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Mechanization of Small-Scale Agriculture in India: Lessons for Enhancing Smallholder Access to Agricultural Machinery

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***Abstract*— Despite its significant potential to enhance productivity, labor efficiency and sustainability, agricultural mechanization in developing economies dominated by smallholder farming systems remains markedly underdeveloped. This underutilization is largely driven by the persistent perception that mechanization is economically unviable and technically unsuitable for fragmented and small-scale agricultural operations. The present paper critically analyzes the evolution of agricultural mechanization in India and identifies institutional and technological pathways that can enable effective access to farm machinery for small and marginal farmers. Employing a narrative analytical approach, the study synthesizes evidence from policy documents, secondary datasets and peer-reviewed literature to examine long-term trends in mechanization intensity, farm power availability, landholding structures and service-based delivery models. The analysis indicates that: (i) mechanization within smallholder systems follows a gradual, cumulative and path-dependent trajectory that is resistant to abrupt technological leapfrogging and purely technocratic solutions; (ii) sustainable mechanization growth must be rooted in localized manufacturing, maintenance and service ecosystems that strengthen self-reliance and reduce dependency on capital-intensive imports; (iii) the development and dissemination of scale-appropriate, affordable and multifunctional machinery are essential for improving adoption under conditions of land fragmentation; and (iv) the successful operationalization of farm machinery depends on integrated, farmer-centric policy frameworks supported by institutional coordination, access to credit, capacity building and custom hiring infrastructure. The study derives policy-relevant insights for designing inclusive mechanization strategies in countries characterized by small-scale farming and constrained rural labour markets, emphasizing the need to align technological innovation with social, economic and agro-ecological realities.**

***Keywords*—Agricultural Mechanization, Small-Scale Agriculture, Smallholder Farmers, Farm Machinery, Multifunctional Machinery.**

I. INTRODUCTION

Agricultural mechanization constitutes a vital component of agrarian economic transformation and plays a decisive role in enhancing agricultural labour productivity, thereby contributing to sustainable food security and the alleviation of rural poverty. Empirical evidence indicates that mechanization is considerably more advanced in countries characterized by large-scale agricultural systems. This dominant development paradigm has compelled countries with predominantly small-scale agriculture to pursue farm consolidation as a prerequisite for mechanization, rather than adopting scale-appropriate mechanization through the use of suitably sized machinery on small and fragmented landholdings (Van Loon et al., 2020). Conversely, agricultural scaling-up must be pursued in parallel with farmland-scale management and agricultural service-scale management, both of which require long-term policy commitment and substantial resource investment (Woltering et al., 2019).

In recent years, renewed scholarly attention has been directed toward the untapped potential of agricultural mechanization, particularly in developing countries dominated by smallholder farming systems. Within the broader agenda of rural revitalization, agricultural mechanization has emerged as an effective instrument for restructuring rural–urban labour dynamics (Belton & Filipski, 2019; Qiao, 2017; Felipe et al., 2016), fostering specialization and division of labour within agricultural production systems (Zhang et al., 2017) and symbolizing the modernization of agriculture (Lu, 2009). Furthermore, mechanization has been recognized as a means to reduce rural–urban income disparities and to expand agricultural operational scales and production efficiency (Takeshima et al., 2020).

When judiciously applied and aligned with local agronomic practices, agricultural mechanization can also contribute to climate change mitigation by conserving natural capital and enhancing environmental sustainability while simultaneously increasing food production (Elagib et al., 2019). In addition, mechanization functions as a critical driver of agricultural commercialization and competitiveness within agri-food markets (Nepal & Thapa, 2009).

Despite these multidimensional benefits, countries characterized by small-scale agriculture have yet to fully harness the potential of mechanization, largely due to the prevailing misconception that such advantages can only be realized through large-scale mechanized systems. To address this constraint, the concept of scale-appropriate mechanization has gained increasing attention in several African and Asian countries. For instance, in Nepal, the adoption of small-scale mechanization strategies has enabled smallholder farmers to access affordable machinery, facilitated mechanized operations in hilly and geographically constrained terrains and significantly improved farm productivity (Paudel et al., 2019). Similarly, in China where agricultural production remains predominantly small-scale the widespread use of small tractors and appropriately sized machinery has effectively met the operational requirements of smallholder farmers (Aryal et al., 2021).

With only approximately 2.5 percent of the world's elemental composition and 4 percent of the world's renewable water supply, India has to sustain around 18 percent of the world's total population and 17 percent of the world's livestock (Mehta et al., 2014; Maan and Chaudhry, 2019). The agricultural sector plays an integral role within the Indian economy accounting for an approximate 18.2 percent of total GDP and total exports valued at Rs. 51.9 billion FY 2024-25 (PTI, 2025). The level of production within the country has reached record highs that can serve as benchmarks for comparative productivity, including food grains of 357.73 million tons, oilseeds of 43 million tons, pulses of 256.83 lakh tons, cotton at 297.24 lakh bales (170 kg each). Of the two most influential strategies for the continued rapid growth of agricultural productivity in the country, the first is the need for the government to implement significant modifications to the agricultural supply-side infrastructure through governmental and agricultural occupational policies regarding land and labor; the second measures the need to fill the significant gap created between the mass migration from rural areas to urban centre locations.

II. Materials And Methods

The present study adopted a narrative review approach to examine the historical evolution, current status and future trajectory of agricultural mechanization in India, with particular emphasis on its implications for small and marginal farmers. In this review of literature, many research papers and documents from the Ministry of Agriculture and Farmers' Welfare (MoAFW), Government of India, Indian Council of Agricultural Research (ICAR) and reports of the Planning Commission/NITI Aayog were considered (Tiwari et al., 2019; Mehta et al., 2013; Sarkar, 2020; Kumar & Kumar, 2021; Mehta et al., 2023). In addition, data and policy briefs from Agricultural Census of India, All India Coordinated Research Project on Farm Implements and Machinery (AICRP-FIM), Vikaspedia: Agriculture and other government and non-government digital repositories were thoroughly analyzed and synthesized to draw meaningful conclusions and present a comprehensive review on the topic "Agricultural Mechanization in India: Status, Challenges and Future Prospects."

Size of Land Holdings and Mechanisation

The average size of land holdings in 2011 was 1.16 ha with only 0.7 per cent (1.0 million) consisting of farms of more than 10 ha but constituting about 11 per cent of the cultivated land while the farms of less than 1 ha (over 67 per cent) constitute about 22 per cent of the cultivated land – the rest of the farms are in the intermediate range with the largest proportion being medium farms (4 to 10 ha) and semi-medium farms (2 to 4 ha) which cultivated 24 per cent each of the total cultivated land in 2011 (Figure 1). Thus, the three categories comprising large, medium and semi-medium farms (20.7 million farm holdings) cultivate between them 56 per cent of the cultivated land – it is apparent that these three categories of farmers have been instrumental not only for the success of agricultural mechanisation in India but for the overall success of the Green Revolution and the remarkable transformation of the food security situation over the past 50 years.

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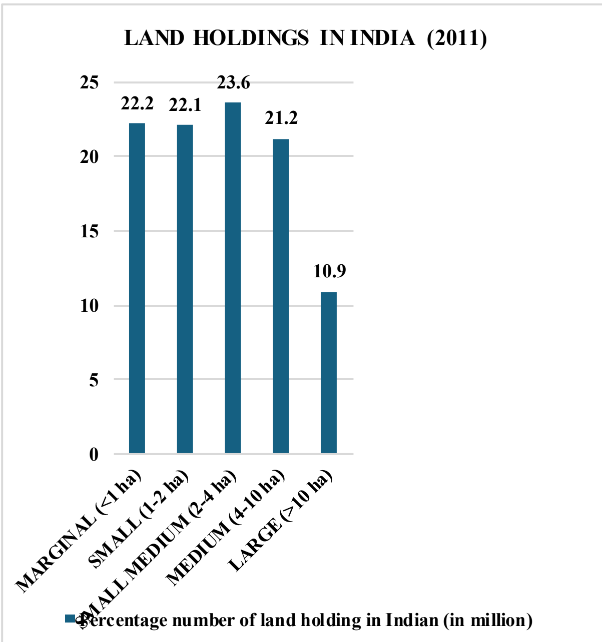

Figure 1 Percentage Number of Land holdings in India

Source: (MOA, 2013)

In 2011, the mean size of the operational holding in India was 1.16 hectares, demonstrating the highly fragmented agrarian structure of the country. The share of large farms (more than 10 hectares) was only about 0.7 per cent of the total holdings (approximately 1 million units), but they controlled almost 11 per cent of the cultivated land. In contrast, marginal holdings (less than 1 hectare) accounted for more than two-thirds of the total holdings but only produced about 22 per cent of the total agricultural area. The remainder of the holdings were classified into intermediate sizes, with semi-medium (2-4 hectares) and medium (4-10 hectares) holdings managing approximately 24 per cent of the total cultivated area (Figure 1). In total, large, medium and semi medium holdings with a total of about 20.7 million holdings, accounted for the management of approximately 56 per cent of the cultivated area. The concentration of operational holdings within these categories has enabled them to be instrumental not only in the significant adoption of farm mechanisation but also in the overall accomplishments of the Green Revolution, thereby increasing India's food capacity for the last 50 years and supporting food security.

While inheritance laws cause ongoing fragmentation of land holdings throughout many states in India, Punjab does not fit this pattern.

Because of the high level of mechanisation and productivity in agriculture in Punjab, the state has seen consistent declines in marginal holdings since the beginning of mechanised agriculture; the percentage of total cultivated area occupied by marginal holdings decreased from 38 percent in 1971, 27 percent in 1991 and 12 percent by 2001, accounting for only 2.4 percent of all cultivated land in Punjab (less than one-third of all land cultivated in Punjab). Semi-medium, medium and large holdings captured 22 percent 43 percent and 27 percent respectively in 2001 and accounted for over 92 percent of the state's agricultural area combined. The same phenomenon has been observed in Haryana and throughout other parts of the country. One factor contributing to this change is rural to urban migration. Many land-holding farmers are moving into cities in search of employment opportunities, but continue to own their farms and farm land; their relatives or tenants then cultivate the land for them while they are gone. This means the actual number of farmers farming their land is much lower than would be obtained from statistics based on owner occupied land holdings. In addition, many marginal and small farmers are working outside their communities to earn income and renting their farmland; this practice has allowed for the consolidation of farm sizes into larger operations. In addition, the land is frequently rented to farmers that own tractors thus, providing farmers that rent the land with the equipment needed to farm it.

Agriculture mechanisation pre-Independence

India has had a rich legacy of agriculture through its long-standing civilization. Originally, agriculture was linked to collecting things from nature such as food, clothing and shelter and using stone tools to plant or collect food materials, etc. Over time as agriculture became more civilized (in accordance with the development of the Vedic Period), there were changes made to tools for agricultural purposes. Animals became domesticated for agricultural work (in addition to being used for hunting, fighting and so on) and the ability to utilize animal-powered implements/instruments gave farmers the ability to prepare fields, plant crops, gather produce (grain and other crops) and transport (grain and produce). The use of these animal-powered tools (indigenous ploughs and bullock-driven implements and tools) enabled farmers to improve their farm efficiencies and reduce their labour input as far as field operations are concerned. Many of these simple animal-powered tools will be the backbone of agriculture for many years in rural India.

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Modern agriculture saw the introduction of mechanization and agricultural technology (such as tractors and improved mechanical equipment) in the 18th and 19th Century under the colonial administrations; the use of these technologies was limited to certain areas of the country and to large estates. The spread of mechanisation in agriculture was severely limited due to small farm sizes, low levels of financial investment into the farm sector by farmers and a lack of institutional support for farmers.

Animal power was the primary source of power for agricultural work; a pair of draught animals could provide about 1,200 to 1,800 hours of farm work annually. As of the early 1970s, approximately 69 percent of all agricultural power in India was still from animal power. This statistic reflects how long farmers have relied upon biological sources of energy in agriculture.

Agricultural production prior to independence was mostly completed with bullock powered ploughs, wooden levellers and soil working tools used for preparing the land; hand tools such as hoes, spades, sickles, crowbars and pick axes were used for harvesting and weeding, while bullock carts were the main transportation methods of agricultural produce and inputs.

In irrigated areas, traditional irrigation systems such as Persian wheels and manually-operated lifting devices to transport water were commonly used. Thus, the agricultural technology of the period was characterized by low capital-intensity, along with heavy reliance on human and animal force.

Agriculture mechanisation post-Independence

In India, agricultural mechanization has changed dramatically over the last several decades as a result of advances in technology, changing demographics and changing socio-economic conditions. Farm mechanization is one of the greatest engineering accomplishments of the twentieth century due to its ability to increase productivity and reduce the amount of labour required to produce food on a large scale. In India, mechanization has evolved from reliance on biological sources of power to reliance on mechanical and electric sources of energy.

The primary source of farm power in India has historically been draught animals, which produced between 1,200 and 1,800 hours of work annually per pair of animals. As a result of increasing levels of mechanization, the use of draught animal power has declined significantly, to approximately 300 to 500 hours annually and is now primarily used for limited types of work, primarily tillage, sowing, inter-cultivation and rural transport.

Consequently, tractors, power tillers and self-propelled machinery have steadily replaced draught animal power, especially in areas suffering from severe labour shortages and rising wage rates. Increasing needs for timely agricultural operations and higher cropping intensity have increased the reliance on mobile mechanical power sources, particularly tractors, power tillers, reapers and combine harvesters.

Evidence of increasing mechanisation is reflected by the rapid growth of power tiller use, with sales of power tillers increasing from less than 18,000 in 2004–05 to over 45,000 in 2016–17 (Rath, 2024). The use of tractors continues to be the most common form of mechanisation for land preparation across the majority of states. In addition, the level of tractor-based power available varies by geographic region according to cropping systems and terrain. The total amount of tractor power available per hectare has grown substantially over the past fifty-three years, from only 0.007 kW per hectare in 1960–61 to an estimated 1.03 kW per hectare in 2013–14, with projections estimating that this will grow to nearly 3.74 kW by 2032–33. This increase in the use of farm power has resulted in not only decreased labour costs and faster turnaround times between crops but also higher yields and greater intensification of cropping patterns (Tiwari et al., 2019).

The levels of mechanisation in agriculture vary significantly from one operation to the next across the country. Currently, there are estimates suggesting that mechanisation accounts for approximately 30-40 percent of tillage and seedbed preparation, approximately 30 percent for seeding and planting, approximately 35-45 percent for plant protection and approximately 60-70 percent for harvesting and threshing. Additionally, spatial disparities exist. The northern states of Punjab, Haryana and the western region of Uttar Pradesh are exhibiting very high overall levels of mechanisation (70-80%) and even up to 80-90 percent for crops produced in rice-wheat systems.

The agricultural machinery industry in India has experienced rapid growth within the last several years, driven by a combination of increased private investments and government incentives for mechanisation. Modern technologies like drones are utilized throughout many regions of India to perform functions such as spraying of crops, application of nutrients, monitoring for pests, estimating yields and managing crops with accuracy.

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In addition, technology is being developed for the automation of repetitive labour-intensive activities including weeding, spraying and harvesting horticultural crops using robotics and artificial intelligence; however, currently, these developments are at best being used on an experimental basis or in the cultivation of commercial-scale quantities of produce (Mehta, 2013).

Future Prospects of Agricultural Mechanization in India

Farm power availability in India has shown a consistent upward trend, increasing from about 0.28 kW per hectare in 1960–61 to nearly 1.83 kW per hectare by 2010–11 and is projected to reach approximately 4.81 kW per hectare by 2032–33. At the same time, the proportion of agricultural workers in the total workforce is expected to decline substantially, falling to about 49.9 per cent by 2033 and further to nearly 25.7 per cent by 2050, which is likely to intensify labour scarcity in rural areas (Kumar & Kumar, 2021). These demographic and structural changes strongly indicate that future agricultural growth will increasingly depend on higher levels of mechanization and automation.

Rapid technological advancement, supportive regulatory frameworks and growing emphasis on sustainable farming systems are expected to shape the next phase of mechanization in India. Emerging digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics and robotics are anticipated to enable precision agriculture by facilitating real-time monitoring of crops, soil and weather conditions, thereby improving decision-making, optimizing input use and enhancing productivity (E, 2024). Such technologies can significantly reduce wastage of water, fertilizers and pesticides while increasing operational efficiency.

Mechanization for Climate Resilience and Sustainability

Future mechanization strategies must align closely with climate-smart agricultural practices to mitigate the adverse impacts of climate variability. Mechanized operations can support conservation agriculture through minimum tillage, residue management, efficient irrigation systems and precision input application, thereby improving soil health and water-use efficiency (Ahmad et al., 2020). In addition, integration of renewable energy sources, particularly solar-powered machinery and agrivoltaics systems, offers promising opportunities to combine agricultural production with clean energy generation, reducing dependence on fossil fuels and enhancing long-term sustainability (Tiwari et al., 2019).

Economic and Institutional Challenges

Despite promising technological prospects, several constraints may hinder widespread mechanization, particularly among small and marginal farmers. High initial investment costs, limited access to institutional credit and fragmented landholdings continue to restrict machinery ownership (Sarkar, 2020). Moreover, effective utilization of advanced equipment requires adequate technical training, extension services and maintenance infrastructure, which remain insufficient in many rural regions (Karnani, 2022). Strengthening digital literacy and extension networks will therefore be critical to ensuring that farmers can fully benefit from new technologies.

Digital platforms and mobile-based applications are expected to play a pivotal role in improving access to mechanization services by connecting farmers with machinery owners, repair services and input suppliers. Such digital ecosystems can facilitate real-time service booking, reduce transaction costs and improve transparency in custom hiring arrangements (Cheruku & Katekar, 2021).

Mechanization Models for Smallholder Dominated Agriculture

Given that Indian agriculture is predominantly characterized by small and fragmented holdings, future mechanization must prioritize scale-appropriate and affordable technologies. Lightweight, multipurpose and low-horsepower machines are more suitable for small plots and can significantly improve labour productivity without imposing excessive financial burdens. The design and dissemination of equipment suited to small and marginal farmers will remain a central policy priority.

At the same time, large commercial farms and plantation systems require advanced, high-capacity machinery to ensure efficiency, quality control and profitability. Plantation sectors such as tea, spices, horticulture and commercial fruit estates increasingly rely on specialized mechanized systems for harvesting, grading and processing, highlighting the need for differentiated mechanization strategies tailored to diverse farming structures across the country.

Integration of Mechanization with Traditional Practices

While mechanization often introduces modern production methods, it is essential that technological adoption does not undermine locally adapted farming practices that have evolved over generations.

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Future mechanization frameworks should therefore aim to integrate modern equipment with traditional cropping systems, ensuring that mechanized solutions remain compatible with local ecological and cultural contexts. This approach can promote smoother technology adoption and reduce resistance among farming communities.

Expansion of Custom Hiring and Service-Based Models

Service-oriented mechanization models are expected to become increasingly important in achieving economies of scale in smallholder-dominated regions. Custom Hiring Centres (CHCs), farmer producer organizations (FPOs) and app-based machinery rental platforms enable farmers to access expensive equipment without bearing full ownership costs. These institutional arrangements facilitate timely farm operations and enhance machinery utilization rates, thereby improving overall cost efficiency (Mehta et al., 2023).

Precision and Site-Specific Farming Systems

Future mechanization is likely to emphasize site-specific management through sensor-based technologies, automated guidance systems and farm management software. Tools for real-time soil moisture monitoring, nutrient assessment and pest surveillance will support precise input application, reduce environmental impacts and improve crop performance. Such systems are particularly relevant for addressing regional variability in soil and climate conditions across India.

III. Conclusion

Agricultural mechanisation in India has emerged as a vital component of sustainable agricultural growth in the context of declining farm sizes, rising labour shortages and increasing climate variability. Although farm power availability has improved substantially over the decades, the adoption of mechanisation remains uneven, particularly among small and marginal farmers who constitute the majority of the farming population. Technological advancements such as precision agriculture, sensor-based input management, artificial intelligence and renewable energy–driven machinery offer significant potential to enhance productivity, resource-use efficiency and climate resilience. However, high initial investment costs, limited access to credit, inadequate training and poor availability of appropriately scaled machinery continue to constrain adoption. Institutional innovations such as custom hiring centres, machinery banks and digital service platforms can play a crucial role in improving access to mechanisation through shared-use models.

Therefore, future mechanisation strategies must be inclusive, region-specific and farm-size sensitive, integrating modern technologies with local practices. A coordinated policy, financial and extension framework is essential to ensure that mechanisation contributes not only to higher productivity but also to equitable and environmentally sustainable agricultural development.

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