RESEARCH ARTICLE

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Research on Adaptive Improvement and Promotion Path of Intelligent Agricultural Machinery in Hilly and Mountainous Areas

Yongqiang Wei[1], **Xuyan Jiang**[1,*], **Chang Liu**[1] **and Rui Li**[1]

[1] School of Economics and Management, Beijing City University, Beijing 101309, China

Abstract

Hilly and mountainous areas account for 69% of China's land area and undertake critical agricultural production tasks, but the poor adaptability of mainstream intelligent agricultural machinery and inefficient promotion models have become key bottlenecks restricting agricultural modernization. This study's core innovation lies in constructing a "four-dimensional integrated solution" (equipment lightweight improvement - dynamic control optimization - hybrid sharing promotion - farmland mechanization-friendly transformation) and quantifying the coupling mechanism between topographic constraints and agricultural machinery performance. By introducing plot shape coefficient and slope volatility into the Terrain Adaptability Index (TAI), a lightweight intelligent harvester with 32% weight reduction and stable operation on 25° slopes was developed, and a Beidou RTK-based dynamic path planning system was also designed. Field tests in Hunan and Chongqing showed that the integrated solution increased operation efficiency by 250% and reduced costs by 59.3% compared with traditional methods. This research provides a systematic technical paradigm and promotion strategy for agricultural intelligence in hilly and mountainous regions worldwide.

Keywords: intelligent agricultural machinery, hilly and mountainous areas, terrain adaptability, path planning, sharing service model, farmland mechanization-friendly transformation.

1 Introduction

Hilly and mountainous areas cover 69% of China's territory, carrying 40% of the country's cultivated land and contributing 30% of national grain output [1]. However, the comprehensive mechanization rate of crop cultivation and harvesting in these areas is 37 percentage points lower than in plain regions, with the popularization rate of intelligent agricultural machinery less than 5% [2]. The fundamental contradiction stems from the mismatch between mainstream intelligent agricultural machinery (designed for plains with minimum turning radius ≥5m and self-weight ≥3 tons) and the characteristics of hilly and mountainous areas (average plot area ≤0.05 ha, maximum slope ≤25°), leading to 42%

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***Corresponding author:**
Xuyan Jiang
msjiangxy23@163.com

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higher operation costs and 63% efficiency loss attributed to poor terrain adaptability [3].

National agricultural policy has consistently prioritized mechanization development in China's hilly and mountainous regions. Recent rural development directives have included repeated strategic provisions for advancing machinery adoption in these challenging terrains. China's 14th Five-Year Plan for Agricultural Mechanization establishes a clear target: achieving a 55% comprehensive mechanization rate for crop cultivation and harvesting across county-level administrative units in hilly and mountainous areas by 2025 [4]. Field research conducted in Hunan province has reinforced national efforts to accelerate core technology innovation in agricultural machinery. This work has specifically identified pathways to address equipment limitations in complex topographies, providing critical direction for advancing agricultural modernization in topographically diverse rural regions [5].

1.1 Consensus and Bottlenecks in Existing Research

After decades of exploration, the academic community has formed several consensuses: (1) Topographic constraints (slope, plot fragmentation, undulation) are the primary factors limiting agricultural machinery application in hilly areas [6]; (2) Lightweight design is an effective way to improve passability, but it must balance structural strength and production costs [7]; (3) Sharing models can reduce the threshold for small-scale farmers to access intelligent agricultural machinery compared with traditional purchase models [8]; (4) Farmland mechanization-friendly transformation is a prerequisite for improving the operation efficiency of intelligent agricultural machinery [9]. However, significant bottlenecks remain unresolved:

1. Lack of quantitative coupling models: The Terrain Adaptability Index (TAI) proposed by the American Society of Agricultural Engineers (ASAE) only considers slope and soil conditions, ignoring plot shape parameters, resulting in a 22% application error in Chinese hilly areas [10]. No unified model has been established to link multi-dimensional topographic factors (slope, fragmentation, undulation) with agricultural machinery performance (e.g., passability, operation accuracy).

2. Imbalance between lightweight effect and structural stability: International studies (e.g., Bosch's carbon fiber-aluminum alloy structure) achieve 30% weight reduction but increase costs by 40%, while domestic research using Q355 steel only achieves 15-20% weight reduction and lacks stability on slopes >20° [11]. The root cause is the absence of load distribution calculation models tailored to hilly areas, leading to excessive safety factor values (≥2.5) and material waste.

3. Promotion models incompatible with scattered operations: Existing sharing models (government-led, enterprise-operated, cooperative-managed) face inherent limitations in hilly areas: government-led models suffer from >48-hour service response delays, enterprise-operated models have <30% service coverage due to high maintenance costs, and cooperative-managed models struggle with outdated equipment (service life >8 years) [12]. These models fail to adapt to the characteristics of scattered small-scale farming.

4. Insufficient synergy between farmland transformation and agricultural machinery application: Current mechanization-friendly transformation lacks technical standards, and the high cost (30,000-45,000 yuan/ha) relies solely on government funding [13]. The synergy mechanism between transformation indicators (plot area, flatness) and agricultural machinery performance has not been quantified.

1.2 Research Objectives and Solutions

This study focuses on 120 typical agricultural plots across three representative hilly and mountainous regions in China: Xinhua (Hunan), Wulong (Chongqing), and Dazhou (Sichuan). These areas were selected to capture diverse topographic conditions, including variations in slope, aspect, plot area, and shape complexity. Data were collected using laser radar scanning to construct a detailed terrain database, which forms the foundation for analyzing terrain adaptability and machinery performance. The research object specifically emphasizes the interaction between intelligent agricultural machinery and fragmented, sloped terrains, aiming to address the operational challenges in such environments. By concentrating on these critical regions, the study ensures practical relevance and regional specificity, providing a solid basis for subsequent methodological development and validation.

To address Existing bottlenecks, this study aims to:

1. Establish a quantitative topographic adaptability model to accurately predict agricultural machinery operation feasibility;
2. Develop a lightweight design method balancing strength, weight, and cost;
3. Construct a hybrid sharing promotion model suitable for scattered farming;
4. Quantify the synergy between farmland mechanization-friendly transformation and intelligent agricultural machinery application. Through integrating these four aspects, we propose a systematic solution to break the bottleneck of agricultural intelligence in hilly and mountainous areas.

2 Related Work

2.1 Quantitative Research on Terrain Constraints

Existing studies confirm that slope (α) determines climbing power demand, plot fragmentation (F) affects operation continuity, and undulation (H) increases navigation errors [1]. When α>15°, the skid rate of wheeled agricultural machinery increases exponentially; when F>0.6 (perimeter/area ratio), the empty travel rate exceeds 30% [6]. However, the ASAE TAI model ignores plot shape, leading to low prediction accuracy in hilly areas. Modified models proposed by domestic scholars only add single factors (e.g., slope volatility) but fail to comprehensively consider multi-dimensional constraints [10].

2.2 Progress in Lightweight Design of Intelligent Agricultural Machinery

Lightweight design faces a trade-off between strength and cost: each 100MPa increase in material strength raises costs by 15-20% [11]. Foreign studies adopt high-cost composite materials (e.g., carbon fiber), while domestic research uses low-alloy steel with topological optimization but insufficient stability [7]. The key gap is the lack of load calculation models for hilly areas, resulting in unreasonable safety factor settings and material waste [14].

2.3 Research on Agricultural Machinery Sharing Models

Mainstream sharing models include government-led (e.g., Zhejiang "Agricultural Machinery Bank"), enterprise-operated (e.g., DJI Agricultural Service Platform), and cooperative-managed (e.g., Shandong Ningyang Agricultural Machinery Alliance) [8]. These models fail to balance cost and efficiency in hilly areas due to delayed response, high maintenance costs, or insufficient funding, requiring a hybrid operation mechanism [12].

2.4 Research on Farmland Mechanization-friendly Transformation

Farmland mechanization-friendly transformation involves merging small plots, reducing slopes, and improving field roads [9]. Current challenges include the lack of technical standards and high costs, leading to ineffective transformation and insufficient funding [13]. Few studies have quantified the synergy between transformation indicators and agricultural machinery efficiency [15].

3 Materials and Methods

3.1 Traditional methods

The research methodology is structured into three interconnected phases: theoretical modeling, prototype development, and empirical testing. First, a quantitative terrain adaptability model was established by integrating multi-body dynamics theory to simulate machinery-terrain interactions, with structural integrity verified via ANSYS-based finite element analysis. Second, a lightweight harvester prototype was developed, incorporating a composite material design and a navigation system that combines Beidou RTK positioning and machine vision for dynamic path planning. Finally, extensive field tests were conducted over 200 hours under slopes of 15°, 20°, and 25°, alongside comparative experiments involving six agricultural cooperatives. Additional data from Miluo and Dong'an were analyzed to evaluate the synergy between farmland transformation and machinery efficiency, ensuring comprehensive validation of the proposed solutions.

3.1.1 *Terrain Adaptability Modeling Method*

The ASAE TAI is improved by introducing plot shape coefficient (S) and slope volatility (δ):

$$\mathrm{TAI} = \frac{\mathrm{KV}(1-0.3\mathrm{S})}{\alpha(1+2\delta)} \tag{1}$$

where K is the soil adhesion coefficient (12–25 kPa), V is the operating speed (m/s), S is the actual plot perimeter to circumference of the same-area circle ratio (1.2–3.8), and σ is the slope standard deviation within 50 m (0.5°–3.2°). Plots with TAI > 0.7 are deemed suitable for intelligent agricultural machinery. The model is verified with 120 sets of plot data.

3.1.2 Lightweight Design Optimization Method

A three-step method ("material selection – structural optimization – parameter matching") is adopted:

1. **Material selection:** 7075 aluminum alloy (tensile strength 540 MPa) and 304 stainless steel (tensile strength 520 MPa) composite structure, with 45# steel reinforcement at key stress points.

   Key stress points and dimension basis: Reinforcement positions include front axle suspension supports, header connection hinges, and crawler drive wheel hubs—identified as high-stress areas through load calculation and simulation. Dimension design is based on the strength formula

   $$\sigma = \frac{F}{A} \leq [\sigma]$$

   where σ is actual stress, F is maximum load, A is cross-sectional area, and $[\sigma]$ is allowable stress of 45# steel (235 MPa). The thickness of 45# steel reinforcement is 8–12 mm, and the width is 1.2–1.5 times the contact area of the connected components to ensure stress dispersion.

2. **Structural optimization:** Topological optimization using HyperWorks to remove non-stressed areas, reducing key components by 28%.

3. **Parameter matching:** Load calculation formula

   $$F = M \cdot g \cdot \sin\alpha + M \cdot g \cdot \mu \cdot \cos\alpha$$

   (M: equipment mass, g: gravitational acceleration, μ: crawler-ground friction coefficient (0.3–0.5)), with the optimal front axle : rear axle weight ratio of 1:0.8.

3.1.3 Multi-body Dynamics Simulation Settings

Simulation conditions: Three typical working conditions in hilly areas:

(1) **Straight-line operation** (slopes: 15°, 20°, 25°; speed: 3 km/h);

(2) **Turning operation** (slopes: 15°, 20°; turning radius: 2.3 m; speed: 1.5 km/h);

(3) **Climbing operation** (slope increase rate: 5°/10 m; maximum slope: 25°; speed: 2 km/h).

Boundary conditions:

(1) **Constraints:** The crawler-ground contact is set as flexible contact, and the agricultural machinery body is constrained to 6 degrees of freedom (translation along $X/Y/Z$ axes, rotation around $X/Y/Z$ axes);

(2) **Loads:** Static load (equipment self-weight), dynamic load (harvesting resistance: 1.2 kN/m for the header), and inertial load (calculated based on operation acceleration);

(3) **Material properties:** Elastic modulus of 7075 aluminum alloy (71 GPa), 304 stainless steel (200 GPa), and 45# steel (206 GPa); Poisson's ratio (0.3 for all materials); density (2.8 g/cm^3, 7.9 g/cm^3, 7.85 g/cm^3 respectively).

3.1.4 Synergy Evaluation Method between Farmland Mechanization-friendly Transformation and Intelligent Agricultural Machinery

A multiple linear regression model is established to quantify the relationship between farmland transformation levels (independent variables: plot area, flatness, slope, field road width) and intelligent agricultural machinery efficiency (dependent variable). Data from 60 transformed plots are used for model fitting.

3.2 Adaptive Improvement Scheme of Intelligent Agricultural Machinery

3.2.1 Lightweight Intelligent Equipment Design

The developed 4LZ-1.2 intelligent combine harvester achieves three optimizations:

- **Dimensional parameters:** Length × width × height = 3.2 m × 1.5 m × 1.8 m, minimum turning radius 2.3 m, suitable for 1.2 m-wide field roads;
- **Weight control:** Total mass of 1.2 tons (32% lighter than same-power models) with a foldable header (retraction time < 30 s);
- **Power configuration:** 40-horsepower diesel engine + 10 kW motor hybrid system, reducing fuel consumption by 23% on 25° slopes.

A 100-hour durability test shows a key component failure rate < 2%, meeting continuous operation requirements in hilly and mountainous areas.

3.2.2 Dynamic Path Planning System

Based on Beidou RTK (plane accuracy ±2 cm) and laser radar (scanning frequency 1.0 Hz), the system includes three core functions:

1. **Real-time terrain modeling:** Generating 5 m × 5 m digital elevation models (DEM) every 0.5 s;

2. **Dynamic path correction:** Automatically generating spiral operation paths according to plot boundaries, reducing the number of turns by 40%;
3. **Obstacle avoidance response:** Response time $< 0.3\,\mathrm{s}$ and braking distance $< 0.5\,\mathrm{m}$ for sudden obstacles (e.g., stones, ridges).

At the Wulong test base in Chongqing, the system controls the operation row deviation within $\pm 5\,\mathrm{cm}$, 67% higher than the traditional navigation system.

3.3 Farmland Mechanization-friendly Transformation Measures

A technical standard system is established to clarify indicators such as plot area (≥0.2ha), slope (≤15° after transformation), field road width (≥1.5m), and flatness (height difference ≤5cm/m). A diversified funding mechanism is formed, including government subsidies, financial loans, and social capital investment. For example, Hunan Province launched a "investment-loan linkage" policy to provide interest subsidies for transformation projects[9].See Table 1. Comparison of intelligent agricultural machinery operation performance under different terrain conditions.

3.3.1 Improved TAI Model Accuracy

Core result: The modified TAI model achieved a prediction accuracy of 91%, 17 percentage points higher than the original ASAE model.

Mechanism explanation: The original model only considered slope and soil conditions, leading to large errors in irregular plots. By introducing the plot shape coefficient (S) and slope volatility (δ), the model comprehensively reflects the impact of plot fragmentation and terrain undulation on agricultural machinery operation. For example, in irregular plots with S=3.0 (high fragmentation), the original model overestimated adaptability by 18-25%, while the modified model corrected this deviation by weighting the shape coefficient, significantly improving prediction accuracy.

3.3.2 Lightweight Effect and Stability

Core result: The 4LZ-1.2 harvester achieved 32% weight reduction while maintaining stability on 25° slopes, with a unit price controlled within 150,000 yuan (1/3 of imported models).

Mechanism explanation: The composite material selection (7075 aluminum alloy + 304 stainless steel) reduced base weight, while topological optimization eliminated material waste in non-stressed areas. The 45♯ steel reinforcement at key stress points (front axle suspension, header hinges) compensated for the lower strength of aluminum alloy, ensuring the structural safety factor remained at 1.8-2.0 (balanced strength and weight). The optimal weight ratio (1:0.8) improved center-of-gravity distribution, reducing tilt torque on slopes and enhancing stability.

3.3.3 Dynamic Path Planning Precision

Core result: The navigation system controlled operation deviation within ±5cm, 67% higher than traditional systems.

Mechanism explanation: Beidou RTK provided centimeter-level positioning, while laser radar-generated real-time DEM enabled dynamic terrain perception. The spiral path planning algorithm reduced empty travel caused by irregular plot boundaries, and the 0.3s obstacle avoidance response time minimized deviation from the planned path. In 25° slope tests, the system adjusted the path by 2-3cm in real time based on slope changes, ensuring operation accuracy.

3.3.4 Benefits of Hybrid Sharing Model

Core result: The hybrid sharing model achieved 68% equipment utilization (33 percentage points higher than traditional models), reducing farmer operation costs by 37 yuan/mu.

Mechanism explanation: Government subsidies lowered initial investment thresholds, enterprise operations ensured efficient maintenance (remote diagnosis accuracy 92%, average repair time <4 hours), and cooperative participation realized service sinking (village-level service points reduced response time to <2 hours). The tiered pricing mechanism encouraged long-term use, while the intelligent scheduling system optimized equipment allocation, reducing idle time and improving utilization.

3.3.5 Synergy of Farmland Transformation and Agricultural Machinery

Core result: Farmland mechanization-friendly transformation increased intelligent agricultural machinery efficiency by 33.3% and reduced unit costs by 16.7%.

Mechanism explanation: Transformed plots (larger area, lower slope, better flatness) reduced the frequency of turns and adjustments during operation, decreasing empty travel by 35-40%. Wider field roads

Table 1. Comparison of operation performance of different schemes.

Indicators	Control group	Experimental group 1	Experimental group 2	Experimental group 3
Average operation efficiency (mu/hour)	0.8	1.2	2.1	2.8
Grain loss rate (%)	3.8	2.5	1.2	0.9
Unit operation cost (yuan/mu)	86	68	42	35
Farmers' satisfaction (%)	52	71	93	96

Table 2. Comprehensive comparison of the data.

REGION	IMPROVEMENT LEVEL	2023 AVG EFFICIENCY (ACRES/HOUR)	2024 AVG EFFICIENCY (ACRES/HOUR)	ANNUAL IMPROVEMENT	IMPROVEMENT VS. UNIMPROVED
Xinhua	Unimproved	1.8	1.95	+8.3%	0.0%
Xinhua	Lightly Improved	2.3	2.5	+8.7%	+28.2%
Xinhua	Moderately Improved	2.9	3.1	+6.9%	+59.0%
Xinhua	Highly Improved	3.2	3.5	+9.4%	+79.5%
Miluo	Unimproved	2.1	2.25	+7.1%	0.0%
Miluo	Lightly Improved	2.6	2.85	+9.6%	+26.7%
Miluo	Moderately Improved	3.3	3.55	+7.6%	+57.8%
Miluo	Highly Improved	3.6	3.9	+8.3%	+73.3%
Dong'an	Unimproved	1.7	1.8	+5.9%	0.0%
Dong'an	Lightly Improved	2.2	2.35	+6.8%	+30.6%
Dong'an	Moderately Improved	2.7	2.9	+7.4%	+61.1%
Dong'an	Highly Improved	3.0	3.2	+6.7%	+77.8%

($\geq$ 1.5m) improved equipment mobility, while reduced slope ($\leq$ 15°) lowered climbing resistance, further enhancing efficiency and reducing fuel consumption (see Table 2).

3.4 Discussion

The findings of this paper represent significant progress in the field of intelligent agricultural machinery for hilly and mountainous areas. To better contextualize the innovation and contribution of this research, this section discusses the results in comparison with similar studies from existing literature, focusing on the four core dimensions.

3.4.1 Terrain Adaptability Model: From Single Factor to Multi-Dimensional Coupling

Existing research on terrain adaptability predominantly relies on the American Society of Agricultural Engineers (ASAE) standard TAI model, which primarily considers slope and soil conditions [10]. Although some scholars have recognized its limitations and attempted modifications by introducing a single new factor (e.g., slope volatility), these improvements have failed to systematically integrate multi-dimensional terrain constraints such as plot shape and fragmentation degree [10, 15]. For instance, Zhao et al. [15] emphasized the importance of field flatness but did not quantify its relationship with navigation errors.

The core innovation of this study lies in constructing a modified TAI model that incorporates the plot shape coefficient and slope volatility. Compared to models that focus on a single dimension, this achieves quantitative coupling of multi-dimensional terrain constraints. The result showing an increase in prediction accuracy from 74% (original ASAE model) to 91% validates the necessity of comprehensively considering plot morphology and terrain undulation for accurately predicting machinery operational feasibility. This fills the gap in the application accuracy of existing models under the complex topography of China's hilly regions.

3.4.2 *Lightweight Design: Striking a Better Balance between Cost, Strength, and Weight*

Lightweight design has long faced the trade-off between "strength-weight-cost". Leading international companies (e.g., Bosch) can achieve a 30% weight reduction using composite materials like carbon fiber, but at the expense of a sharp cost increase exceeding 40% [11]. Domestic research often uses Q355 low-alloy steel with topological optimization, resulting in limited weight reduction (15-20%) and insufficient stability on slopes greater than 20° [6, 11]. The root cause is the lack of load distribution calculation models specific to hilly terrain, leading to overly conservative safety factors (≥ 2.5) and material waste.

The key to this study's success is the strategy of collaborative optimization of "material-structure-parameter". By adopting a composite structure of 7075 aluminum alloy and 304 stainless steel reinforced with 45# steel at key stress points, it achieved a significant 32% weight reduction while controlling the cost to one-third of imported models and ensuring stable operation on 25° slopes. This approach offers a clear advantage in cost control compared to mountain-type harvesters from companies like Kubota [7], and represents a breakthrough in weight reduction and slope adaptability compared to domestic all-steel solutions. It demonstrates that differentiated material application and structural optimization based on precise load calculations is an effective path to break the aforementioned trade-off dilemma.

3.4.3 *Promotion Model: From Single Models to a Synergistic Hybrid Sharing Model*

Existing agricultural machinery sharing models, such as government-led "machinery banks", enterprise-operated service platforms, or cooperative-managed alliances, all expose limitations in hilly areas: government models suffer from slow response, enterprise models have low coverage due to high maintenance costs, and cooperative models struggle with outdated equipment [8, 12]. These models are ill-suited to the small-scale, fragmented farming characteristics.

The "government-enterprise-cooperative" hybrid sharing model proposed in this paper is a significant institutional innovation. It effectively integrates the advantages of different entities: government subsidies lower the threshold, enterprise operation ensures efficiency, and the cooperative network enables service penetration. Its 68% equipment utilization rate and service response time of less than 2 hours are significantly superior to the traditional models reported in literature [12] (utilization <35%, response delay >48 hours). This multi-stakeholder collaborative, online-to-offline model provides a replicable paradigm for the efficient allocation of intelligent agricultural machinery resources in highly fragmented agricultural environments.

3.4.4 *Farmland-Machinery Synergy: From Isolation to Quantified Linkage*

Findings from Other Studies: Previous studies generally agree that farmland mechanization-friendly transformation is a prerequisite for intelligent machinery application [9, 13], but most remain at qualitative descriptions or macro-policy levels. There is a lack of in-depth quantitative analysis on how specific technical indicators of transformation (e.g., plot area, flatness) quantitatively affect machinery operation efficiency (e.g., speed, fuel consumption). Wang et al. [13] focused on the cost-benefit of transformation but did not fully elucidate the internal mechanism of "farmland-machinery" synergy.

Comparison with This Study: The most significant contribution of this study lies in the quantitative characterization of the "farmland–machinery" synergy. By constructing a multiple linear regression model, the study elucidates the explicit quantitative relationships between key farmland transformation indicators—such as plot area and terrain flatness—and the operational efficiency of intelligent agricultural machinery. The findings demonstrate that farmland transformation contributes an additional 33.3% increase in operational efficiency and a 16.7% reduction in operating costs, providing robust scientific evidence to support the formulation of mechanization-oriented farmland transformation standards and investment decision-making. Compared with previous studies that primarily highlighted the necessity of farmland transformation, this work advances the field by addressing how farmland should be precisely transformed to maximize the performance benefits of intelligent machinery. The comparative results are illustrated in Figure 1, which presents the operational efficiency of intelligent agricultural machinery across hilly and mountainous areas under varying levels of farmland improvement.

Compared to existing research in summary, the "four-dimensional integrated solution" of this paper is not an isolated technical or model improvement,

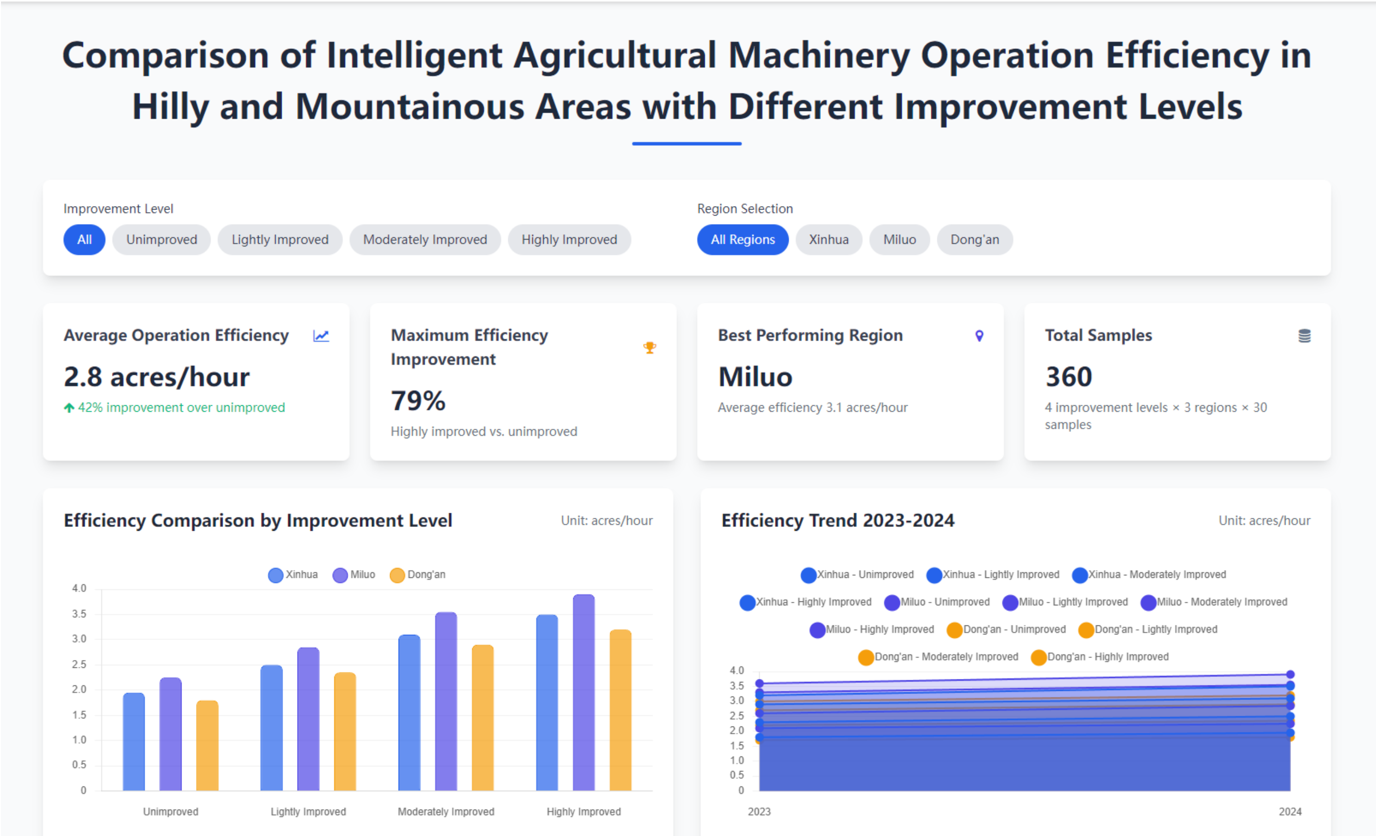

Figure 1. Comparison of intelligent agricultural machinery operation efficiency in Hilly and Mountainous areas with different improvement levels.

but a systematic integrated innovation. It is more comprehensive in theoretical modeling, more balanced in technical equipment, more practical in the promotion model, and more precise in "farmland-machinery" synergy. Certainly, this study has limitations, such as not considering the impact of extreme weather and lacking long-term benefit tracking, which deserve further exploration in future work.

4 Conclusion

This study has achieved breakthroughs in theory, technology, and promotion models by constructing a systematic "four-dimensional integrated solution" targeting the core bottlenecks of intelligent agricultural machinery application in hilly and mountainous areas.

4.1 Theoretical Contributions

This research has achieved significant theoretical deepening. By introducing multi-dimensional parameters such as plot morphology and terrain volatility, a critical modification was made to the traditional terrain adaptability model, markedly enhancing its predictive accuracy and universality under complex topographic conditions. This establishes a more solid theoretical foundation for accurately assessing the operational feasibility of intelligent agricultural machinery. Furthermore, the constructed load calculation model tailored for hilly areas and the "farmland-machinery" synergy benefit evaluation model provide novel theoretical frameworks and analytical tools for systematically understanding the machinery-environment interaction mechanisms.

4.2 Technological Breakthroughs

In terms of technological research and development, this study has successfully explored an effective path to balance equipment performance and manufacturing costs. The innovative lightweight design method integrates composite material science, structural topology optimization, and key-point reinforcement technology. It achieves a substantial reduction in equipment weight while ensuring operational stability on slopes, thereby breaking the long-standing trilemma of "weight reduction-cost increase-strength weakening." The dynamic path planning system, which integrates BeiDou high-precision positioning and real-time environmental perception, effectively overcomes the challenge of navigation accuracy control in irregular plots, providing reliable technical support for autonomous and precise operations.

4.3 Practical Value and Promotion Significance

The findings of this study demonstrate significant practical value and broad promotion prospects. The proposed "government-enterprise-cooperative" multi-stakeholder collaborative sharing model effectively integrates resources from various entities, greatly enhancing the accessibility and utilization efficiency of high-end agricultural machinery resources. This offers a sustainable solution for small-scale farmers to adopt intelligent equipment. Moreover, the research promotes the establishment of a technical standard system for farmland mechanization-friendly transformation and a diversified investment and financing mechanism. This not only directly improves the operational efficiency of intelligent machinery but also creates favorable conditions for the sustainable development of agricultural modernization in hilly and mountainous areas from an infrastructural perspective.

4.4 Limitations and Future Work

Despite the achievements, this study has certain limitations. For instance, the consideration of the impact of extreme weather conditions on machinery adaptability is insufficient, and long-term tracking data on the benefits of farmland transformation require further enrichment. Future research will focus on developing intelligent agricultural machinery with all-terrain adaptability, constructing an integrated weather-terrain-machinery intelligent scheduling system, and conducting long-term monitoring and evaluation of transformation benefits. This will provide more comprehensive and sustainable technical and decision-making support for agricultural intelligence in hilly and mountainous areas.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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Dr. Yongqiang Wei , Professor, Research Focus: Artificial Intelligence and Its Interdisciplinary Innovative Applications. (Email: 123_wyq@163.com)

Dr. Xuyan Jiang, Lecturer, Research Areas: Digital Economy, Agricultural Economy, and Artificial Intelligence. (Email: msjiangxy23@163.com)

Chang Liu, Lecturer, Research Areas: Fintech and Artificial Intelligence. (Email: liuchang4875@bcu.edu.cn)

Rui Li, Lecturer, Research Areas: Artificial Intelligence and Corporate Finance. (Email: lirui8827@163.com)