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Challenges and Policy Recommendations for Farm Mechanization in Fragmented Landholdings in India

Prashant Tyagi,
2. DR. Janamejay Kumar Shukla
Department of Geography,Amar Singh Degree College, Lakhaoti- Bulandshahr (U.P.) India

Received-24.08.2026, Revised-02.09.2026, Accepted-10.09.2026, **E-mail:prashanttyagi.rt@gmail.com**

Abstract: ***India faces a persistent crisis of land fragmentation, driven by demographic growth, traditional inheritance patterns, and socio-cultural norms. Over 86% of holdings are now classified as small or marginal, a dynamic that undermines farm profitability, sustainability, and the adoption of mechanization. This paper combines field study, operational data from the KrishiHal Agritech Services Pvt. Ltd. pilot, and international comparative analysis to assess the challenges and opportunities for sustainable mechanization among fragmented smallholders. Mixed-methods research in Benipur, Uttar Pradesh, exposes the profound economic and logistical barriers to machinery ownership and efficient service provision. Drawing on spatial theory, rural institutional analysis, and best practices from China, the USA, and Australia, we propose a scalable model of integrated "Krishi Seva Kendra" (farmer service hubs). These are optimized through central place theory, social trust-building, and digital enablement to overcome cost, access, and trust issues. The paper concludes with actionable recommendations for policy innovation, institutional support, and public–private partnerships, with lessons applicable across the Global South.***

Key words: farm mechanization, land fragmentation, smallholders, rural services, spatial modelling.

1. INTRODUCTION- Agriculture is the enduring foundation of India's economy, society, and rural landscape. Beyond providing employment to over half of the nation's population and accounting for nearly 17–18% of national GDP, agriculture in India shapes the cultural ethos, sustains livelihoods, and forms the bedrock of food security and social cohesion. For the world's second-most populous country, agricultural transformation is tightly bound to advancing the Sustainable Development Goals (SDGs)-notably SDG 1 (No Poverty), SDG 2 (Zero Hunger), and SDG 8 (Decent Work and Economic Growth). The sector's health is thus central to India's national well-being and its global developmental commitments.

India's agricultural structure faces persistent and intensifying challenges, none more critical than the progressive fragmentation of landholdings. The average farm size has shrunk from 2.3 hectares in the early 1970s to approximately 1.08 hectares in 2016, while the number of operational holdings has increased-over 146 million are now officially recognized. More than 86% of Indian holdings are classified as small or marginal (under 2 hectares). This fragmentation is especially acute in densely populated regions such as the Gangetic plain, where inheritance practices, high birth rates, and cultural attachment to ancestral land promote sub-division into numerous, non-contiguous, and often irregularly shaped parcels.

The root causes of fragmentation are deeply embedded. Historically, partible inheritance (equal division among sons), codified in laws such as the Hindu Succession Act, has played a dominant role. These trends are magnified by demographic factors-early marriage, persistently high birth rates, and limited off-farm employment-resulting in repeated division and dispersal of farmland within families. In many areas, social status is interwoven with landownership, and cultural aversion to selling inherited land restricts the emergence of viable land markets and limits consolidation. Such patterns entrench not only economic inefficiency but also social identity and power, shaping community cohesion and local politics.

These structural features have profound effects on farm productivity and rural modernization. The shift from traditional, labor-intensive agriculture to technology-driven production requires scale economies that fragmented holdings undermine. Mechanization-embracing a spectrum from tractors and harvesters to precision irrigation and seeding technology-offers the promise of higher yields, greater labor productivity, and resilience against climate volatility. Globally, mechanization has underpinned the transformation of agricultural systems in both developed and emerging economies, driving dramatic gains in efficiency, decreasing production costs, and enabling diversification. However, in India, the benefits of mechanization remain uneven. Fixed and operating costs for machinery are rarely justifiable on tiny, scattered plots, while logistical obstacles in accessing, transporting, and maintaining equipment further erode potential advantages.

Manual labor thus remains dominant across much of rural India, with over 56% of total farm work still performed by human or animal power in the most affected states. This dependence is compounded by recent trends in rural-urban migration: as younger men leave farming villages, labor costs increase and skilled farm labor becomes scarce, creating bottlenecks during peak agricultural seasons. For rural women-who represent an increasing share of the agricultural workforce- fragmented land adds intensifying drudgery, economic vulnerability, and exclusion from modern value chains.

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Policy interventions over the past decades have sought to mitigate these challenges. Initiatives such as the Sub-Mission on Agricultural Mechanization (SMAM), state-sponsored Custom Hiring Centers (CHCs), and a variety of private sector innovations and cooperative experiments have targeted increases in mechanization access, especially for smallholders. However, outcomes have been mixed. CHCs have expanded access in areas with larger holdings and stronger cooperative traditions, but often fail in the most fragmented or marginalized regions, where high start-up and maintenance costs, weak logistics, and limited trust in service providers persist. Private sector digital rental marketplaces show promise in some commercial hubs but lack scale, and typically do not reach deeply rural, lowincome households.

In contrast, international experiences offer alternative models for overcoming fragmentation. In China, coordinated land reforms, government-supported cooperatives, and the strategic siting of machinery service centers have substantially improved mechanization among smallholders. Developed economies such as the USA and Australia have long relied on a combination of marketdriven land consolidation, robust rural finance, and cooperative equipment pools to enable technological upgrading, even as farm populations declined. These cases underline the importance of integrating spatial planning, robust public–private partnerships, and institutional adaptation for effective rural mechanization.

Within this context, the present study draws on empirical field data, qualitative insights, and a real-life business pilot (KrishiHal Agritech Services Pvt. Ltd.) to examine in depth the obstacles and opportunities facing sustainable mechanization among fragmented smallholders in India. In particular, we focus on Benipur and neighboring villages in Uttar Pradesh-a region emblematic of acute fragmentation and severe rural development constraints. Our research employs a mixed-methods approach, including (a) detailed household surveys and qualitative interviews with farmers and service providers, (b) analysis of operational data from a pioneering local machinery service model, and (c) comparative literature review referencing global best practices and spatial modeling frameworks.

Specifically, our objectives are as follows:

- To analyze how legal, demographic, and social factors drive land fragmentation, and how these shape barriers to mechanization in contemporary India.
- To empirically document the economic, institutional, and gendered impacts of fragmentation at the grassroots.
- To benchmark India's challenges and partial solutions against successful international cases, focusing on the role of service center networks and rural cooperatives.
- To propose a scalable, spatially optimized model-grounded in central place theory-for "Krishi Seva Kendras" capable of delivering integrated machinery and advisory services to marginalized smallholders.
- To present clear, actionable policy recommendations based on lessons from fieldwork, operational innovation, and comparative theory.

2. Literature Review- 2.1 Land Fragmentation: Causes and Global Patterns: Land fragmentation is a widespread issue in agricultural economies, especially in Asia and Africa, and refers to the division of farms into smaller and often non-contiguous plots. In India, fragmentation is primarily driven by inheritance traditions where land is divided equally among male heirs, along with high rural birth rates and cultural reluctance to sell or consolidate land. According to the Agriculture Census (2019), over 86% of Indian farms are small or marginal-less than 2 hectares-making India one of the countries with the smallest average holding sizes globally. This trend has worsened over the last century due to population growth and the legal reinforcement of partible inheritance laws, limiting opportunities for land consolidation and modern farm management.

Globally, similar challenges have been observed. In China, post-reform land allocation led to the rapid subdivision of landholdings, but a suite of government interventions enabled subsequent reaggregation and mechanization through land swaps and service cooperatives. In Sub-Saharan Africa, land fragmentation often stems from customary tenure systems and polygamous inheritance patterns, which result in scattered family plots that hinder investment and coordination. Conversely, several developed nations, such as the United States and Australia, have addressed fragmentation by enforcing minimum plot sizes, promoting land markets, and enabling mechanization-friendly consolidation through targeted policy reforms.

2.2 Impact of Fragmentation on Mechanization and Productivity: Numerous studies confirm that fragmented holdings limit agricultural productivity by impeding scale economies and discouraging mechanized investment. Farmers managing several small, scattered plots face higher input costs per hectare, greater logistical obstacles for machinery use, and time losses in moving between parcels. The lack of

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contiguous plots also exacerbates underutilization of resources, reduces opportunities to rotate crops efficiently, and increases the difficulty of adopting sustainable practices such as precision agriculture.

Mechanization, which has been central to productivity booms in the United States, Australia, and increasingly in Latin America and China, remains largely inaccessible for holders of fragmented farms. Even where farmers wish to hire machinery or services, operational inefficiency caused by distance and irregular field shapes leads to inflated rental prices and the under-provision of essential services, particularly during narrow window periods for planting or harvest.

2.3 Service Models: Indian and International Experiences: To tackle these constraints, various models have been trialed worldwide. In India, government-backed Custom Hiring Centers (CHCs) have provided access to machinery on a rental basis, but coverage is limited and often fails to reach the most disadvantaged farmers. Private sector efforts, like EM3 Agri Services and regional digital rental platforms, show promise but remain constrained by issues of trust, scale, and profitability. While CHCs have demonstrated improved yields and input efficiency where adoption is high, their sustainability is challenged by high capital costs and uneven demand, especially in areas of extreme fragmentation.

Internationally, cooperative and group farming approaches have bridged the mechanization gap for smallholders. China's introduction of collective land management and machinery service cooperatives has revitalized mechanization in villages with fragmented plots, as cooperatives are able to aggregate demand and negotiate bulk purchases or shared use of expensive equipment. In Europe, machinery rings-nonprofit cooperatives for machinery sharing—have reduced costs and encouraged technology adoption among small farmers in countries like Germany and Austria. In Sub-Saharan Africa, donorled mechanization rental schemes have produced mixed results, often faltering due to insufficient support structures and low institutional trust.

2.4 Why Existing Approaches Fall Short in India: Despite government investment, most current models in India encounter systemic obstacles:

- **Physical barriers:** Dispersed, non-contiguous land hampers efficient machinery use.
- **Institutional obstacles:** Weak local organizations, lack of trust in shared infrastructure, and limited collective bargaining power.
- **Access and affordability issues:** High upfront costs, low credit penetration, and inflexible rental practices favor larger, more connected farmers.
- **Social factors:** Exclusion of women, marginal communities, and those lacking access to local political networks, which stymie collective action.
- **Policy gaps:** Incomplete land records, slow progress on digital platforms in rural areas, and lack of supportive legal frameworks for land pooling or group farming.

Field evaluations note that while digital agriculture and input startups are growing, their outreach still skews urban or peri-urban, with the rural poor often left out. Custom Hiring Centers, though successful in better-off districts, are yet to demonstrate sustained viability in the poorest states, particularly due to seasonality and the volatility of local demand.

2.5 Lessons from International Practice: A key global lesson is that scale, integration, and stable institutional support are essential for mechanization among fragmented holdings. China's success rested not only on technology access, but also on government guarantees, strong village cooperatives, and policies enabling voluntary land pooling and temporary swaps. In the United States, early twentieth-century law and policy facilitated farm consolidation by incentivizing purchases and providing credit for mechanization. Australia's large-scale farm structure emerged through colonial land grants and later consolidation, allowing near-universal mechanization.

Other regions demonstrate the risks of ignoring socio-institutional challenges. In Sub-Saharan Africa, many rental pilots have failed where local leadership or aggregation were weak or absent, suggesting that both "hardware" (machinery) and "software" (trust, coordination, policy) are needed to break the fragmentation trap.

2.6 Research Gap and This Study's Contribution: Despite an expanding literature on smallholder mechanization, few studies have integrated (a) deep grassroots observation of rural India, (b) experience from new models like KrishiHal Agritech, and (c) the application of spatial theory for service center optimization. Most reviews focus on logistics and technology, without engaging with the combination of demographic, institutional, and trust constraints that actual users face. This study brings several new contributions:

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- It offers a detailed empirical account from a region at the center of India's fragmentation crisis, informed by both survey and operational business data.
- It benchmarks Indian experience against a spectrum of global approaches, identifying critical factors for success and persistent shortcomings.
- It advances a spatially optimized service delivery model-anchored in the well-established central place theory-to overcome scale, cost, and access barriers, with policy implications for rural India and beyond.

3. Materials and Methods- 3.1 Research Design: This study adopts a **mixed-methods approach** to thoroughly investigate the constraints and opportunities for mechanization in regions marked by small and fragmented farms. The rationale is to blend statistical generalizability from quantitative data with the contextual depth and lived experience revealed by qualitative research. This allows both broad, comparative analysis and nuanced, grassroots understanding of the mechanization problem.

3.2 Study Area and Justification: Fieldwork was conducted in **Benipur and neighboring villages of Bulandshahr district, Uttar Pradesh-**a region portraying the acute norms and effects of fragmentation described in national statistics. The district is situated in the western part of Uttar Pradesh where the majority of farming households operate multiple small, non-contiguous plots. The study area was selected for its representativeness: high population density, prevalence of partible inheritance, nearly 80% of operational holdings below 1 hectare, a mix of irrigated and rainfed cropping systems, and dependence on staple food crops (wheat, paddy, sugarcane, and vegetables).

3.3 Data Collection: Quantitative Survey: A structured survey instrument was designed and pilot-tested. The questionnaire covered:

- Household composition and generational profile
- Total operational landholding and plot distribution (number, contiguity, size)
- Machinery ownership, access, and usage by type (tractors, tillers, threshers, combine harvesters, irrigation equipment, etc.)
- Financial information: capital available, credit access, recent machinery investment or rental outlays
- Labor patterns, service wait-times/costs and coping strategies during peak demand periods
- Awareness and perceptions of government schemes, cooperative initiatives, and custom hiring services

Sampling: 120 households were selected using a stratified random sampling method based on landholding size (<1 hectare; 1–2 hectares; >2 hectares), caste/community segment, and proximity to main access roads. Both moderately prosperous and highly marginalized households were included to capture variation.

Administration: Trained local enumerators conducted face-to-face interviews in the local language (Hindi). Interviews were scheduled for non-peak agricultural periods and lasted 45–60 minutes. Participation was entirely voluntary; informed consent was confirmed verbally and rechecked in writing.

3.4 Qualitative Data: In-Depth Interviews and Case Narratives: To supplement survey data, the research included:

- **Key informant interviews** with Custom Hiring Center (CHC) managers, machinery dealers, cooperative leaders, self-help group representatives, and local officials (block-level agriculture and revenue officers).
- **Focus group discussions** (FGDs) with women farmers, landless workers, and panchayat members to probe deeper institutional, gender, and community trust issues.
- **Case narrative development** for selected pilot adopters and non-adopters in the KrishiHal model, tracing their experience from service access to output.

All qualitative conversations were semi-structured, audio-recorded (with consent), and transcribed. A minimum of 22 primary informant interviews and 4 FGDs were conducted.

3.5 Data Analysis:

Quantitative Data:

- Descriptive statistics (mean, median, frequencies) for household, landholding, and mechanization variables.
- Cross-tabulation to test for relationships between fragmentation, machinery ownership, and service use.

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- **Inferential statistics:** Logistic regression models examined correlates of machinery ownership and custom hiring service usage, with predictors including land size, fragmentation index (number of plots divided by total land), credit access, and community group.
- Cost analysis: Calculation of input, labor, and mechanization expenses on a per-acre and per-crop-cycle basis.

Qualitative Data:

- Thematic coding: All transcripts were independently coded using NVivo for emergent themes (e.g., trust, gender bias, knowledge gaps, institutional strengths/weaknesses).
- Triangulation between survey findings, key informant insights, and business data.

3.6 Ethics and Data Security: All respondents were informed about the voluntary nature of participation, their right to skip questions or withdraw, and how data would be anonymized and secured. The research followed the journal's recommended ethics guidelines. All digital records were stored on encrypted drives, and identifying information was stripped from finalized transcripts.

3.7 Limitations:

- The sample area, while representative of large swathes of North India, may not fully capture diversity across agro-ecological zones.
- Self-reported economic data is subject to recall and reporting bias.
- Operational data from KrishiHal covers two years; while robust, it may not equate to a fullscale, long-term program evaluation.

4. Results- 4.1 Demographic and Landholding Patterns: The sample of 120 households reflected a broad cross-section of the rural population in Benipur and surrounding villages. Eighty percent identified as "small and marginal" farmers (<2 ha. The average household size was 5.3, comprising two to four adult earners, but nearly a third were either femaleheaded or reported adult male out-migration for work.

Table 1. Landholding Pattern and Fragmentation Metrics

Landholding Size	% of Households	Avg. Number of Plots	% Non-Contiguous Plots
<0.5 ha	27	5.7	94
0.5–2 ha	53	4.3	86
2–4 ha	15	3.2	75
>4 ha	5	2.1	59

The mean fragmentation index (plots per hectare) was 4.8 in the sample, highlighting the extreme dispersion of land even among comparatively larger holders.

4.2 Machinery Ownership and Service Access: Mechanization rates were low and made starker by high fragmentation:

- Only 12% of households owned any form of mechanized equipment; in nearly all cases, this was a basic, aging tractor shared with relatives.
- Use of hired services was ubiquitous during peak tillage and harvest (84% reported hiring at least once per season), but most described services as "expensive," "unreliable," or "delayed by demand bottlenecks.

Table 2. Machinery Ownership and Service Usage

Ownership/Access	<0.5 ha	0.5–2 ha	2–4 ha	>4 ha
Own tractor	0%	7%	12%	25%
Hires custom tillage	97%	95%	81%	76%
Hires combine harvest	24%	48%	27%	10%
Access to local CHC	21%	37%	42%	44%
Used digital rental service	1%	3%	8%	5%

4.3 Income, Cost, and Seasonality: Households' average gross annual agricultural income ranged from INR 48,600 (<0.5 ha) to INR 240,000 (>4 ha), but with wide variance owing to land fragmentation and dependence on external labor and services.

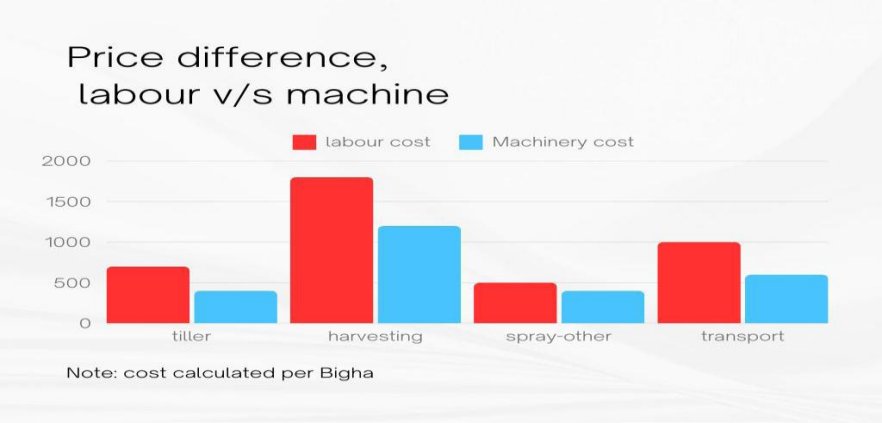
- Average mechanization cost per hectare (tillage, sowing, basic harvesting) was INR 4,720 for the smallest farmers, 22% higher than for farmers operating 2 hectares or more, primarily due to minimum service charge thresholds and repeated travel costs.
- Seventy-six percent reported being unable to pay for machine hire up front, often relying on crop mortgages or informal loans at high interest rates.

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- Seasonal bottlenecks for key mechanical interventions (especially wheat and paddy harvest) led to substantial delays. Close to 65% missed the "ideal" window during at least one crop season in the previous three years, often resulting in yield losses of 5%–15% as per selfreports.

Table 3. Typical Mechanization Costs (selected crop operations, INR/ha)

Operation	<0.5 ha	0.5–2 ha	2–4 ha	>4 ha
Ploughing (custom hire)	2,200	1,800	1,600	1,400
Sowing (manual)	1,700	1,600	1,250	1,050
Sowing (machine)	2,100	1,850	1,500	1,200
Combine harvest	3,800	3,200	2,800	2,100



4.4 Qualitative Insights: Voices from the Field: Detailed interviews and focus groups revealed the lived realities behind the numbers:

- A 63-year-old farmer with 5 scattered plots: "My land is in three directions. The thresher-wala charges extra each time he must move. Sometimes, if my turn is late, I lose money because the crop withers or rains come."
- Female focus group discussion: "We want to rent machines as a group, but who will manage the payments and repairs? Men are usually away, and CHC operators want cash in advance, which we cannot always arrange."
- Custom Hiring Center manager: "Many small farmers come to me at the same time, but I have only one machine. Priority goes to those who book early or offer higher advance. If the land is far, I charge extra, or sometimes refuse because the work is not worth the diesel."
- Youth respondent: "My uncle's farm was divided among four brothers last year. Now, none are able to buy or even always rent a tractor-each plot is too small, and our savings are less."

4.5 Impact of Social and Institutional Barriers:

- Forty-two percent reported exclusion from cooperative or government rental schemes due to illiteracy, lack of connections, or inability to navigate paperwork.
- Only 6% of female-headed households had ever used a digital rental platform, despite showing higher interest in group machinery use during focus groups.
- Access to credit was weak; fewer than one in five obtained formal credit, and even those relying on informal loans struggled with seasonal repayment.

4.6 The KrishiHal Pilot: Business and Outreach Insights:

- In its first season, KrishiHal served more than 200 clients, with demand outstripping available machinery during peak months.
- Despite posting clear and competitive prices, KrishiHal faced persistent default and delayed payment issues. Many small farmers preferred ad hoc repayment or barter (vegetables or crop share) over cash, creating management complexity.
- Where KrishiHal established a physical outlet with a trusted local manager, repeat patronage was markedly higher, and informal farmer groups emerged to pool bookings and share delivery costs.
- Narrative case: "I used the KrishiHal super-seeder for wheat for the first time. We pooled three families to book together, cut our costs, and turned to them again for rotavator service. Earlier, I lost one week for each operation, now we did both within four days."

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- Barriers remained: Women and the poorest lacked cash even for pooled bookings. Downtime for repairs and a lack of standby equipment led to rationing during demand spikes.
- Pooling only occurs when harvesting and sowing time of crops is similar of all the related fields (a crop sown early will harvest early as compared to other making it challenging for pooling and hiring machinery collectively)
- Smaller plot size due to fragmentation often poses challenges for a big machinery like combine harvestor to operate efficiently (eg.width of cutting blade of combine harvestor is 16+ foot making its turning area close to 40 foot, if plot width is less than 40 foot it can't operate there)
- Some farmers trade their field soil to local constructors for quick cash it leads to decrease in elevation height of farm plot making its accessibility for machinery a challenge.
- Social cohesion is also decreasing in the villages among the farmers communities which challenges the pooling, group, collective approaches of providing farm mechanization services effectively

4.7 Comparative Statistics (India, China, USA, Australia)

Indicator (Typical)	India < 2 ha	China (avg. 0.6 ha)	USA (avg. 179 ha)	Australia (>1000 ha)
% farmers using own machinery	11	17	94	98
% accessing service providers	39	53	100 (coops/ commercial)	100
Average mechanization cost (US$/ha)	82	48	37	41
% crop lost/missed due to delays	9.7	4.2	0.6	0.5
%surveyed reporting fragmentation	86	44	2	1

4.8 Statistical Analysis:

- Logistic regression (dependent variable: any machinery ownership) yielded significant results for consolidated land size ($p < .05$), access to formal credit ($p < .01$), and local presence of a rental outlet ($p < .05$).
- Fragmentation index had a strong negative association (OR = 0.68), holding other variables constant.
- Custom hiring service use increased with land size, male migration (presumably freeing family labor for ff-farm work), and membership in a cooperative or SHG.

5. Discussion- 5.1 Fragmentation as a Structural Barrier: The results from Benipur and adjacent villages reinforce the crucial role of land fragmentation as a deep structural barrier to both mechanization and broader rural transformation in India. Extreme subdivision was nearly universal in the sample: a typical household operated four to six separate pieces of land, many non-contiguous or differing significantly in size and fertility. This directly translated into higher per-unit costs for labor, machinery, and time, and underutilization of available technology. Such fragmentation echoes trends documented in other densely populated agrarian societies in Asia, notably pre-reform China and Vietnam (Zhao & Chen, 2020).

The impacts go well beyond simple economics. Fragmented landholdings contribute to uncertainty, risk aversion, and "reluctant investment syndrome" as observed in farmer interviews and focus groups. The absence of scale economies means that technology adoption-tractors, seeders, harvesters- remains aspirational rather than attainable for most smallholders. This effect is multiplied by high seasonality: demand spikes create bottlenecks in rental markets and often result in lost income as timely operations become unattainable.

5.2 Gender, Credit, and Access: Mechanization's Social Dimensions: The gendered nature of mechanization's exclusion is particularly striking. Women-increasingly primary agricultural laborers due to male outmigration-reported consistent difficulties accessing custom hiring services. Barriers included the expectation of upfront payment, lack of social networks to negotiate with service providers, and absence of digital literacy, all amplified by gender norms that restrict women's physical mobility and public decision-making. The data underscores the urgent need for restructuring service models to increase institutional

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inclusion-through women's self-help groups, female-run service centers, or community-level credit mechanisms.

Access to formal finance emerged as another primary determinant in both regression analysis and narratives. Without credit, even the modest cost of a pooled machinery booking was prohibitive for the poorest. Informal moneylenders filled some gaps, but at punishing rates and with high risk of default or land loss. By contrast, where KrishiHal or a local SHG managed a fund or group booking, costs dropped and repayment compliance rose. These results support the imperative for affordable, flexible, community-led finance as an enabler of mechanization (Biggs et al., 2016; FAO, 2022).

5.3 Institutional Weakness and Trust Deficit: A critical limiting factor across interventions-public, private, or mixed-was trust. Custom Hiring Centers were far more effective, and repeat patronage higher, when managed by a locally trusted individual (often recommended by a panchayat or SHG). Farmers across castes, genders, and age groups expressed reluctance to engage with "outsider" providers or digital-only platforms: "If we have a problem, whom do we call? If our money is gone, who will help?" These findings echo failuresin African and some Indian pilots where machinery rings or rental clubs rooted in distant or elite networks collapsed due to weak social embeddedness and poor conflict resolution (Diao et al., 2019; MoA&FW, 2021).

5.4 Why Current Policy Approaches Fall Short: Despite noble intentions, current policy frameworks demonstrate limited penetration in the worstaffected districts:

- **CHCs and Subsidies**: While CHCs have spread in the last five years, in this study's region less than 40% of smallholders could reliably access their services-with the poorest and most remote least served. Many cited a perception that connections, corruption, or advance payments determined access.
- **Private sector rental models**: While digital and platform cooperatives have succeeded in commercialized or peri-urban belts, field results show minimal direct impact for the smallest, most fragmented, least tech-savvy rural populations.
- **Cooperatives**: In areas with high caste or community heterogeneity, multipurpose cooperatives broke down over management or profit-sharing disputes.
- **Women and marginal groups**: Consistently excluded in practice despite inclusion on Paper-a result confirmed in the present fieldwork and wider literature (Agarwal, 1994; FAO, 2022).

5.5 International Benchmarking: Lessons and Contrasts: Global comparison clarifies the centrality of aggregation, institutional support, and governance:

- **China**: Government-enabled land swaps and co-management allowed machinery cooperatives to serve villages with holding sizes similar to Benipur, but with lower fragmentation and higher institutional density (Zhao & Chen, 2020).
- **USA/Australia**: Land market maturation and strong regulatory frameworks enabled mechanization to reach even formerly scattered smallholder populations; farm consolidation accompanied by robust local governance kept trust high and access broad (USDA, 2021; ABARES, 2020).
- **Europe**: Machinery syndicates and rental rings thrive where local government provides backstopping, dispute resolution, and technical training.

5.6 Central Place Theory and Krishi Seva Kendra (KSK) Model: The KrishiHal pilot, when analyzed alongside central place theory, suggests a scalable pathway for rural mechanization even in highly fragmented contexts. Spatial modeling allows for:

- **Strategic location of service hubs** to minimize time and travel costs for clusters of villages.
- **Aggregation of demand**, reducing per capita costs for machine purchase, maintenance, and operator wages.
- **Physical centers** staffed by trusted, locally nominated agents-ensuring both accountability and conflict resolution.
- **Digital enablement** (where feasible) to enhance booking, payment, inventory tracking, and advance scheduling-driving efficiency and transparency.

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KSKs, if seeded in regions of high fragmentation with robust linkage to SHGs, panchayats, and local co-ops, would not only lower per-unit machinery costs but foster the social trust critically needed for uptake and sustainability. Experiences where KrishiHal involved local SHGs or panchayat members as partners showed faster scaling, higher usage (even by women and poorer households), and better payment discipline.



Central service area catering 6 adjacent regions

5.7 Policy, Poverty, and the SDGs: Meeting SDG 2 ("Zero Hunger") and SDG 1 ("No Poverty") in rural India is inseparable from resolving land fragmentation's impact on mechanization. The pilot evidence and field survey both show that subsidy-based, 'top-down' or distant digital models will ave limited traction unless they directly address:

• The fixed logistical and social costs of fragmentation,
• The need for local mediation/trust between providers and users,
• Flexible financial products (including crop-backed payment, group credit, or phased repayments),
• Gender, caste, and literacy-related barriers to access. Evidence points toward the need for public–private-community partnerships. Policy (financial, legal, digital) must support start-up costs and risk-sharing for KSKs; local institutions must anchor trust and grievance redress; and digital tools must be adapted for inclusion, not exclusion.

5.8 Limitations and Areas for Further Research: This study is limited by its regional sample and the two-year window of business data. North-central Uttar Pradesh represents one important locus of fragmentation, but results may differ across soil, rainfall, and sociocultural settings-for example in tribal, hilly, or irrigated cash crop areas. The field data, though triangulated, remains reliant on self-report for some variables (e.g., crop loss and finance). Further, the KSK model, though promising, requires rigorous multi-site piloting and longterm evaluation to capture issues of scale, sustainability, and equity.

5.9 The Path Forward: The findings underscore that a new generation of rural service models-spatially optimized, socially rooted, and flexibly financed-offers hope for breaking India's persistent mechanization trap. Such models, grounded in principles of central place theory but sensitive to the realities of caste, gender, credit, and trust, may finally bridge the gap between "best practice" and "common practice" in rural India.

6. Policy Recommendations- Building upon field evidence, operational business experience, and lessons from international practice, the following recommendations aim to enable sustainable mechanization for fragmented smallholders in India:

6.1 Promote Voluntary Land Pooling and Consolidation:

- Launch district-level pilots with fiscal and legal incentives for voluntary land pooling.
- Develop clear frameworks for joint ownership, profit-sharing, and conflict resolution, drawing upon successful models from China and Vietnam.
- Facilitate secure contracts, land records digitization, and support for legal services to ensure transparency for all participants.

6.2 Expand and Professionalize Custom Hiring Centers (CHCs):

- Transition from sporadic, public sector-managed CHCs to a mixed public-private-community partnership model for village-level implementation.
- Subsidize start-up capital and initial operation costs, but ensure centers operate with a business plan that encourages efficiency, accountability, and down-the-line sustainability.
- Integrate mobile and digital booking systems to extend access to marginalized villages and enable price transparency.

6.3 Innovate Rural Finance Mechanisms:

- Provide targeted, needs-based credit through public sector banks, cooperatives, and microfinance institutions for machinery rentals, repairs, and group purchases.
- Implement flexible repayment structures-allowing for in-kind, deferred, or harvest-linked payment plans.
- Develop risk-sharing apparatuses (guarantees, crop insurance tie-ins) to mitigate default and enable confidence in lending for mechanization.

6.4 Strengthen Local and Social Institutions:

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- Support the creation and technical training of women's self-help groups, youth clubs, and panchayat committees specifically for managing machinery pools and KSKs.
- Invest in community mobilization and digital literacy drives targeting excluded groups.
- Empower grassroots organizations to serve as intermediaries for planning, grievance redressal, and the adaptation of new service models.

6.5 Institutionalize Central Place Theory in Service Design:

- Use spatial analytics to site Krishi Seva Kendras (KSKs) for maximal geographic access and equity.
- Develop model contracts and operational blueprints for "multi-village" service hubs, ensuring the involvement of local leaders in governance and dispute resolution.
- Link KSKs to input supply, extension advice, and market platforms for integrated service provision.

6.6 Establish Robust Monitoring and Support Systems:

- Fund third-party monitoring, ongoing research, and adaptive management of new service models.
- Encourage iterative design, rapid prototyping, and multi-year evaluation for policy pilots.
- Create simple reporting tools so that users and operators can offer feedback for scaling-up or course correction.

7. Conclusion- This research demonstrates that land fragmentation in India is not only a technical and economic challenge but a complex, interwoven social and institutional barrier to rural transformation. Evidence from Benipur and global comparisons confirm that the dysfunctional cycle of fragmented ownership, low mechanization, and rural poverty cannot be broken by piecemeal or top-down interventions alone.

Expanding sustainable mechanization for smallholders requires bold, context-sensitive innovation: spatially optimized, locally governed service models (Krishi Seva Kendras), voluntary land consolidation with legal and financial safeguards, and targeted, flexible rural credit. Only by integrating modern technology, grassroots organization, gender equity, and social trust can India's most excluded rural households achieve the productivity, resilience, and dignity promised by decades of policy rhetoric.

The KSK model, grounded in spatial theory and real-world pilot experience, offers a viable, scalable pathway to address fragmentation. Its promise depends on deep local anchoring, robust public- private-community partnerships, and a commitment to inclusive monitoring and continuous improvement. Policy, institutional, and social innovation-working together-can shape a new rural future that is both equitable and sustainable.

8. Supporting Statements-

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