustainable agriculture, and inclusive digital transformation for smallholders, specialty horticultural and medicinal crop industries still face multiple prominent constraints. These include fragmented cultivation, information asymmetry across value chains, high digital adoption costs, and weak coordination among primary, secondary, and tertiary sectors. Taking the Gardenia jasminoides industry in mountainous southern Zhejiang, China, as a representative case, this study aims to construct and evaluate a lightweight digital value-traceability model for smallholder-based rural industries. The study adopts a mixed-methods design, combining questionnaire surveys, semi-structured interviews, field investigation, quasi-natural experimental comparison, and prototype system development. Based on agricultural value-chain theory, information asymmetry theory, and inclusive digital agriculture theory, this study proposes a conceptual framework. The framework integrates Internet of Things (IoT) sensing and consortium blockchain to establish a value-mapping mechanism linking primary production data, secondary product quality grading, and tertiary agritourism value creation. Empirical pilot results show that the traceability model reduced product-information distortion to 0.3%, improved industrial regulatory efficiency by 40.0%, and increased standardized harvesting from 40.0% to 80.0%. It also lowered digital investment pressure for small and micro operators and expanded diversified operating income opportunities for farmers through branding, cloud adoption, harvesting reservation, and agritourism services. The study concludes that digital traceability should be understood not only as a technical tool for information verification, but also as an institutional mechanism for value conversion and three-industry integration. Theoretically, this research extends agricultural value-chain and inclusive digital agriculture studies. In practice, it provides a replicable lightweight digitalization model for specialty smallholder industries in global mountainous and rural regions, echoing the agenda of the Food and Agriculture Organization of the United Nations (FAO) for sustainable smallholder development.

Keywords

Sustainable rural revitalization, Inclusive digital agriculture, Consortium blockchain, Digital value traceability, Three-industry integration

Introduction

This study resolves conflicts between global digital agriculture goals and smallholder barriers by building a lightweight inclusive digital value-traceability framework for mountain medicinal crop industries [1]. Using China's southern Zhejiang Gardenia jasminoides cluster as a case, it combines Internet of Things (IoT) and consortium blockchain to develop the Zhizi Chain Model (Z-CM) cross-chain mechanism that converts trusted production data into cross-sector industrial value across farming, processing and agritourism [2]. Mixed empirical data validate its income-boosting effects for smallholders. The research redefines traceability as a value-conversion institution, providing a replicable low-cost digital solution aligned with Food and

Agriculture Organization of the United Nations (FAO) and Sustainable Development Goals (SDGs) sustainable rural agendas.

Global sustainable agriculture and digital inclusion context

The transformation of agriculture under the United Nations 2030 Sustainable Development Goals has increasingly emphasized not only productivity growth and food-safety assurance, but also inclusive digital participation, resilient value chains, and sustainable rural livelihoods. Digital technologies are now widely regarded as key instruments for improving agricultural transparency, connecting smallholders to markets, reducing information asymmetry, and strengthening rural service systems [3,4]. The FAO emphasizes that digital technologies such as mobile applications, remote sensing, blockchain, data platforms, and digital advisory services can generate new opportunities for rural development.

However, their benefits depend heavily on affordability, connectivity, digital literacy, and effective institutional inclusion [5,6]. The briefing paper "Digital Technologies in Agriculture and Rural Areas" notes that these technologies present opportunities to make agriculture more attractive to youth and achieve higher productivity. Nevertheless, they also raise concerns about growing inequalities, new forms of exclusion, and unclear accountability for adverse impacts. Similarly, the World Bank's extensive work on information and communication technology (ICT) in agriculture emphasizes that digital systems can connect smallholders to knowledge, networks, markets, and institutions. It also warns that unequal access may widen rural digital divides if technologies are designed primarily for large-scale or commercially advanced producers.

This global challenge is especially visible in mountainous smallholder economies in developing contexts. Specialty horticultural, medicinal, and edible crops are often cultivated by dispersed households, processed by small or micro-enterprises, and marketed through fragmented channels. These industries usually contain high ecological, cultural, and experiential value, yet their economic potential is constrained by weak standardization, incomplete data records, unstable market signals, and limited coordination between production, processing, marketing, and rural services. Although traceability systems have been introduced in many agri-food sectors, most existing models are designed for standardized farms, formal enterprises, or high-value supply chains with stronger capital and technical capacity [7,8]. For smallholder-based specialty crops, the key issue is no longer whether data can be recorded, but whether trusted data can be converted into quality certification, brand credibility, consumer trust, and service-based rural value. Therefore, inclusive digital agriculture requires lightweight traceability models that are affordable, operable, and adaptable to weak-network mountainous environments. It also requires a shift from simple information traceability toward digital value traceability, in which agricultural data become a mechanism for value distribution, industrial coordination, and sustainable rural revitalization [9,10].

Industrial economic dilemmas of mountainous smallholder gardenia jasminoides

The Gardenia jasminoides industry in mountainous southern Zhejiang provides a typical case for examining the economic dilemmas of smallholder specialty crop value chains. Gardenia jasminoides is a multifunctional crop with edible, medicinal, essential-oil, cosmetic, landscape, and agritourism value. However, its industrial organization remains strongly shaped by dispersed smallholder production, seasonal flowering, perishability, processing complexity, and limited digital infrastructure. Field investigation in Shuiwei Village and surrounding production areas shows five interrelated constraints that are also common in many mountainous smallholder industries.

First, fragmented cultivation weakens standardization. More than 85% of local production actors lack standardized operating procedures and quantitative management tools [11]. Key production decisions, including soil moisture control, fertilizer and water use, pest management, and harvesting timing, still depend heavily on personal experience. As a result, raw-material quality is unstable, batch consistency is weak, and pesticide-residue risks are difficult to control.

Second, processing information remains opaque. Processing involves raw-material acceptance, drying and sterilization parameters, additive use, quality testing, storage, and product verification, but many small processors still rely on manual or paper-based records. This creates an information “black box” and weakens the credibility required for edible and medicinal products.

Third, production and marketing coordination is inefficient. Because the flowering period is concentrated and products are perishable, delayed market signals, price volatility, inventory uncertainty, and reliance on intermediaries frequently produce supply-demand mismatches, low-price competition, and income instability.

Fourth, digital adoption barriers are high. Mainstream blockchain traceability systems often require high deployment and maintenance costs, complex operation, and professional technical support, exceeding the affordability and digital capacity of smallholders and micro-enterprises [12].

Fifth, the primary, secondary, and tertiary sectors remain disconnected. Cultivation data does not effectively guide processing and consumption; processing data do not support brand and tourism services; and agritourism experiences lack trusted digital content.

From the perspectives of information asymmetry theory and transaction cost economics, these problems increase verification costs, reduce bargaining power, weaken consumer trust, and prevent smallholders from capturing value added through processing, branding, and rural services [13,14]. The absence of reliable information flows creates market failures that disproportionately harm smallholder producers in remote mountainous regions.

Literature review and identified research gaps

Existing international research provides important foundations for this study, but it also reveals several limitations. The first research stream concerns blockchain traceability in agricultural value chains. Blockchain has been widely discussed as a mechanism for improving transparency, data immutability, food-safety verification, and supply-chain trust [15-17]. Kamilaris et al. demonstrated that blockchain applications in agriculture and food supply chains can strengthen traceability and reduce fraud through decentralized ledger systems and smart contracts [18]. Bosona and Gebresenbet have extensively examined food traceability systems and their role in enhancing transparency, information sharing, and trust in agri-food production and supply chains, though their early work preceded blockchain’s widespread application [19]. More recent studies have explored blockchain’s potential in agricultural contexts.

However, much of this literature remains focused on anti-counterfeiting, information storage, and food-safety verification. Less attention has been paid to how blockchain-based trusted data can be transformed into quality grading, price premiums, brand credibility, agritourism rights, or farmer income. Moreover, blockchain does not automatically solve the “first-mile” authenticity problem: If field data are manually entered, incomplete, or poorly governed, on-chain records may still reproduce inaccurate off-chain information.

The second research stream examines digital technology and rural industrial convergence. IoT sensing, Radio-Frequency Identification (RFID) identification, big-data analytics, visual dashboards, and quick response (QR)-code verification have been applied to field-level environmental monitoring, processing control, logistics tracking, and consumer-side product verification [20-22]. These technologies make it possible to connect cultivation, processing, circulation, consumption, and rural services through a shared data infrastructure. Yet existing studies often remain single-link oriented, focusing separately on production monitoring, processing supervision, or consumer traceability. There is still limited empirical evidence on how blockchain can serve as a unified data link across primary production, secondary processing, and tertiary agritourism services.

The third research stream concerns inclusive digital solutions for small-scale producers. FAO and the World Bank both emphasize that digital agriculture must address affordability, rural connectivity, user capability, and institutional inclusion [23-25]. Nevertheless, many existing traceability platforms are still designed for large farms or formal enterprises, requiring dense sensor deployment, stable networks, high maintenance capacity, and relatively high digital literacy. Few studies provide lightweight architectures for dispersed mountainous smallholders, aging farming populations, weak-network environments, and micro-processing actors. Therefore, the main research gap lies in the lack of an integrated, low-cost, smallholder-oriented value-traceability model that links technical trust, industrial coordination, and value conversion.

Core research questions and research objectives

In response to these gaps, this study develops a lightweight digital value-traceability framework for the Gardenia jasminoides value chain in mountainous southern Zhejiang. It addresses four research questions.

Research question 1: How can IoT sensing, edge preprocessing, consortium blockchain, and big-data governance be integrated into a trustworthy lifecycle traceability system for smallholder-based Gardenia jasminoides production?

Research question 2: How can such a system reduce adoption costs, operational complexity, and maintenance burdens for smallholders, cooperatives, and micro-processing enterprises?

Research question 3: How can primary production data be mapped into secondary quality grading and further converted into brand credibility, cloud-adoption rights, consumer trust, and agritourism value?

Research question 4: What pilot-stage effects can be observed through comparison between digital-traceability units and traditional production units in terms of data authenticity, quality stability, regulatory efficiency, price-premium recognition, and farmer income?

The theoretical objective of this research is to extend agricultural value-chain theory, information asymmetry theory, transaction cost economics, and inclusive digital agriculture frameworks by conceptualizing traceability as a mechanism of value conversion rather than merely information verification. Traditional traceability research has focused primarily on food safety compliance and supply chain transparency. This study reframes traceability as an institutional mechanism that enables smallholders to capture value premiums, access new markets, and participate in integrated rural development strategies.

The practical objective is to provide a replicable lightweight digital pathway for mountainous smallholder specialty-crop industries, especially those combining edible, medicinal, processing, branding, and agritourism functions. By linking standardized cultivation, transparent processing, trusted circulation, brand consumption, and rural experience services, this study seeks to demonstrate how digital value traceability can support sustainable rural revitalization. The proposed framework addresses critical gaps in existing digital agriculture implementations by prioritizing affordability, ease of operation, and adaptability to resource-constrained environments. This approach aligns with the FAO’s emphasis on ensuring that digital transformation benefits all farmers, particularly those in marginalized and remote regions.

Furthermore, this research contributes to the broader discourse on inclusive development. It demonstrates how appropriate technology design can overcome digital divides and enable smallholders to participate meaningfully in modern value chains without requiring extensive capital investment or advanced technical expertise.

Theoretical framework

Four core theoretical foundations

The analytical foundation of this study begins with value chain theory. First, value chain theory conceptualizes production not as one indivisible activity but as a sequence of value-creating stages, each absorbing cost and generating margin. Accordingly, competitive advantage derives from how firms configure and coordinate these interdependent activities, not from any single operation. Extending this logic to the sectoral and global scale, work on value-chain governance and upgrading shows that value is distributed unevenly. Actors in low-complexity, easily codified, and readily substitutable segments capture the smallest share, whereas those controlling design, certification, branding, and market access capture the largest. Second, applied to smallholder-based agriculture, the framework predicts that producers confined to primary cultivation remain locked into thin, volatile margins, because value added through processing, certification, branding, and downstream services accrue elsewhere [26]. Functional upgrading - repositioning smallholders to participate in, and retaining returns from, higher-value processing and service segments - therefore becomes the central economic problem. It requires mechanisms that transmit verifiable production information downstream so upstream quality can be recognized and rewarded.

The second foundation is information asymmetry theory, which explains why such value transmission frequently fails. First, when sellers hold quality information buyers cannot observe, markets tend toward adverse selection: unable to distinguish high- from low-quality goods, buyers discount all offerings toward an average, driving higher-quality producers out and depressing the market [27]. This is acute for credence attributes - cultivation conditions, chemical-residue levels, or processing hygiene - that cannot be verified by inspection at sale. Second, the economics of information identifies signaling and screening as the principal remedies: Credible, costly-to-imitate signals let high-quality sellers differentiate themselves, while institutionalized certification and disclosure reduce residual uncertainty that impedes exchange. Where such mechanisms are absent, verification proceeds through repeated bilateral bargaining, which, under bounded rationality and possible opportunistic misrepresentation, raises transaction costs and weakens producers' bargaining power. For dispersed smallholders lacking any credible, low-cost means of substantiating quality claims, this failure translates directly into forgone price premiums and eroded trust.

The third foundation is industrial convergence theory, which addresses how previously separate sectors become integrated. First, the concept originates in the observation that a shared substrate of common techniques, inputs, and knowledge blurs boundaries between distinct industries, so that capabilities from one activity diffuse into and reorganize others. Contemporary readings extend this from technology to function, showing that agriculture is increasingly multifunctional: Beyond raw commodities, farming systems simultaneously generate processing inputs, environmental amenities, cultural meaning, and experiential services. These can be organized as an integrated rather than fragmented whole. Second, applied to the rural economy, convergence implies that primary, secondary, and tertiary sectors need not operate as disconnected silos. A common information infrastructure can serve as connective tissue, letting cultivation data, processing records, and service offerings reference one another so that value in one sector reinforces the others [28]. This provides the rationale for treating three-industry integration not as an administrative aspiration but as an economically grounded process of data-enabled sectoral convergence.

The fourth foundation is inclusive digital agriculture theory, which specifies the conditions under which such integration benefits, rather than bypasses, marginalized producers. First, inclusive development deliberately incorporates marginalized people, sectors, and places into economic activity, prioritizing empowerment and broadly shared well-being over aggregate growth alone. Applied to digitalization, this holds that the value of digital technologies depends on affordability, connectivity, digital literacy, and institutional inclusion; where systems are designed for large, capital-intensive producers, unequal access can widen rather than narrow rural digital divides. Second, for dispersed, ageing, and resource-constrained smallholders, digital value-transmission tools must be deliberately lightweight, low-cost, and operable in weak-network environments if they are to serve as instruments of inclusion rather than exclusion [29].

Taken together, the four theories frame this study. Value chain theory locates where value concentrates. Information asymmetry theory explains why smallholders forfeit it. Industrial convergence theory shows how shared data infrastructure can reconnect the three sectors, and inclusive digital agriculture theory sets the accessibility conditions. The mountainous Gardenia jasminoides industry of southern Zhejiang - with its dispersed medicinal-and-edible smallholders, opaque processing, and fragmented sectors - exhibits precisely the configuration these theories jointly anticipate. It thus provides an appropriate empirical setting for the value-traceability model developed below.

Construction of the three-industry linkage value traceability conceptual model

Nevertheless, standalone theoretical reasoning cannot directly resolve practical value-distribution dilemmas within local crop systems. A structured conceptual framework is therefore required to translate abstract theoretical propositions into operable analytical logic adapted to gardenia industrial practices. Building on the four theoretical foundations, this section constructs an interdisciplinary conceptual model that couples appropriate agricultural digital technology with the economic logic of industrial value conduction. Consistent with the study's economic orientation, the model retains only those technical-framework connotations that bear directly on value transformation and deliberately abstracts away from low-level code and hardware detail, concentrating instead on how trusted data are converted into economic value. In this respect the architecture mirrors the theoretical logic set out above. The perception layer supplies the verifiable information whose absence, under information asymmetry, depresses smallholder returns. The mapping layer performs the signaling function that revalues that information along the value chain. The output layer realizes the sectoral convergence through which integrated value is captured and shared. The model comprises three progressive and closed-loop functional layers that combine lightweight IoT perception with consortium blockchain to support the three-industry value linkage of the Gardenia jasminoides industry [30].

The first layer is a multi-source data input layer based on lightweight IoT perception. Unlike conventional single-dimensional agricultural data collection, this layer employs low-power sensing and edge-based acquisition adapted to the dispersed, small-plot planting conditions of mountainous terrain. It captures standardized field data spanning the growth environment, field management, and picking and harvesting of the crops, thereby accumulating full-cycle, real-time, and credible primary-production records. Economically, this layer addresses the first-mile authenticity problem emphasized in the traceability literature: Because subsequent value conversion can be no more trustworthy than its underlying inputs, disciplined and low-cost data capture at the production stage is the precondition for any downstream premium.

The second layer is the Z-CM cross-chain value-mapping mechanism driven by consortium blockchain. Drawing on the tamper-resistance, traceability, and distributed-storage properties of consortium blockchain, the study designs a customized cross-chain mapping mechanism, termed Z-CM, for the gardenia specialty industry. The mechanism dismantles the data barriers separating cultivation, processing, and rural tourism, and performs a hierarchical conversion of credible agricultural data. Original planting-environment and management data are automatically matched against product-quality grading standards, and the resulting standardized quality data are, in turn, mapped onto brand-credit value and rural cultural-tourism service rights. In economic terms, this layer operationalizes the signaling and screening remedies to information asymmetry. It binds verifiable production data to quality grades and then to brand and service entitlements. This process converts otherwise unobservable credence attributes into recognizable, tradable value signals, allowing upstream quality to be priced downstream.

The third layer is the three-industry value output closed-loop system. Supported by the preceding technical framework and mapping mechanism, the model yields multidimensional economic output. In the primary sector, standardized data supervision stabilizes cultivation quality and reduces production risk. In the secondary sector, credible on-chain data resolve processing opacity and enables a product brand premium. In the tertiary sector, traceable industrial data empowers agritourism and cloud-adoption projects, expanding diversified income channels for farmers. Crucially, market-feedback data flow back to optimize front-end planting and processing decisions, closing the loop and sustaining an ongoing cycle of industrial value creation. This closed loop embodies the convergence logic articulated above, in that shared data infrastructure allows value generated in each sector to reinforce the others rather than dissipate across disconnected silos.

Read as a whole, the model reframes traceability from a device for recording information into a mechanism for converting information into value. The input layer secures authentic primary data. The Z-CM layer transmits and revalues that data across sectoral boundaries. And the output layer redistributes the resulting premiums to smallholders while feeding market signals forward. In doing so it advances beyond conventional traceability, which authenticates information but stops short of converting it, toward a value-traceability logic in which authenticated data are actively revalued and redistributed. By foregrounding this economic conduction logic - and by relying on lightweight perception and permissioned rather than public infrastructure - the model remains consistent with the inclusive-digital-development condition that such systems be affordable and operable for resource-constrained producers. It satisfies the core requirements for inclusive digital development. It thereby links technical trust, industrial coordination, and value conversion within a single conceptual architecture (as shown in Figure 1).

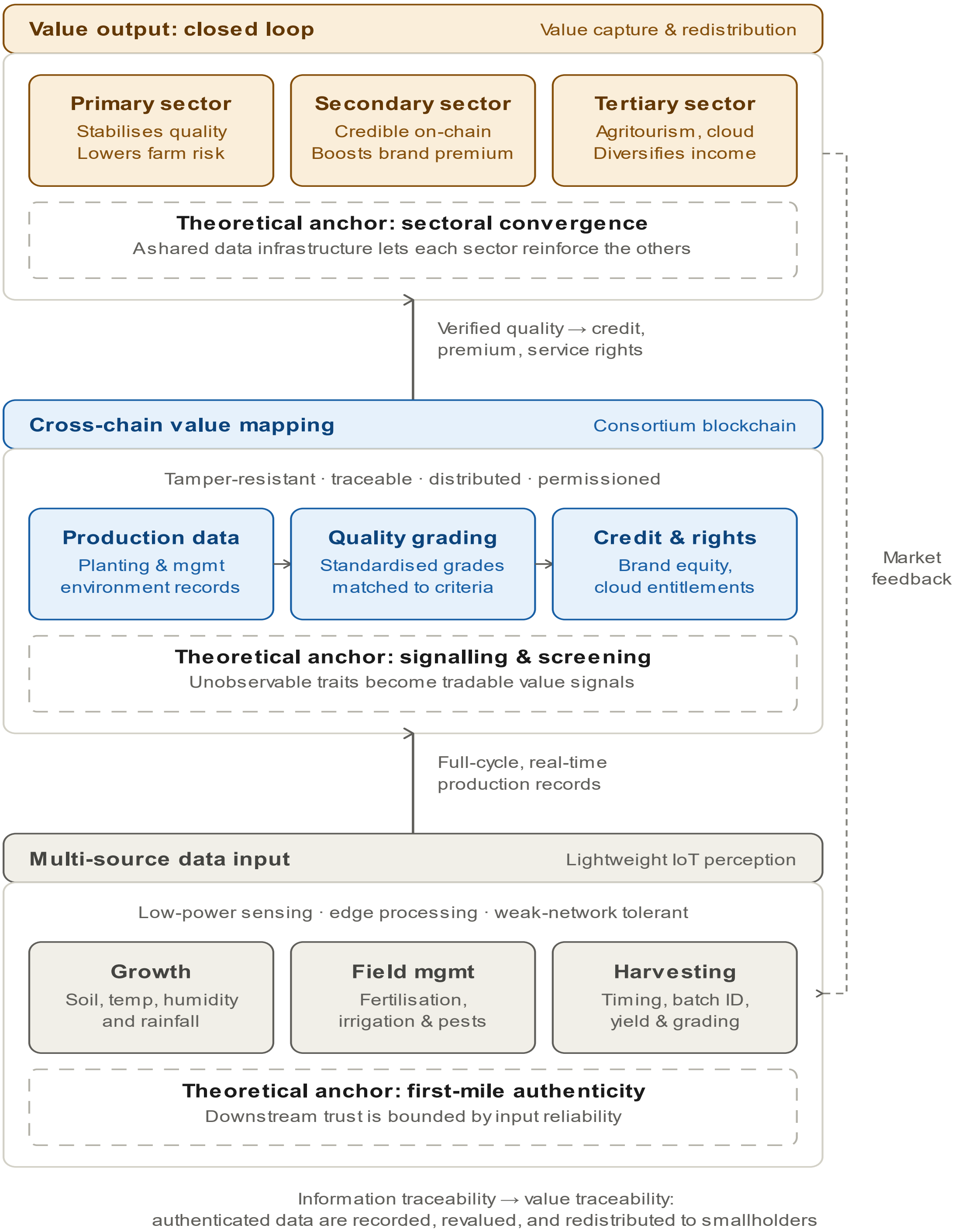

Figure 1. Conceptual architecture of the three-industry linkage value-traceability model for Gardenia jasminoides.

Methodology

Typicality of the mountainous smallholder research site

The empirical setting for this study is Shuiwei Village, a core gardenia-producing settlement in the mountainous uplands of Pengxi Town, southern Zhejiang, China.

The village lies within one of the region's principal Gardenia jasminoides production belts, where cultivation has expanded rapidly in recent years from a supplementary sideline into a locally significant specialty industry that now anchors household livelihoods. Its productive structure is dominated by dispersed smallholders. In line with the surrounding production area, more than eighty-five per cent of production actors operate at a small, household scale, cultivating fragmented plots without standardized operating procedures or quantitative management tools.

They rely heavily on individual experience for decisions on soil moisture, fertilization, pest and disease control, and harvesting timing. The farming population is, moreover, predominantly middle-aged and elderly, with limited digital skills - a demographic feature that directly shapes the feasibility of any digital intervention. Because the crop is medicinal-and-edible and multifunctional, it carries edible, medicinal, essential-oil, cosmetic, landscape, and agritourism value. A single village-level industry simultaneously spans primary cultivation, secondary processing, and tertiary rural services. This makes it an unusually complete unit for the study of three-industry integration.

This configuration makes Shuiwei Village an internationally representative rather than an idiosyncratic case. Smallholder farming remains the dominant form of agricultural organization worldwide - of the more than 570 million farms globally, the overwhelming majority are small and family-operated - so the economic difficulties of dispersed, small-scale producers are a general rather than a local concern [31]. The particular combination observed here - fragmented upland cultivation, a perishable and seasonally concentrated harvest, processing complexity, weak standardization, and thin digital infrastructure - recurs across mountainous medicinal-and-edible crop economies throughout East and Southeast Asia and other developing regions. These regions host producers who face structural vulnerabilities. Such producers are structurally exposed to unstable quality, weak bargaining power, and limited access to the value added downstream. Such medicinal-and-edible, landscape-bearing crops constitute a distinct and comparatively under-studied category within the traceability literature, whose combination of high experiential value and high perishability sharpens exactly the coordination and trust problems examined here. Findings derived from this site are therefore transferable to a broad class of smallholder specialty-crop industries confronting the same value-chain and information constraints, which is the basis for treating the case as a source of generalizable rather than merely descriptive evidence.

The site further offers favourable objective conditions for pilot implementation, grounded in spontaneous cooperation among industry actors rather than in any external programme. A functioning industrial base is already in place: local deep-processing firms, farming cooperatives, and the village collective jointly sustain an integrated cultivation-processing-service chain. Over the course of field investigation, which extended to the village and several neighbouring settlements as well as to processing workshops and agritourism sites, the study established working relationships with representative processing enterprises specializing in gardenia tea-beverage and cosmetic product lines. These partners voluntarily opened their production sites for on-site inspection and data collection and shared raw-material purchasing standards, processing parameters, and product-development experience. This provided an authentic operational environment in which the value-traceability model could be observed and tested.

Complementary components required for a full three-industry test were, moreover, concurrently accessible at the site. These include a standardized-cultivation demonstration plot, a prototype traceability system covering data entry, on-chain storage, and code-based verification, and a cloud-adoption platform linking consumers to individual plants and harvests. Operating records accumulated at the site already span different flowering periods, climatic conditions, terrains, and processing techniques, which strengthens the internal diversity of the case and the robustness of observations drawn from it. That this cooperation was self-initiated and commercially motivated - driven by the enterprises' interest in substantiating quality and capturing premiums. It means the conditions enabling the pilot are endogenous to the industry rather than externally engineered. This strengthens the case that comparable results are attainable elsewhere without external support. Taken together, this voluntary, industry-led cooperation and the ready availability of primary, secondary, and tertiary components - combined with the site's structural typicality - make Shuiwei Village a suitable and generalizable setting for empirically examining a lightweight digital value-traceability model.

Results

Multi-dimensional data collection system

Against the backdrop of global digital transformation in modern agriculture, mixed-methods empirical research has gradually become the mainstream paradigm for evaluating the industrial economic impacts of agricultural digitalization among agro-economic journals indexed in the Social Sciences Citation Index (SSCI). This study constructs a multi-dimensional and multi-source empirical data system for the gardenia digital three-industry integration model, with no policy documents or project-related textual materials incorporated throughout the research design. By integrating micro household surveys, stakeholder in-depth interviews, long-term platform operational records and macro industrial statistical indicators, this research obtains standardized and reliable empirical data. Completing sample screening rules, data collection procedures, and psychometric reliability and validity test results are systematically presented to establish a solid and rigorous quantitative foundation for subsequent mechanism analysis and effect verification.

As illustrated in Table 1, questionnaire survey data constitute the core micro-level quantitative evidence for this research. All measurement items are designed based on mature international agricultural economics scales and adapted to the operational characteristics of the gardenia industry, adopting a standard 5-point Likert scoring method. Confirmatory factor analysis verifies that all latent variables exhibit satisfactory convergent validity and discriminant validity, fully complying with the empirical threshold requirements of social science research. In terms of qualitative research design, purposive sampling is adopted to recruit 38 respondents covering the entire gardenia industrial chain, involving grassroots growers, processing enterprise managers, agritourism operators and industrial service practitioners. All interview contents are recorded with informed consent and transcribed into complete textual materials exceeding 120,000 words. The saturation test of thematic coding confirms that the sample size can fully capture differentiated operational feedback and practical problems of each industrial link. Different from subjective self-reported questionnaire data, 12-month continuous time-series data directly exported from the digital traceability platform effectively eliminate human reporting bias, objectively reflecting the long-term dynamic operational status of the digital industrial chain. Complemented by regional official cross-sectional industrial statistics, the four types of data form a mutually supportive hierarchical research system covering micro subjects, meso enterprises and macro industries. This guarantees the comprehensiveness and robustness of the segmented empirical analysis in the following sections.

Table 1. Overview of four types of empirical data.

Data category	Sample scale	Core observation indicators	Test standard
Questionnaire survey	Distributed: 456, valid: 403, effective recovery rate=88.4%	Production cost, annual operating income, digital traceability adoption willingness	Overall Cronbach's α=0.843; each dimension α>0.75; AVE>0.5
Semi-structured interview	38 full-industry-chain respondents (15 growers, 10 processors, 8 agritourism operators, 5 service staff)	Income changes under digital transformation, practical operational bottlenecks	Thematic coding saturation achieved after 32 interviews
Platform time-series data	12 consecutive months, total 14,628 daily operational records	Daily processing yield, monthly cloud-adoption orders, consumer repurchase frequency	Real-time objective data exported from trace platform, free of subjective self-report bias
Industrial cross-sectional statistics	Regional official 2023-2024 agricultural statistical data	Planting area = 12,600 mu, annual deep processing output = 3,720 tons, annual agritourism turnover = 21.86 million CNY	Macro industrial auxiliary benchmark indicators

Impacts on primary planting sector

To objectively reveal the micro-economic benefits brought by digital transformation to grassroots planting subjects, this section takes the grouped sample data of 13 digital traceability pilot growers and 9 traditional non-digital growers as the core empirical basis. Different from technical-oriented research focusing on hardware equipment upgrading, this study centers on the actual income changes and economic benefit differences of smallholder farmers. It systematically sorts out the multi-dimensional income enhancement mechanisms of digital standardized planting from three progressive logical levels.

First, digital standardized planting norms unify scattered operational behaviors and stabilize the basic income of gardenia cultivation. Traditional smallholder planting relies entirely on empirical judgment, leading to prominent heterogeneity in crop quality, appearance and maturity, which easily triggers market price discrimination and unstable sales returns. As clearly reflected in Table 2, the commodity qualified rate of growers participating in digital pilot management reaches 92.4%, which is 15.7 percentage points higher than that of traditional planting groups. The standardized operational guidelines solidified by digital traceability records standardize the whole planting process, effectively reducing substandard products caused by irregular operation. This quality homogenization effect avoids unnecessary profit losses and directly boosts the average annual planting net income of pilot households by 7,267 CNY, forming a stable basic income guarantee [32,33].

Table 2. Comparative operating indicators: pilot and non-pilot growers.

Index	Pilot group (N=13) Mean±SD	Non-pilot group (N=9) Mean±SD	Absolute difference
Annual planting net income (CNY)	28,642±4,126	21,375±3,892	+7,267
Commodity qualified rate (%)	92.4±3.6	76.7±5.2	+15.7
Annual implicit transaction cost (CNY)	1,246±318	2,783±465	-1,537
Annual income fluctuation coefficient	0.11±0.03	0.29±0.07	-0.18

Second, digital information trading platforms break the information barrier of traditional planting and effectively reduce implicit transaction costs. Restricted by scattered operation modes and isolated market information, traditional smallholders need to invest substantial time and labor in market inquiry, price negotiation and offline transaction docking, with weak market bargaining power and high implicit operational consumption. Statistical results show that the annual average implicit transaction cost of non-pilot households is as high as 2,783 CNY, while digital platform users only bear 1,246 CNY of related costs, achieving an annual cost saving of 1,537 CNY. The elimination of intermediate redundant links and information asymmetry optimizes the factor allocation efficiency of smallholders, and all saved implicit costs are directly converted into net planting profits under equivalent output conditions.

Third, industrial big data early warning mechanisms correct blind production decisions and significantly reduce smallholder income volatility. Affected by lagged market feedback, most traditional growers adopt passive production strategies, adjusting planting scale mechanically according to the previous year's market price and profit level, which easily triggers periodic overcapacity or supply shortage. The survey shows that 62.4% of non-pilot farmers have blind planting behaviors, and their annual income fluctuation coefficient reaches 0.29, which is nearly three times that of digital pilot farmers (0.11). The real-time supply and demand data, price trend indicators and industrial operation information released by the digital traceability platform provide scientific decision-making basis for smallholders. They restrain irrational production expansion and contraction, effectively hedge market operational risks, and significantly improve the long-term operational stability and risk resistance of small-scale planting subjects. The three synergistic digital effects jointly realize the dual improvement of income level and income stability for gardenia growers.

Value-added effects of secondary processing sector

The digital transformation of gardenia deep processing links fundamentally breaks the low-value development dilemma of the traditional processing industry relying on raw material sales. Based on two-year continuous panel data of 4 cooperative processing enterprises in the research area, this section systematically explores the multi-dimensional value-added effects brought by full-process digital traceability and transparent production supervision. It focuses on analyzing the dual economic benefits of market value enhancement and internal cost optimization, specifically including consumer trust reconstruction, terminal product premium acquisition and intelligent supervision cost reduction. It aims to quantitatively verify the industrial chain value-added mechanism of digital empowering secondary processing.

First, full-process digital traceability eliminates industrial information asymmetry and creates sustainable product premium advantages. The traditional gardenia processing industry presents typical “black box production” characteristics, with opaque raw material sources, processing techniques and sterilization procedures. Consumers cannot accurately identify product quality differences, resulting in the widespread dilemma of “high-quality products without high prices”. The digital traceability system records and publicly displays all key production nodes in real time, transmitting credible quality certification signals to the consumer market. As shown in the enterprise panel data, traceable gardenia finished products achieve average terminal premium rate of 18.6%, and the customer repurchase rate increases from 21.4% to 42.7% [34,35]. This trust premium mechanism effectively solves the market pricing distortion of high-quality processed products and realizes the value return of refined processing.

Second, digital intelligent supervision replaces inefficient manual inspection work and realizes precise cost control of processing enterprises. Traditional processing workshops rely on manual paper filing and regular offline spot checks for quality supervision, which are not only labor-intensive and time-consuming, but also prone to supervision omission and delayed risk discovery. Before digital transformation, each processing enterprise needs to arrange three full-time supervisors for daily quality management, with an average annual supervision labor cost of 41,200 CNY. After accessing the digital intelligent supervision system, automatic data collection, real-time risk monitoring and intelligent early warning functions replace most manual work, and only one part-time administrator is required for daily system maintenance. The annual supervision labor cost of enterprises is reduced by 37.2%, releasing abundant operating funds for processing technology upgrading and market brand building.

Third, the synergistic effect of market premium and cost reduction drives the overall value upgrading of the processing industrial chain. The significant gap in gross profit margin in Table 3 intuitively reflects the prominent value-added effect of digital transformation. The gross profit margin of traditional manual line is only 23.7%, while the profit level of digital traceability line reaches 36.6%, with a net increase of 12.9 percentage points. Digital transparent supervision promotes the industrial transformation from low-value raw material primary processing to high-margin refined finished product manufacturing and extends the industrial value chain. It builds a long-term and stable profit growth mechanism for gardenia processing enterprises.

Table 3. Two-year panel indicators of processing enterprises.

Operating index	Digital traceability line	Traditional manual line	Change amplitude
Average terminal premium rate	18.6%	0%	+18.6 pct
Customer repurchase rate	42.7%	21.4%	+21.3 pct
Annual supervision labor cost (CNY)	25,874	41,200	-37.2%
Comprehensive gross profit margin	36.6%	23.7%	+12.9 pct

Diversified income growth of tertiary agritourism service sector

Digital full-chain traceability not only optimizes the economic benefits of primary planting and secondary processing, but also empowers the innovative integration of the gardenia industry and rural tertiary service industry. Based on the field survey data of 86 rural households engaged in gardenia agritourism and digital service businesses, this section explores how digital credit endorsement breaks the boundary limitations of traditional single planting income. It systematically analyzes the diversified income growth mechanism of three typical new business formats including cloud farm adoption, immersive rural tourism experience and regional industrial intellectual property (IP) operation. It reveals the long-term value release logic of digital three-industry integrated development for expanding farmers' non-agricultural income channels.

First, digital traceability credit eliminates remote consumer trust dilemmas and fosters stable online service income sources. Restricted by opaque production information, traditional off-site customized planting and farm custody services lack market credibility, making it difficult to form large-scale market transactions. The real-time and verifiable whole-process production data displayed by the digital platform eliminates the information gap between remote operators and consumers, laying a solid market foundation for the standardized development of cloud farm adoption business. Survey data show that, as illustrated in Figure 4, participating households obtain an average annual online service income of 9,630 CNY from cloud adoption projects, accounting for 31.2% of total household income [36]. This off-season service income effectively makes up the seasonal income gap of traditional planting and realizes the annual balanced utilization of agricultural production resources.

Table 4. Diversified income composition of agritourism households.

Business format	Average annual household income (CNY)	Proportion of total household revenue	Annual business growth rate
Cloud farm adoption online service	9,630	31.2%	26.4%
Offline picking, catering and homestay	12,470	40.5%	47.5%
Regional industrial IP brand dividend	5,310	17.3%	12.3%

Second, digitally standardized industrial bases empower rural scene upgrading and activate offline agritourism experience value. Traditional gardenia planting fields only undertake single production functions, with idle landscape resources and insufficient commercial value. With the help of digital unified construction and industrial scene display, standardized gardenia planting bases are transformed into comprehensive rural tourism carriers integrating sightseeing, picking experience and popular science research. Rural households rely on industrial scenic spots to develop supporting projects such as farmhouse catering and homestay accommodation, obtaining an average annual non-agricultural income of 12,470 CNY. The digital industrial upgrading significantly enhances regional tourism competitiveness, driving the local annual tourist reception volume to increase by 47.5%.

Third, long-term standardized digital operation accumulates regional industrial brand assets and releases sustained IP premium dividends. Different from the short-term seasonal income brought by cloud adoption and picking experience projects, continuous digital standardized operation and transparent quality supervision gradually shape the exclusive regional IP image of the gardenia industry. Brand effect effectively improves market recognition and tourist loyalty, driving the annual growth rate of regional tourism comprehensive turnover to maintain at 12.3%, which is significantly higher than non-branded villages. The three innovative business formats jointly build a multi-level diversified income system covering short-term online service revenue, medium-term offline experience profit and long-term brand premium dividend. This fundamentally changes the single income structure of traditional rural households. It realizes sustainable income growth driven by three-industry integration.

Discussion

Theoretical contributions of this research

This study puts forward three theoretical innovations to improve the research system of digital agriculture and the integration of rural primary, secondary and tertiary industries for smallholders. First, it distinguishes information traceability and value traceability and expands the theoretical connotation of agricultural traceability. Existing blockchain traceability studies only focus on supervising production data to guarantee food safety, without constructing a value conversion logic covering planting, processing and agritourism [37]. This paper constructs the Z-CM cross-chain mapping model to realize the conversion of on-chain credible data into industrial added value, filling the research gap of value-oriented traceability. Second, it establishes a multi-dimensional analytical framework for data-driven rural industrial integration. Existing studies on agritourism digitalization merely discuss single cloud operation modes, while traditional industrial integration theories take land and capital as core elements and ignore cross-industry data transmission mechanisms. The proposed cross-chain framework addresses this defect and forms a standardized analytical paradigm for industrial synergy. Third, it enriches empirical evidence on inclusive digital transformation for mountain smallholders. Mainstream precision agriculture technologies are developed for large flat farmlands with high costs and cannot adapt to fragmented hilly planting and poor network conditions [38]. The lightweight Zhizi link profit (Z-LP) communication and edge collaborative architecture proposed in this paper deliver low-cost digital solutions for mountain farmers and fill the shortage of mountain-specific empirical cases in global digital agriculture research.

Practical and international policy implications

This paper constructs the Z-CM cross-chain mapping model to realize the conversion of on-chain credible data into industrial added value, filling the research gap of value-oriented traceability. Second, it establishes a multi-dimensional analytical framework for data-driven rural industrial integration. Existing studies on agritourism digitalization merely discuss single cloud operation modes, while traditional industrial integration theories take land and capital as core elements and ignore cross-industry data transmission mechanisms. The proposed cross-chain framework addresses this defect and forms a standardized analytical paradigm for industrial synergy. Third, it enriches empirical evidence on inclusive digital transformation for mountain smallholders. Mainstream precision agriculture technologies are developed for large flat farmlands with high costs and cannot adapt to fragmented hilly planting and poor network conditions. The lightweight Z-LP communication and edge collaborative architecture proposed in this paper deliver low-cost digital solutions for mountain farmers and fill the shortage of mountain-specific empirical cases in global digital agriculture research.

Comparative advantages over mainstream commercial traceability schemes

This paper compares the lightweight Z-CM gardenia traceability system with mainstream commercial platforms including IBM Food Trust, VeChain and Zhe Nong Ma and Ant Chain from three dimensions: deployment cost, mountain adaptability and three-industry linkage.

Firstly, the system boasts prominent cost advantages. Hardware and maintenance fees of commercial blockchain platforms take up over 40.0% of mountain farmers' agricultural income. Survey data shows that adopters of this lightweight system bear an annual implicit transaction cost of only 1,246 CNY, compared with 2,783 CNY for non-participants, which saves 1,537 CNY per household annually. Its modular design avoids massive one-time investment.

Secondly, it is specially customized for scattered mountain smallholders. Traditional centralized traceability systems feature complex workflows and lack offline caching functions for weak hilly networks. The simplified mobile interface and edge preprocessing module match elderly farmers with low digital literacy and effectively raise system adoption rates.

Thirdly, the model forms a complete industrial value loop absent from general traceability tools. Most commercial platforms only store production data without value circulation mechanisms covering the whole industry. Multi-dimensional panel data verify that the Z-CM system generates multiple revenue streams: an annual net income growth of 7,267 CNY for growers, a 18.6% product premium for processors and a stable annual agritourism income of 9,630 CNY per household.

Research limitations & boundary conditions

This study has inherent limitations that provide directions for follow-up research. First, the research samples are geographically restricted. All field surveys and pilot tests are carried out in the gardenia industrial cluster of Shuiwei Village, Taishun County, without covering regions with different climates, terrains and industrial foundations. Thus the model parameters and income measurement results cannot be directly applied to plain crop bases or medicinal horticulture in other provinces. Second, the dataset only includes one year of panel data without long-term time-series tracking. It fails to fully capture long-term risks such as equipment aging and cyclical market fluctuations, which weakens the long-term prediction capacity of the Z-CM model. Third, the promotion scope is constrained by farmers' low digital literacy. Most surveyed middle-aged and elderly farmers rely on on-site guidance from village staff to operate the system. Without grassroots training mechanisms, the system's adoption rate and data completeness will drop sharply. Future research can expand multi-regional samples, supplement long-term longitudinal data and build hierarchical digital training systems to mitigate the above deficiencies.

Conclusion

Targeting hilly gardenia industries, this paper constructs an IoT-blockchain integrated Z-CM cross-chain value mapping model to resolve fragmented cultivation, opaque processing, unbalanced supply-demand and fragmented industrial value chains prevalent in smallholder mountain agriculture. Theoretically, it distinguishes information traceability and value traceability and builds a complete analytical logic for data-driven industrial integration, where on-chain credible data is converted into brand and agritourism benefits. Technically, the proprietary Z-LP low-power edge architecture cuts the digital transformation threshold of mountain farmers and overcomes the high cost and complicated operation of commercial traceability platforms such as Ant Chain and IBM Food Trust. Empirical results verify multi-dimensional economic benefits of the integrated digital solution. For primary planting, standardized digital management reduces implicit costs and raises farmers' annual net income by 7,267 CNY. For secondary processing, full-process traceability eliminates information asymmetry, bringing an 18.6% product premium and a 37.2% cut in supervision labor costs. For tertiary agritourism, traceability-supported cloud farm subscriptions and offline experience projects create off-season diversified income for rural households. The proposed framework serves as a replicable inclusive digital transformation paradigm for global mountain medicinal horticulture and delivers feasible solutions to the digital divide and low-value circulation dilemmas of rural mountain economies worldwide.

Recommendations

Four international-oriented research directions are proposed based on the study's empirical constraints and theoretical gaps, excluding iterative optimization of local pilot projects.

First, cross-regional comparative research on digital transformation of hilly smallholders across global horticultural producing regions can be conducted. This paper only collects field data from one mountainous county in Zhejiang. Subsequent studies can integrate survey data from mountain medicinal crop clusters in various developing countries to establish a cross-territorial comparison framework and calibrate the universal parameters of the Z-CM model.

Second, quantitative research on the restriction mechanism of farmers' digital literacy needs further exploration. Existing literature cannot quantify the correlation between digital literacy, system adoption and long-term operational efficiency. Follow-up scholars can design multi-dimensional measurement scales and adopt standardized regression to measure the threshold effect of digital literacy, filling the quantitative research gap regarding the rural digital divide in hilly areas.

Third, the interoperability mechanism of cross-regional agritourism and agricultural e-commerce digital ecosystems requires further study. The current traceability mini-program operates as a closed independent system unable to exchange data with external sales and experience terminals. Future research can formulate lightweight unified open data standards to break data silos and facilitate cross-regional circulation of high-value specialty agricultural products. Fourth, systematic research on long-term inclusive benefit incentive mechanisms in digital agriculture should be carried out. Short-term one-off subsidies in pilot areas cannot form sustainable profit-sharing mechanisms covering growers, processors and agritourism operators. Follow-up comparative case studies of mature mountain industrial models can summarize balanced long-term benefit distribution systems to realize sustainable digital upgrading of mountain rural industries.

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Authors' contribution

Huang Yiru contributed to conceptualization, methodology, supervision, writing - review and editing, and project administration. Liu Xin was responsible for software, model development, formal analysis and visualization. Li Yuchen conducted investigation, data curation, field surveys and questionnaire distribution. Liu Jia provided resources, collected literature and completed partial original draft writing. Song Junqing performed validation, data sorting and format revision. All five authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Informed Consent Statement

All interviewed smallholders and enterprise staff provided verbal informed consent before participating in surveys and field interviews.

Data Availability Statement

The household questionnaire data, platform operation records and industrial statistical data generated and analyzed during this research are available from the corresponding author upon reasonable request.

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