AATCC Review

28 June 2025: Received
16 August 2025: Revised
24 August 2025: Accepted
23 September 2025: Available Online

https://aatcc.peerjournals.net/

Original Research Article

Open Access

Status of agricultural mechanization in himachal pradesh: a comprehensive assessment of power sources, challenges, and policy pathways

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ABSTRACT

Agricultural mechanization in the hill and mountain ecosystems of India plays a vital role in reducing drudgery, enhancing productivity, and ensuring timeliness in farming operations. Himachal Pradesh, a predominantly agrarian state located in the north-western Himalayas, offers a distinctive case where steep topography and fragmented landholdings shape the mechanization landscape. The present paper compiles and analyses state-level data related to land use, operational holdings, power sources, farm machinery population, and labour economics to evaluate the prevailing status of mechanization. The findings reveal that the state continues to rely heavily on animal and manual power, which together account for nearly 78% of total farm power, while mechanical sources contribute only about 22%. The mechanization intensity (MI) is estimated at 1.34 kW/ha well below the national average of 2.50 kW/ha indicating considerable potential for improvement.During the course of the study, challenges emerged due to inconsistencies in data availability, variation in regional record-keeping, and the absence of disaggregated information for hill-specific operations. The difficult terrain and scattered machinery records further limited the ability to establish precise spatial linkages between power use and landholding patterns. Despite these limitations, the study offers an important and timely contribution by presenting a consolidated picture of the mechanization scenario in Himachal Pradesh. It identifies key bottlenecks such as the lack of Custom Hiring Centers (CHCs), weak service networks, and the limited policy emphasis on terrain-suitable machinery. Beyond identifying the existing gaps, the paper calls for targeted policy actions that encourage the use of renewable energy-driven power sources, promote small-scale and terrain-adaptive technologies, and foster green mechanization approaches aligned with environmental and social sustainability goals. The outcomes of this study extend their relevance beyond Himachal Pradesh, offering valuable perspectives for other hill and mountain regions of India, and enriching the ongoing dialogue on achieving sustainable mechanization in topographically challenging farming systems.

Keywords: *Agricultural mechanization, Hill farming; Himachal Pradesh, Farm power, Mechanization intensity, Custom Hiring Centers; Mountain agriculture; Sustainable mechanization; Terrain-adapted machinery.*

1. Introduction

Agriculture in India continues to serve as a cornerstone of the rural economy, providing livelihood to nearly 45% of the population [1]. Within this national framework, Himachal Pradesh, a predominantly hilly and mountainous state located in the western Himalayas, presents a unique agricultural landscape characterized by small and fragmented holdings, varied agro-climatic zones, and diverse crop patterns. The total geographical area of the state is 55,673 km^2, of which 547,556 hectares constitute the net sown area. This area is characterized by a large number of operational holdings belonging to the marginal category, cultivating small landholdings of less than one hectare. [2]. In such topographically challenging conditions, mechanizationhas emerged as a critical factor in improving agricultural productivity, reducing drudgery, and optimizing input use efficiency.

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DOI: https://doi.org/10.21276/AATCCReview.2025.13.04.507

However, unlike the plains of Punjab and Haryana, where large-scale mechanization has transformed farming practices, mechanization in Himachal Pradesh has remained limited due to the mountainous terrain, small landholdings, and low purchasing powerof farmers [3]. Despite these limitations, the state has made considerable strides in adopting small-scale and power-operated equipment such as power tillers, mini threshers, and small-scale irrigation pumps, suited to its hill agriculture context [4]. The agricultural sector of Himachal Pradesh is primarily dominated by cereal crops such as wheat, maize, barley, and paddy, along with high-value horticultural crops like apple, plum, peach, apricot, cherry, and citrus fruits. The state's horticulture-based economy has been a driver of rural income and mechanization demand, particularly in fruit harvesting, grading, and post-harvest operations [5&6]. Despite this, the mechanization intensity in the state remains low, recorded at approximately 1.25 kW/ha, compared to the national average of 2.5 kW/ha [7].

A key feature of Himachal's mechanization landscape is the high reliance on animal and manual power, with draft animals still used for ploughing and tillage operations. The mechanization index, therefore, reflects a hybrid system combining traditional and modern power sources [8].

The low penetration of tractors and power tillers underscores the need for region-specific mechanization strategies, especially those focusing on light-weight, self-propelled, and renewable-energy-powered machinery suited for hill farming [4]. Further, the lack of Custom Hiring Centers (CHCs) in the state, as indicated by the absence of such facilities across all 12 districts, has exacerbated challenges for small and marginal farmers who cannot afford individual ownership of machines. CHCs can play a pivotal role in improving access to machinery, lowering per-unit costs, and encouraging collective mechanization [9]. In alignment with the national initiatives, such as the Sub-Mission on Agricultural Mechanization (SMAM, 2014 onwards) under the National Mission on Agricultural Extension and Technology, Himachal Pradesh has also sought to promote farm mechanization suited to small and hilly terrains. However, despite these policy efforts, the progress in the state remains modest when compared with its neighbouring plains states. For instance, the tractor density in Himachal Pradesh is approximately 44 tractors per 1,000 hectares, significantly lower than Punjab (162 tractors per 1,000 ha) and Uttarakhand (72 tractors per 1,000 ha) [7]. This disparity reflects the strong influence of topography, land fragmentation, and purchasing capacity on mechanization adoption. While several national and regional studies have evaluated mechanization trends in the plains regions of northern India, limited empirical analysis exists for hill ecosystems such as Himachal Pradesh, where terrain complexity, small landholdings, and accessibility issues constrain conventional mechanization approaches. The present study, therefore, addresses this research gap by providing a comprehensive assessment of the mechanization status, power source distribution, and institutional limitations specific to Himachal Pradesh's hill farming systems.

This paper aims to analyse thestatus, structure, and challenges of farm mechanization in Himachal Pradesh using state-level data. It evaluates the population of farm machinery and power sources, examines farmer categorization, and assesses mechanization gaps across districts. By doing so, it seeks to highlight potential pathways for improving mechanization through technological adaptation, policy intervention, and renewable energy integration, key pillars for ensuring sustainable agricultural growth in hilly ecosystems.

2. Materials and Methods

The present study was undertaken for the state of Himachal Pradesh, located in the north-western Himalayan region of India, extending between 30°22′40″ to 33°12′40″ N latitude and 75°45′55″ to 79°04′20″ E longitude (Fig. 1). The state is administratively divided into 12 districts and covers a total geographical area of 55,673 km^2. Agriculture in the region is predominantly characterized by small and fragmented holdings due to its undulating and mountainous terrain. The net sown area of the state is about 547,556 hectares, which is spread across altitudinal zones ranging from 350 m to 6,000 m above mean sea level, providing a wide range of agro-climatic conditions suitable for both cereal and horticultural crop cultivation [2]

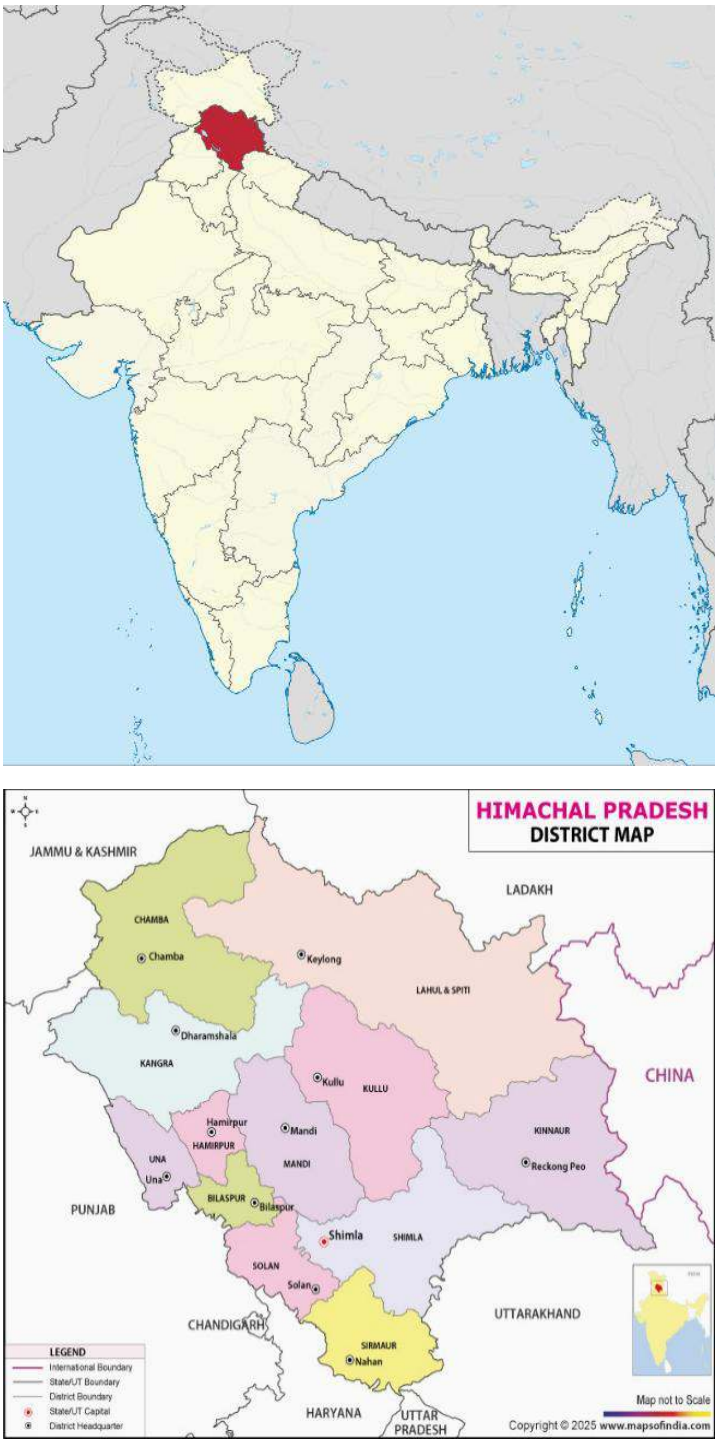

Figure 1. Map showing the location of Himachal Pradesh, India

To capture temporal and spatial variations in mechanization, data from 2015 to 2025 were analysed to assess decadal trends in farm power availability, machinery density, and adoption patterns. The study primarily relied on secondary data collected from authentic institutional sources, including the Department of Agriculture, Himachal Pradesh (Statistical Report 2024–25), the Statistical Abstract of Himachal Pradesh (2021–22), the Agricultural Census (2015–16 and 2020–21), and ICAR Mechanization Index Reports (2022). The specific datasets on tractor and power tiller counts, along with other machinery inventories, were sourced from the Department of Agriculture Statistical Report 2024–25, ensuring updated state-level accuracy.

The methodological framework followed a structured sequence from data collection to interpretation illustrated in Figure 2. The process included:

1. Data Collection (official statistical records, census reports, literature sources)
2. Variable Selection (farm size, power source, machinery type, and labour cost)
3. Data Analysis (mechanization intensity, percentage distribution, trend analysis)
4. Interpretation and Mapping (district-wise mechanization pattern and comparative evaluation).

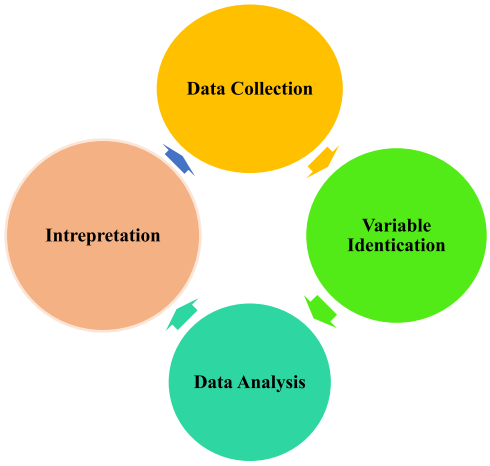

Figure 2. Flow diagram showing the methodological framework of the study

The mechanization intensity (MI) of the state was computed using the standard formula [10]:

$$MI = \frac{P_m}{A_c}$$

Where P_m represents the total mechanical power available in kilowatts (kW) and A_c denotes the net cultivated area (in hectares). This ratio provided a comparative measure of the degree of mechanization within the state relative to the national average, highlighting the progress and gaps in the mechanization process.

For spatial visualization, a GIS-based map (Figure 3) was generated using ArcGIS 10.8, depicting the district-wise variation in mechanization intensity (kW/ha) across Himachal Pradesh. This enabled the identification of regional disparities, with higher mechanization observed in accessible mid-hill districts such as Kangra, Una, and Mandi, and lower levels in high-altitude regions like Lahaul-Spiti and Kinnaur.

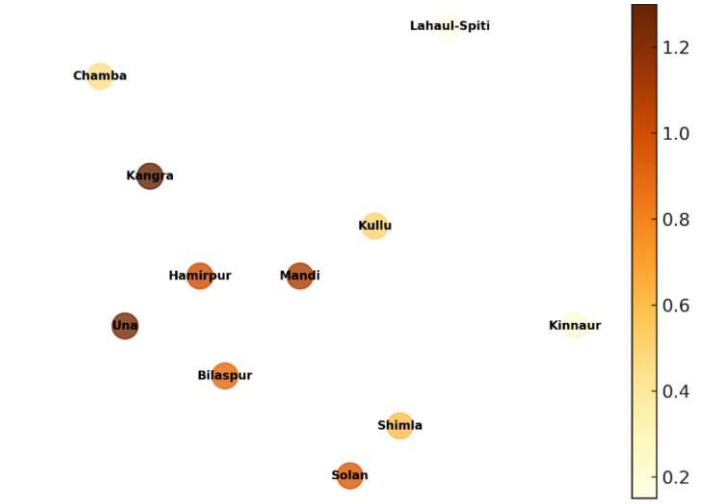

Figure 3. Spatial variation in mechanization intensity (kW/ha) across districts of Himachal Pradesh

The data interpretation and statistical analyses were carried out using Microsoft Excel (2021) and SPSS (Version 25). The descriptive statistics, including mean, range, and percentage, were employed to summarize the data, while trend analysis and comparative evaluations across power sources were conducted to identify dominant mechanization patterns. This integrated methodological approach provided a clear, data-driven, and spatially explicit understanding of mechanization dynamics in Himachal Pradesh's hill agriculture.

3. Results and Discussion

3.1 Demographic and Agricultural Profile

Himachal Pradesh, with a total population of 6.865 million, comprises 3.482 million males and 3.383 million females, distributed across 20,690 villages (Government of Himachal Pradesh, 2022). Agriculture remains the primary source of livelihood for the majority of its rural population. The agricultural landscape is dominated by small and marginal farmers, who constitute nearly 88.8% of all operational holdings, cultivating about 55% of the net sown area. Specifically, 71.4% of the holdings are marginal (0–1 ha), followed by 17.4% small (1–2 ha), 8.2% semi-medium (2–4 ha), 2.6% medium (4–10 ha), and only 0.3% large (>10 ha) as illustrated in Fig. 4. This fragmentation of landholdings significantly influences the adoption and scale of farm mechanization, as smaller plots limit the use of large, conventional machinery [4 & 8].

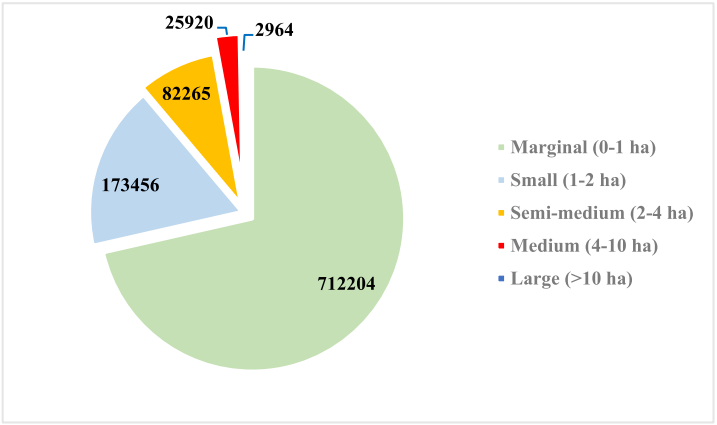

Figure 4. Distribution of operational holdings across farm size categories in Himachal Pradesh (Agricultural Census)

The net sown area of 547,556 hectares is unevenly distributed between seasons, with 341,460 ha under kharif crops and 365,700 ha under rabi crops, while an additional 115,800 ha is cultivated with sugarcane and other post-rabi crops. This cropping pattern indicates a dual-season agricultural system dependent on rainfall and supplementary irrigation, creating demand for flexible, small-scale mechanization suited to variable terrains.

3.2 Composition of Power Sources

The analysis revealed a diverse composition of agricultural power sources in Himachal Pradesh. The state's farming systems continue to rely heavily on animal power, with an estimated 456,587 draught animals actively used for primary tillage, transport, and inter-cultivation. This dependence reflects both cultural continuity and the constraints of terrain, where steep and narrow terraces restrict the operation of large machines [11 & 12]. In contrast, the presence of 24,162 tractors and 21,550 power tillers marks a gradual transition towards mechanization, particularly in mid-hill and valley regions where

accessibility allows machine movement (Fig.3). Additionally, 11,452 internal combustion engines (diesel/petrol), 9,537 electric motors, and 5,850 solar or renewable energy units were recorded, indicating a growing diversification of power sources. The recent inclusion of solar-powered equipment is a positive sign of green mechanization and reflects alignment with sustainable development initiatives. The composition of farm power sources further underscores this imbalance (Fig. 5). Animal power continues to dominate, contributing approximately 77.8% of total farm power availability, followed by tractors (4.1%), power tillers (3.7%), internal combustion engines (1.9%), electric motors (1.6%), and solar or renewable energy sources (0.9%). This distribution indicates that Himachal Pradesh remains in a transitional phase of mechanization, wherein traditional and modern systems coexist.

The trend analysis from 2010 to 2025 shows that while the number of tractors and power tillers has steadily increased, the population of draught animals has gradually declined. However, the rate of mechanization expansion has been slower compared to neighbouring states such as Punjab and Uttarakhand. For instance, tractor density in Himachal Pradesh is estimated at 44 tractors per 1,000 ha, compared to 127 tractors per 1,000 ha in Punjab and 63 tractors per 1,000 ha in Uttarakhand [2]. This contrast demonstrates how topography and holding size remain decisive constraints on mechanization intensity in the Himalayan belt.

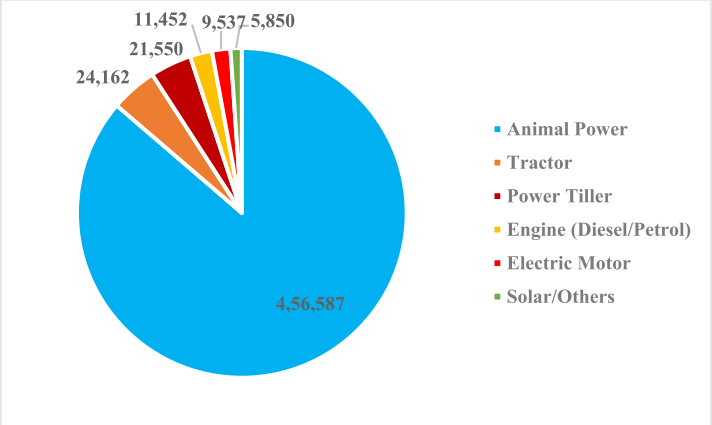

Figure 5. Composition of Power Sources in Himachal Pradesh

Despite these advancements, the mechanization intensity (MI) remains below 1.5 kW/ha, considerably lower than the national average of 2.5 kW/ha [2]. The continued dominance of animal power in certain zones demonstrates that Himachal Pradesh is still in a transitional phase of mechanization, balancing between traditional practices and modern technological adoption.

3.3 Farm Machinery Distribution

The distribution of farm machinery across categories highlights the imbalance between traditional and modern tools. The state has approximately 1,024,089 animal-operated plows, while the number of tractor-operated ploughs and rotavators remains relatively low due to the limited use of heavy equipment on sloped fields. The number of threshers (55,679) indicates moderate mechanization in post-harvest operations, particularly in wheat- and paddy-growing districts such as Kangra, Una, and Mandi [13].

However, machinery for other critical operations such as sowing, spraying, and reaping remains sparse.

The absence of combine harvesters and custom hiring centers (CHCs) across all 12 districts represents a major bottleneck in the mechanization chain. Without CHCs, small and marginal farmers face economic and logistical barriers to accessing machinery, resulting in delayed farm operations and lower productivity. The establishment of CHCs could significantly enhance machinery utilization and reduce the per-hectare operational cost [9].

3.3.1 Comparative Analysis of Mechanization Intensity, Power Composition, and Trends

District-wise comparison revealed notable spatial variation in mechanization intensity across Himachal Pradesh (Fig 6). The highest values were observed in Kangra (1.30 kW/ha), Una (1.25 kW/ha), and Mandi (1.10 kW/ha), where relatively level terrain and better infrastructure have facilitated machinery adoption. In contrast, high-altitude and steeply sloped districts such as Kinnaur (0.20 kW/ha) and Lahaul–Spiti (0.15 kW/ha) recorded the lowest mechanization intensities due to limited accessibility and smaller farm sizes. The state average of 1.34 kW/ha remains below the national benchmark of 2.50 kW/ha, emphasizing the wide disparity between hill and plain regions of India.

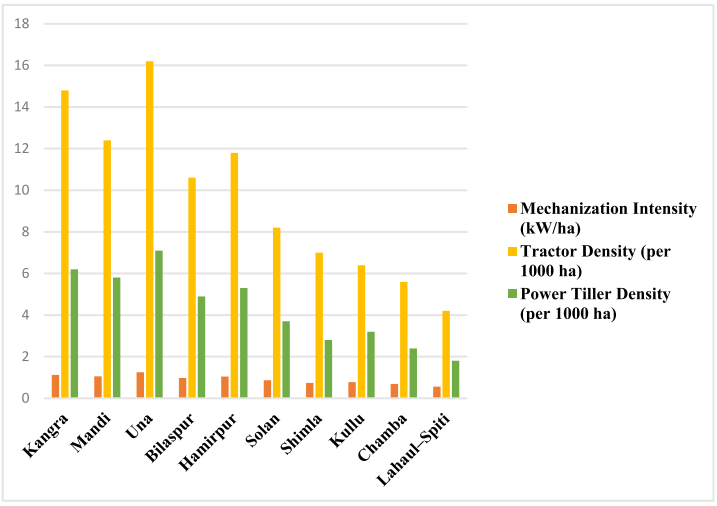

Figure 6. District-wise Mechanization Intensity in Himachal Pradesh

A correlation and regression analysis between operational holding size and mechanization intensity revealed a strong positive relationship ($r = 0.76$, $p < 0.001$). The fitted regression equation, $MI = 0.485 + 0.106 \times$ Farm Size ($R^2 = 0.58$), indicates that approximately 58% of the variation in mechanization intensity can be explained by holding size alone. This finding supports the hypothesis that small and fragmented landholdings significantly restrict access to mechanical power and modern farm machinery. Consequently, cooperative ownership models and Custom Hiring Centers (CHCs) are essential for enhancing mechanization accessibility among small and marginal farmers.

The comparative and statistical analyses collectively reveal that mechanization in Himachal Pradesh remains uneven and context-specific. The districts with better terrain, road access, and horticultural diversification exhibit higher mechanization intensity and faster adoption of small-scale power-operated machinery. Moreover, the expansion of horticulture, particularly apple and stone fruits, has created localized demand for equipment such as sprayers, pruning machines, and small power tillers, linking crop diversification directly with mechanization advancement.

These patterns suggest that mechanization strategies for the hill states should be closely aligned with both terrain and crop specialization to ensure inclusive and sustainable development.

3.4 Labour Availability and Hiring Costs

Agricultural labour continues to play a vital role in the state's farming systems. The average daily wage for male labourers was reported at Rs. 750, while for female labourers it was Rs. 700. The rising wage rates, coupled with seasonal labour shortages, particularly during sowing and harvesting periods, have created economic pressure on smallholders to seek mechanical alternatives [3]. However, the small plot sizes make individual machinery ownership financially unviable, further justifying the need for shared or cooperative models of mechanization. The cost of mechanical operations such as ploughing, sowing, spraying, and threshing varies across the state due to terrain and transport limitations. In areas with accessible terrain, power tillers and mini-tractors have proven to be more economical and efficient than animal-drawn implements, offering improved timeliness and labour savings.

3.5 Challenges in Mechanization Adoption

Several constraints hinder the widespread adoption of mechanization in Himachal Pradesh. These include the fragmented and terraced nature of land, which limits the manoeuvrability of large machinery; low purchasing capacity of smallholders; lack of service and repair facilities in remote regions; and limited institutional support for machinery sharing and financing [8 & 14]. Furthermore, the absence of mechanization training programs for farmers and rural youth reduces awareness about the benefits and safe operation of modern machines.

Despite these challenges, there are promising opportunities for promoting mechanization tailored to hill farming conditions. The lightweight and self-propelled machines such as mini-reapers, compact threshers, and power tillers, have shown strong potential for adoption. The integration of renewable energy technologies, particularly solar-powered irrigation and spraying systems, also offers sustainable pathways to overcome energy and cost constraints.

3.6 Prospects and Policy Implications

The findings suggest that future mechanization strategies in Himachal Pradesh must be location-specific and scale-appropriate. The focus should be on the development of compact, multipurpose machinery designed for narrow terraces and steep slopes. The establishment of district-level Custom Hiring Centers equipped with small machinery pools can enhance accessibility and reduce individual investment burdens. Policy interventions should also promote mechanization clusters, integrating cooperative ownership models and training programs to build operator skills.

Moreover, the government's thrust on green and renewable energy-based mechanization can help the state transition towards an environmentally sustainable farming system. Introducing subsidies for solar-operated power tillers, pumps, and dryers, along with maintenance support schemes, will bolster farmer confidence and long-term adoption. Such targeted interventions can significantly enhance farm productivity, labour efficiency, and income stability, aligning with the broader goals of sustainable hill agriculture [2 & 11].

4. Conclusion and Future Scope

The present study reveals that agriculture in Himachal Pradesh continues to rely predominantly on traditional power sources, with animal power contributing nearly 77.8%, followed by tractors (4.1%), power tillers (3.7%), engines (1.9%), electric motors (1.6%), and solar/other sources (0.9%). This dominance of animal power reflects the topographical constraints and small landholdings typical of the hill region, which limit the adoption of large-scale mechanization. However, the gradual introduction of compact tractors, solar irrigation pumps, and small-scale power tillers has improved farm efficiency and reduced labor dependency in recent years. Despite these advances, the mechanization intensity of the state, estimated at 0.84 kW/ha, remains below the national average of 2.02 kW/ha, indicating substantial untapped potential. To bolster sustainable mechanization, emphasis should be placed on developing terrain-specific lightweight machines, expanding custom hiring centers for machinery access, and integrating renewable energy-powered equipment to reduce reliance on fossil fuels. Future research should focus on developing and field-testing terrain-specific machinery prototypes suitable for steep and undulating landscapes. Detailed spatial mapping of farm power distribution using GIS-based tools can further improve mechanization planning. Additionally, studies evaluating socio-economic impacts of Custom Hiring Centers and renewable energy-based farm equipment in hilly regions would bolster evidence-based policymaking. Furthermore, strengthening farmer training programs on efficient machine use and maintenance, along with policy incentives aimed at achieving power availability beyond 1.5 kW/ha by 2030, can significantly transform the state's agricultural landscape, ensuring productivity enhancement while promoting environmental sustainability.

Author Contributions

Sheik Aadil Mushtaq: Methodology development, data analysis, manuscript writing, and correspondence.

Radhna Gupta: Conceptualization, literature review, and data compilation.

Sushant Bhardwaj: Statistical analysis, graphical representation, and result interpretation.

Obaid Zaffar: Review of policy framework, editing, and technical validation.

Rajinder Kumar: Field information verification, proofreading, and final manuscript approval.

All authors read and approved the final manuscript.

Acknowledgement

The authors gratefully acknowledge the support and cooperation of the Department of Agriculture, Himachal Pradesh, for providing access to statistical data and field insights essential for this study. Special thanks are extended to the Indian Council of Agricultural Research (ICAR) and the All India Coordinated Research Project (AICRP) on Ergonomics and Safety in Agriculture and Allied Sector for their invaluable support and guidance throughout this study. Their continued efforts in promoting agricultural mechanization and technology dissemination have been instrumental in shaping this work.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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