Agri-Machinery and Mechanization: Boosting High-Value and Crop-Specific Agriculture

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Abstract

The mechanization of agriculture is, in a very real sense, a key to yet better production and perhaps profitability. This research looks into how agricultural machinery and mechanization fit into different crop-specific farming methods, concentrating on how these practices are adopted, their effects, and the opportunities available in certain areas.

Data gathered from farmers through surveys provides insight into the main factors that influence their choices regarding mechanization. The early results show a clear link between how much mechanization is used and the yields of crops. Farmers who use mechanized methods generally report better yields than those who stick to traditional practices. Mechanization plays a key role in the cultivation of crops such as wheat, rice, mustard, groundnut, and various vegetables, helping improve efficiency and productivity on farms. Popular equipment includes disc ploughs[1], rotavators[2], threshers[3], and rice trans planters.

In addition, the research looks at how farm size, income levels, and access to information affect the decision to adopt mechanization. Farmers with more land and higher incomes tend to invest in advanced machinery, often thanks to help from financing through dealers or other farmers. However, smaller farmers traditionally resort to renting equipment or performing normal farming due to limited budgets. It also indicated the most important factors influencing equipment choice: compatibility with crop types, ease of operation, cost-effectiveness, and modernization. The goal of this study is to offer practical guidance to policymakers, agricultural equipment makers, and other interested parties to encourage sustainable mechanization and help improve the productivity and profitability of crop-specific agriculture."

Keywords: Agricultural Mechanization, Crop-Specific Farming, Farm Equipment, Yield Improvement, Sustainable Mechanization, Productivity, Profitability.

[1] Disc ploughs-A farm implement used for deep tillage, turning over the soil to bring nutrients to the surface.

[2] Rotavators- A powered machine used for tilling soil and preparing land for planting by breaking up and aerating the soil.

[3] Threshers-Machines used to separate grains from their stalks and husks.

P. Kulkarni and S. Sharma (eds.), *Proceedings of the IBA IEA Conference on Economics and Public Policy (Ecofluence 2024)*, Advances in Economics, Business and Management Research 335,
https://doi.org/10.2991/978-94-6463-766-3_12

1. Introduction

Indian agriculture is changing at a rapid pace, and at the centre of this revolution is mechanization. As producers look for methods to increase production and respond to increasing demand for high-value produce, advanced machinery is not only becoming an option, but an imperative. This research delves into how Agri-machinery is being embraced by various crop types, revealing actual decisions farmers take depending on their farm size, income, and access to information. Through this understanding, we hope to deliver actionable insights that can enable wiser, more sustainable farming—enabling not just farmers but the entire agricultural ecosystem.

2. Literature Review

Agricultural mechanisation is in rabbit hole much the farming is efficient now, LAND IS LESS LABOUR INTENSIVE NOW AND EVERYTHING IS AVAILABLE AT DIGITAL HANDS OF FARM. It was decades of improvement from mechanization, agricultural commercialization up variations on its tool adopting its adoption has simply been slowly. Or, is India riding the crest of a world competitiveness in cropping system? or Rather a Potential yes we have inefficiencies in accessibility and Doctors Shortage (But market is Not Saturate yet). Moving towards that future of a more sustainable and productive mechanization (AI, IoT, machine learning – coming sooner rather than later — intelligent solutions working harder (and more sustainably) The objective of the present review (synthesis of previous studies) is to get updated status advance, bottlenecks and opportunities in agricultural mechanization particularly applied for India. Sakthi Priya and Chandrakumar (2022)

Author	Title	Published	Date of Publication	Key Findings
Madhusudan Bhattarai, Gajendra Singh, Hiroyuki Takeshima, and Ravindra S. Shekhawat	**Agricultural Machinery Industry in India**	**In the Book, An Evolving Paradigm of Agricultural Mechanization Development**	**2020**	• The mechanization has increased productivity in the agricultural arena and reduced drudgery in labour. It has radically transformed India from traditional farming practices to modernized, technology-driven farming. • The Green Revolution of the 1960s played a crucial role in accelerating mechanization, introducing advanced equipment like irrigation pumps, tractors, combine harvesters, and reapers. • India has emerged as a cost-competitive global leader in agricultural machinery, supported by domestic manufacturing, technological advancements, and foreign collaborations.

				• The industry faces issues related to standardization and quality enhancement, which hinder the efficiency and reliability of agricultural machinery. • There is a growing need for innovation and mechanization in specialized crops to ensure sustainability and global competitiveness in the agricultural machinery sector.
Sudarshan C. Awatade, S. R. Kashiwarr, S. Ghosh, and U. R. Dongarwar	**Transforming Agriculture Through Mechanizatio n**	Not mentioned	**February 2018**	• Mechanization plays a crucial role in transforming Indian agriculture, which supports around 60% of the rural population and ranks among the top global producers of key crops like wheat, rice, and sugarcane. • Agricultural productivity in India faces challenges such as erratic monsoons, labour shortages, low youth participation, inadequate mechanization, and imbalanced subsidy distribution. • India's mechanization adoption rate remains low at 35-40%, significantly lagging behind countries like the U.S. (95%), Brazil (75%), and China (57%). • Farm power availability in India has improved from 1.47 kWh/ha in 2005 to 2.02 kWh/ha by 2013, reflecting the impact of government initiatives (NMAET). • Global agricultural equipment market was projected to reach USD 200 billion by 2018, highlights how mechanization is becoming increasingly important in helping farmers boost productivity and farm more sustainably.
Shibeshi Fekadu Tolesa and Yonas Muleta Gejea.	**Analysis of the role of technological advancement s in agriculture: A systematic literature**	**ResearchGate** .	**November 2024**	• Some of the modern agricultural technologies, namely precision agriculture, smart farming, genetic engineering, and automation, have really revolutionized traditional farming in Ethiopia.

	review of evidence from Ethiopia			• With reverberating effects, small farmers now have options to access reliable and timely information about weather, market prices, and crop management. Thanks to the Internet, mobile applications, and online platforms. • Precision farming technologies, including GPS, GIS, and remote sensing, have enhanced resource efficiency by enabling precise field mapping, soil analysis, and targeted input application. • The development of compact, affordable agricultural machinery, such as mini-tractors and tillers, has reduced labour dependency and improved productivity for small-scale farmers. • The adoption of these technologies highlights their potential in promoting sustainable farming practices, increasing efficiency, and addressing food security challenges in Ethiopia and beyond.
Ashok Gulati and Ritika Juneja	**Farm Mechanizatio n in Indian Agriculture with Focus on Tractors**	**Zentrum für Entwicklungs forschung (ZEF)**	**September 2020**	• Indian agriculture has transitioned from traditional human and animal labour to mechanization, with tractors playing a significant role in productivity and transformation. • India is the largest global producer of tractors, with tractorization contributing significantly to farm efficiency and agricultural growth. • Several factors are responsible for the demand for tractors: Farmers' income level, credit availability, and alternative mechanization of farm operations. • Constraints faced by farmers with respect to optimum utilization of tractors increasingly raise questions regarding the viability of such investments despite institutional credit and support from the government.

				• Innovations like the Custom Hiring Model and "Uberization" enhance accessibility by enabling small farmers to share machinery on a pay-per-use basis, reducing ownership costs.
Gajendra Singh	**Agricultural Mechanisation Development in India**	**Indian Journal of Agricultural Economics**	**Jan.-March 2015**	• Mechanization, along with high-yielding varieties, fertilizers, and irrigation, it played a key role during the Green Revolution, helping India triple its grain production and significantly reduce hunger. • Larger farms in Punjab and Haryana benefited early from mechanization, while smallholders relied on custom hiring services due to financial constraints. • Key drivers of mechanization include government policies, institutional credit, and rural electrification, though challenges like uneven adoption and limited access persist. • Innovations such as zero-till seed drills and laser land levellers improve resource efficiency and accessibility, particularly for small-scale farmers. • The study emphasizes the need for inclusive policies, public-private partnerships, and research-driven innovations to address mechanization disparities and promote sustainable agricultural development.
P.K. Joshi, Pratap Singh Birthal, and Nicholas Minot	**Sources of Agricultural Growth in India: Role of Diversification towards High-Value Crops**	**Working or Discussion Paper**	**November,2006**	• Agricultural growth in India during the 1980s was primarily driven by technology-led yield improvements, whereas the 1990s saw a shift towards price increases and diversification into high-value crops. • Diversification into fruits and vegetables contributed significantly to crop income

				growth, accounting for **27% in the 1980s** and **31% in the 1990s**. • Growth patterns varied regionally, with price-led expansion in the grain-focused northern and eastern regions, while southern and western regions experienced diversification-driven growth. • Furthermore, as per the study, investment in research, market linkages, and infrastructure development contributes to promoting agricultural diversification and income growth sustainability. • High-value crop diversification-oriented policy interventions may maximize farmers' profitability, thus facilitating a more equitable regional development of agriculture.
Madhusudan Bhattarai, Gajendra Singh, Hiroyuki Takeshima, and Ravindra S. Shekhawat	**Farm Machinery Use and the Agricultural Machinery Industries in India**	**International Food Policy Research Institute (IFPRI)**	**2020**	• India is the largest global tractor market, producing **660,000 tractors annually**, with **90% sold domestically**, highlighting the strong demand for mechanization. • Early investments into **rural electrification, infrastructure, and knowledge transfer by importing tractors** were key to mechanization success. • Custom hiring services and private sector facilitation have improved access to machinery for farmers, addressing affordability and accessibility. • Empirical analysis shows that **tractors primarily replace bullocks, indirectly enhancing yields**, while **combine harvesters both save labour and improve yields**. • Despite small farm sizes, mechanization has significantly contributed to India's agricultural transformation by increasing productivity and efficiency.

Anupam Sarkar	**Agricultural Mechanizatio n in India: A Study on the Ownership and Investment of Agricultural Implements**	**In the journal Millennial Asia**	**August, 2020**	• Agricultural mechanization in India has expanded significantly, driven by **time and cost savings, productivity improvements, and government subsidies**. • Among different land holding sizes, access to irrigation, and availability of credit, there are different patterns of machinery ownership and investment, which drives mechanization adoption. • The disparities in the use of machinery remain across different crops and regions, and therefore require specific policy interventions. • The study points out that rental services are playing a key role in making farm machinery more accessible to small and marginal farmers. • Agro-ecological characteristics are important for mechanization trends, affecting investment decisions and farming profitability.
Michael R. Langemeier and Gregg Ibendahl	**Crop Machinery Benchmarks**	**Journal Article**	**2014**	• The average **machinery investment per acre** was **$227**, while the **machinery cost per acre** was **$82** for Kansas farms from **2008 to 2012**. • Machinery investment and cost were significantly correlated with **farm size, crop intensity, and asset turnover ratio**, impacting financial performance. • The study emphasized the need to **balance machinery investment with operational efficiency and profitability** to maximize returns. • Strategies such as **custom hiring and increasing machinery usage** can help farmers optimize costs while maintaining productivity. • Controlling machinery costs is crucial for enhancing **financial performance while ensuring timely agricultural operations**.

Michael R. Langemeier	**Benchmarking Crop Machinery Cost and Investment**	**Journal Article**	**October 29, 2021**	• The **machinery cost per acre** for the case farm in west central Indiana was **$99.53**, while **machinery investment per acre** was **$458**. • Key cost components included **depreciation, interest, repairs, and fuel**, which significantly impact overall farm expenses. • Larger farms tend to have **lower machinery costs per acre** due to **economies of scale**, making mechanization more cost-effective. • Comparing **machinery benchmarks across similar farms** helps identify efficiency gaps and optimize resource allocation. • Strategic decision-making is essential to **balance machinery investments with long-term profitability and operational efficiency**.
C.R. Mehta, N.S. Chandel, Kumkum Dubey	**Smart Agricultural Mechanization in India—Status and Way Forward**	**Smart Agriculture for Developing Nations as part of the Advanced Technologies and Societal Change (ATSC)**	**09 March 2023**	• Smart farming integrates **AI, IoT, robotics, UGVs, and UAVs** to replace traditional, labour-intensive farming methods with efficient, data-driven solutions. • **Precision agriculture (PA) optimizes input usage**, while **smart farming incorporates real-time sensing, adaptive learning, and predictive decision-making** for better farm management. • **IoT technology enables remote monitoring and control of farms**, with sensor data analysed using AI algorithms to enhance decision-making. • **Digital agriculture enhances efficiency, resource utilization, and sustainability** in both small and large farms, improving overall productivity. • Continuous innovation in **smart farming is essential to address future challenges** related to

				global food security and agricultural productivity.
M. Ravikishore , P. Supriya and K. Rama Subbaiah	**Farm Mechanisation 2.0: The Future of Indian Agriculture**	**Food and Scientific Reports (General Report)**	**November 2022**	• **India's farm mechanization level is between 40-45%**, significantly lower than industrialized countries where it exceeds 90%. • **Technological advancements such as AI, IoT, robotics, and Big Data** are playing a crucial role in modernizing Indian agriculture. • **Mechanization 2.0 integrates AI-driven analytics and automated machinery**, enhancing efficiency and precision in farming operations. • **Custom hiring services and Farming-as-a-Service (FAAS) models** provide small and marginal farmers access to advanced machinery without high ownership costs. • **Policy interventions, financial support, and skill development programs** are essential to increasing mechanization adoption and ensuring sustainable agricultural growth.
Vignesh N. Manavalan, Akash Kumar	**Agriculture 4.0 – Technology & their Place in Agri Value Chain**	**Research Gate**	**February 2022**	• **Agriculture 4.0 integrates IoT, AI, big data, blockchain, and automation** to modernize the agricultural value chain and enhance efficiency. • **IoT-enabled sensors, drones, and AI-based analytics optimize input use, monitor crop health, and improve productivity**, making farming more precise and data-driven. • Big data and AI help decision making relating to weather and disease prediction, as well as resource allocation optimization, thus improving general farm management. • They improve the transparency in supply chains by creating secure farm-to-fork traceability and

				minimizing inefficiencies in agricultural trade. • **Satellite technology and e-business platforms improve market access, reduce food waste, and connect farmers to digital marketplaces**, increasing profitability and sustainability.

3. Research Objectives

Key insights driven from above table, including predicted significance of mechanization in boosting agricultural output and decreasing labour dependency and degree of environmental degradation are used to delineate objectives for research. Many studies highlight that although mechanization has progressed substantially in certain areas, its uptake is still constrained by limited affordability, inadequate knowledge and unequal access to modern implements.

3.1 Assessment of Agricultural Mechanization Levels: The investigation aims to evaluate the degree to which farmers across four districts in Haryana have integrated crop-specific machinery into their agricultural practices.

3.2 Identification of Influencing Factors for Mechanization Adoption: The study will explore the primary determinants that affect the adoption of crop-specific machinery among Haryana's farmers, including variables such as farm size, income, awareness, access to credit, and training opportunities.

3.3 An Analysis of Benefits Associated with Crop-Specific Mechanization: The study is aimed at ascertaining the perceived benefits to crop-specific mechanization, including increases in yields, reductions in labour costs, improvements in efficiency, and quality enhancement in crops.

3.4 Examination of the Challenges that Hinder Mechanization: It seeks to identify some of the critical challenges encountered by farmers in adopting crop-specific mechanization, such as high initial infestation costs, shortage of skilled manpower, lack of machinery, and high expenses of maintenance.

3.5 Evaluation of Awareness and Impact of Government Interventions: Measure the awareness of farmers toward government subsidizations and schemes on agricultural mechanization as one of the specific objectives of the research.

3.6 Identification of Preferred Machinery Features: The investigation aims to ascertain which characteristics of crop-specific machinery—such as cost-effectiveness, user-friendliness, technological advancements, compatibility with crops, and after-sales support—are deemed most significant by farmers during their selection process.

3.7 Analysis of Information Sources on Agricultural Machinery: The research will identify the primary channels through which farmers acquire knowledge about crop-specific machinery, including dealers, peer farmers, agricultural expos, and online platforms.

3.8 Comparison of Mechanization Practices Across Various Crops: This objective entails an analysis of whether the practices and challenges associated with mechanization diverge according to the primary crops cultivated, such as wheat, mustard, bajra, and cotton.

4. Research Methodology

4.1 Cross-Sectional Study: Given that data collection has occurred at a singular point in time, the study will be classified as cross-sectional.

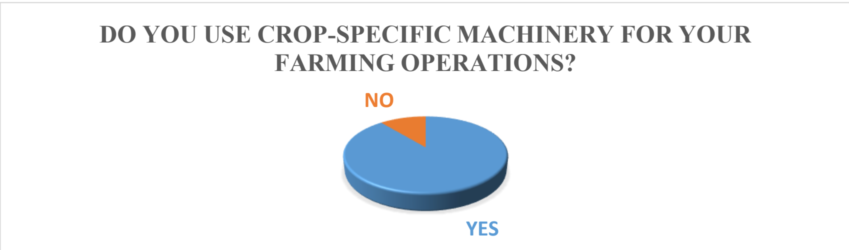
4.2 Data Collection: Primary data has been gathered through a structured survey instrument, which incorporated both closed-ended (multiple-choice) and open-ended questions to facilitate the collection of both quantitative and qualitative data.

4.3 Sampling Strategy: The geographical focus of the study encompasses four districts in Haryana, Rewari, Mahendragarh, Narnaul, Haily Mandi which should be specified in the final report. An explanation of the sampling method employed—whether random sampling, convenience sampling, or another approach—will enhance the credibility of this research. Additionally, detailing the sample size, such as "Data was collected from a total of 100 farmers," will be vital.

5. Data Analysis

5.1 Descriptive Analysis:

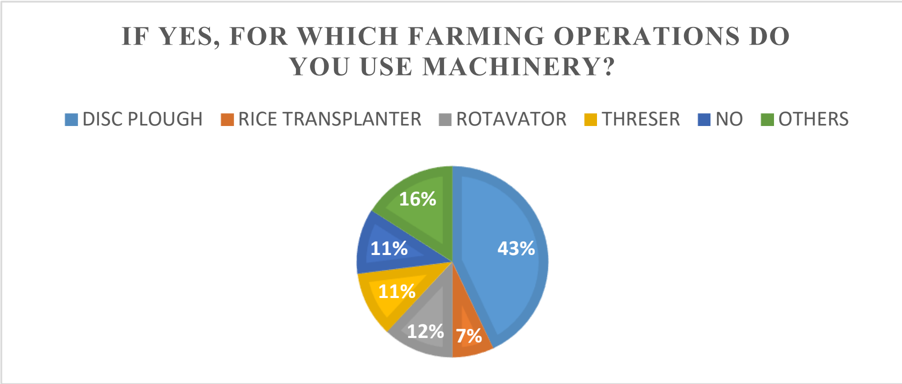
5.1.1 Do you use crop-specific machinery for your farming operations? (Yes/No)



The fact that 89% of farmers use crop-specific machinery indicates the growing normalization of mechanization, enhancing operational efficiency and improving productivity. But the 11% who haven't adopted it likely face challenges—maybe the cost is too high, their farms are too small, or they prefer traditional methods.

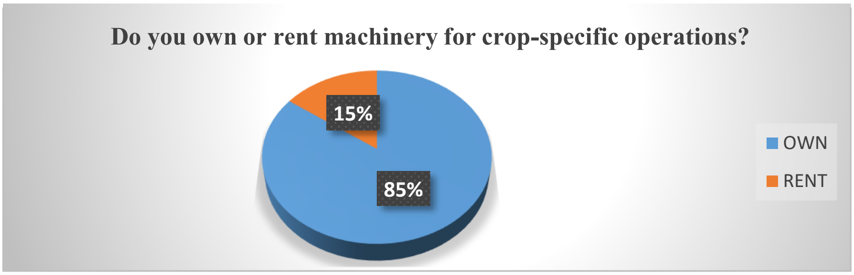
This underscores the need for more affordable solutions, better financing, and awareness programs to ensure all farmers can benefit from modern technology. While progress is clear, there’s still work to be done to make mechanization accessible to everyone.

5.1.2 If yes, for which farming operations do you use machinery?



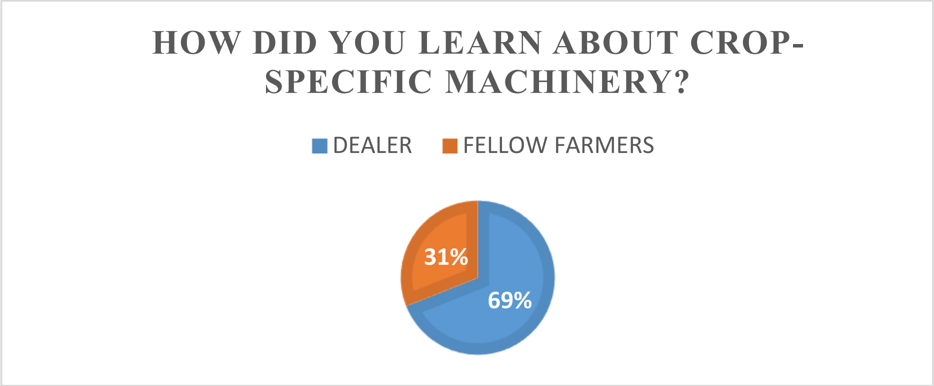
Farmers mostly rely on disc ploughs (43) for land preparation, showing its importance in farming. Rotavators (12) and threshers (11) are used but not as widely, while only 7 use rice trans planters, suggesting transplanting is still largely manual. Interestingly, 11 farmers don't use any machinery, possibly due to small-scale farming or cost concerns. The 'Others' category (16) includes sprayers, groundnut diggers, ridge makers, reapers, and seed drills, suggesting an increasing specialization in mechanization. While land preparation is well-mechanized, there's room for growth in planting, harvesting, and post-harvest operations.

5.1.3 Do you own or rent machinery for crop-specific operations?



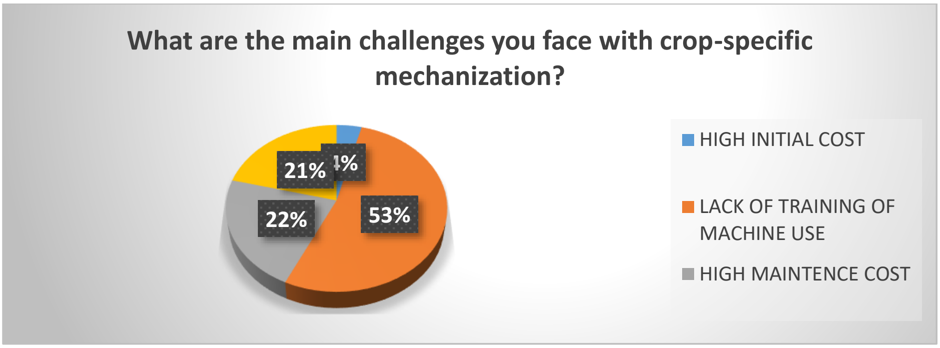
The inclination of farmers on ownership of their machinery stands out in the fact that more than 85 percent prefers owning the equipment to renting it. This shows a less-hasty inclination towards investment on the farm. One could argue that the above applications could be trained, as the tools are very used, better control over operations, or hence, financially capable. The other 15% depend on rental services, which might be an indication of cost constraints, occasional machinery use, or smaller landholdings. While ownership might be predominant, rental services do not lack importance, given that some of them may not require machines often.

5.1.4 How did you learn about crop-specific machinery?



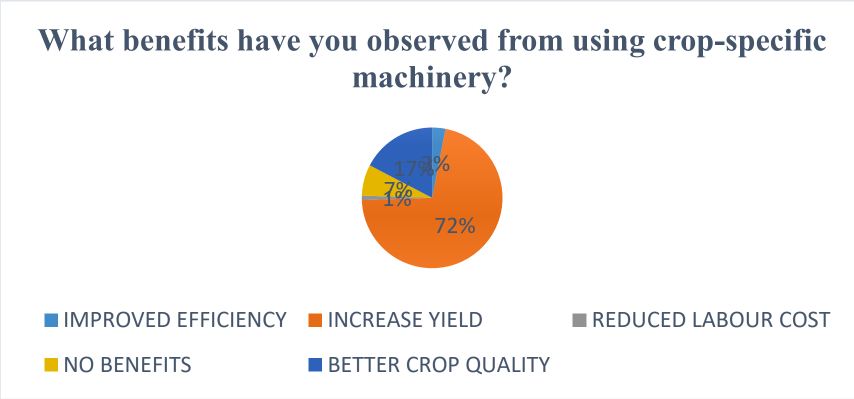
In fact, out of the total majority of farmers, 69% learn about machinery pertaining to the crop from its dealers, which is an indication that sales outlets play a critical role in creating awareness on the commodity. This could be attributed to advertisements, demonstrations, or even trust in the expertise of the dealer. Whereas 31% would get information from fellow farmers, it shows the much significance of word-of-mouth and community influence in making decisions. This indicates that farmers base their choice of machinery on very close experiences and peer recommendation.

5.1.5 What are the main challenges you face with crop-specific mechanization?



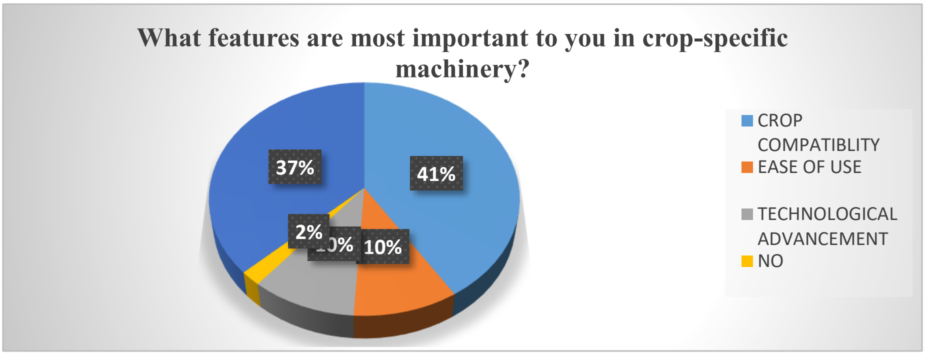
Most commonly cited barriers regarding mechanization of production are the lack of training reported by 53 respondents. It means that there are machines, but many do not use them effectively. High maintenance costs (22) and unskilled labour (21) are also some of the main challenges, indicating that the operation and maintenance of machines are among the majors that continue to hinder action. Surprisingly enough, only four farmers cite high upfront costs as a limitation, which means affordability is not the issue but is in producing and maintaining the machines.

5.1.6 What benefits have you observed from using crop-specific machinery?



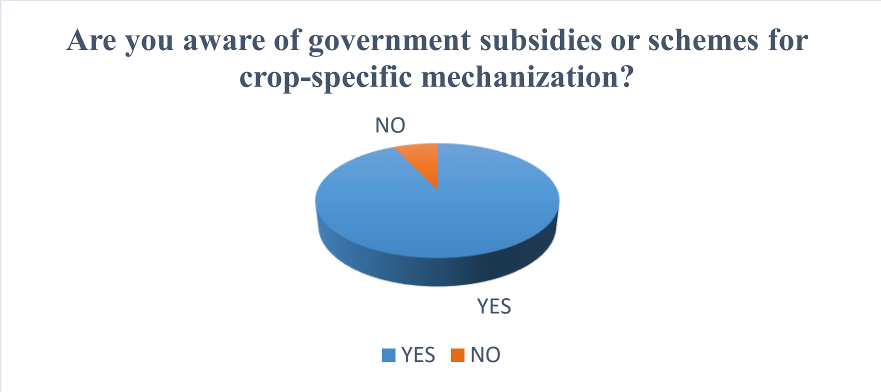
Increased yield (70) is the primary benefit associated with the use of crop-specific machinery in the eyes of the farmers, thus underscoring a direct mechanization-productivity interface. Better quality crops (17) follow as another notable benefit, but it's not emphasized by so many farmers. Strengthening their case for the perceived value of equipment significantly, only 3 farmers pointed to increased efficiency, with just one mentioning reduced labour costs. In other words, farmers see a major value in production increases brought by the equipment rather than in time savings or labour savings. Nonetheless, seven farmers saw no benefits, suggesting that mechanization sometimes does not meet its promises possibly as a result of wrong application, lack of training, or inappropriate choice of equipment.

5.1.7 What features are most important to you in crop-specific machinery?



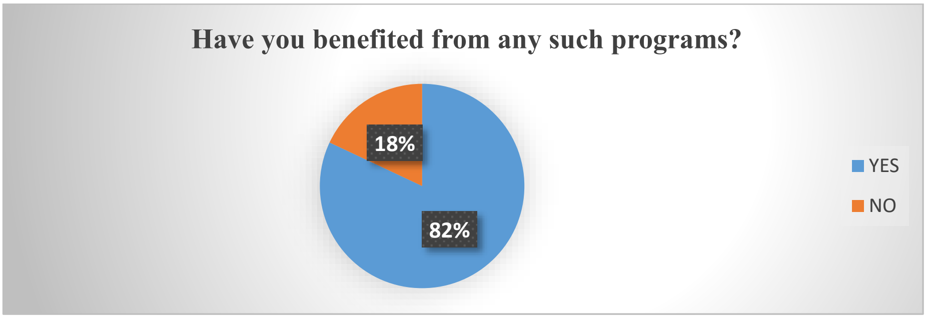
Farmers prioritize crop compatibility (41 responses) and cost-effectiveness (37 responses) when choosing machinery, showing that they want equipment that works well for their specific crops without being too expensive. Ease of use (10) and technological advancement (10) matter to some, but they take a backseat to practicality and affordability. Only 2 farmers said "No" to specific preferences, indicating that most have clear expectations when investing in machinery.

5.1.8 Are you aware of government subsidies or schemes for crop-specific mechanization?



Very high awareness (93%) exists on the government subsidies for crop-specific mechanization, indicating that most farmers are well informed of available support. Seven percent are still unaware of such issues, but nonetheless, there remains a small gap that could be addressed through improved outreach and communication. Ensuring that every single farmer is able to access these benefits will in turn benefit further adoption of mechanization.

5.1.9 Have you benefited from any such programs?



The majority of the farmers (82%) actually benefited from the government subsidy program, indicating that the program is getting into and reaching these farmers and effectively supporting them. On the contrary, 18% of farmers who have not received any benefit from these programs could do so due to lack of access, bureaucratic problem developments, or eligibility issues on the part of the farmers. Solving these issues would help bring more farmers into accessing available support.

5.2 MANOVA Analysis:

Why did we use it?

We performed a MANOVA, which enabled us to analyse the simultaneous effect of multiple independent and control variables on multiple dependent variables. Because of the nature of our study—outcomes such as the degree of mechanization, annual expenditures, perceived benefits, and frequency of machinery utilization may be correlated with one another—a MANOVA informs us of these multivariate relationships as a whole vs. running each dependent variable as an independent outcome.

Predictor	Test Statistic	Value	Num DF	Den DF	F Value	Pr > F
Intercept	**Wilks' lambda**	0.5896	4	83	14.4423	0
	Pillai's trace	0.4104	4	83	14.4423	0
	Hotelling-Lawley trace	0.696	4	83	14.4423	0
	Roy's greatest root	0.696	4	83	14.4423	0
X1	**Wilks' lambda**	0.9548	4	83	0.9823	0.4218
	Pillai's trace	0.0452	4	83	0.9823	0.4218
	Hotelling-Lawley trace	0.0473	4	83	0.9823	0.4218
	Roy's greatest root	0.0473	4	83	0.9823	0.4218
X2	**Wilks' lambda**	0.9083	4	83	2.0949	0.0888
	Pillai's trace	0.0917	4	83	2.0949	0.0888
	Hotelling-Lawley trace	0.101	4	83	2.0949	0.0888
	Roy's greatest root	0.101	4	83	2.0949	0.0888
X3	**Wilks' lambda**	0.8738	4	83	2.9967	0.0231
	Pillai's trace	0.1262	4	83	2.9967	0.0231
	Hotelling-Lawley trace	0.1444	4	83	2.9967	0.0231
	Roy's greatest root	0.1444	4	83	2.9967	0.0231
X4	**Wilks' lambda**	0.8517	4	83	3.6141	0.0091
	Pillai's trace	0.1483	4	83	3.6141	0.0091
	Hotelling-Lawley trace	0.1742	4	83	3.6141	0.0091
	Roy's greatest root	0.1742	4	83	3.6141	0.0091
X5	**Wilks' lambda**	0.7892	4	83	5.5418	0.0005
	Pillai's trace	0.2108	4	83	5.5418	0.0005
	Hotelling-Lawley trace	0.2671	4	83	5.5418	0.0005
	Roy's greatest root	0.2671	4	83	5.5418	0.0005
X6	**Wilks' lambda**	0.8754	4	83	2.9547	0.0246
	Pillai's trace	0.1246	4	83	2.9547	0.0246
	Hotelling-Lawley trace	0.1424	4	83	2.9547	0.0246

	Roy's greatest root	0.1424	4	83	2.9547	0.0246
X7	**Wilks' lambda**	0.9219	4	83	1.7569	0.1454
	Pillai's trace	0.0781	4	83	1.7569	0.1454
	Hotelling-Lawley trace	0.0847	4	83	1.7569	0.1454
	Roy's greatest root	0.0847	4	83	1.7569	0.1454
X8	**Wilks' lambda**	0.6763	4	83	9.9305	0
	Pillai's trace	0.3237	4	83	9.9305	0
	Hotelling-Lawley trace	0.4786	4	83	9.9305	0
	Roy's greatest root	0.4786	4	83	9.9305	0
X9	**Wilks' lambda**	0.3311	4	83	41.9183	0
	Pillai's trace	0.6689	4	83	41.9183	0
	Hotelling-Lawley trace	2.0202	4	83	41.9183	0
	Roy's greatest root	2.0202	4	83	41.9183	0
X10	**Wilks' lambda**	0.905	4	83	2.1778	0.0785
	Pillai's trace	0.095	4	83	2.1778	0.0785
	Hotelling-Lawley trace	0.105	4	83	2.1778	0.0785
	Roy's greatest root	0.105	4	83	2.1778	0.0785
X11	**Wilks' lambda**	0.9835	4	83	0.3471	0.8454
	Pillai's trace	0.0165	4	83	0.3471	0.8454
	Hotelling-Lawley trace	0.0167	4	83	0.3471	0.8454
	Roy's greatest root	0.0167	4	83	0.3471	0.8454
X12	**Wilks' lambda**	0.9125	4	83	1.9889	0.1037
	Pillai's trace	0.0875	4	83	1.9889	0.1037
	Hotelling-Lawley trace	0.0959	4	83	1.9889	0.1037
	Roy's greatest root	0.0959	4	83	1.9889	0.1037
X13	**Wilks' lambda**	0.9277	4	83	1.6164	0.1778
	Pillai's trace	0.0723	4	83	1.6164	0.1778
	Hotelling-Lawley trace	0.0779	4	83	1.6164	0.1778
	Roy's greatest root	0.0779	4	83	1.6164	0.1778

Interpretation:

- Farmers with larger landholdings tend to invest more in mechanization, likely because managing bigger farms manually is tough ($p = 0.0231$). The type of crops grown plays a big role too—some crops naturally require more specialized machinery ($p = 0.0091$). Those who follow modern farming methods benefit more from mechanization compared to traditional farmers ($p = 0.0005$).

- Machines Make a Difference: Simply using crop-specific machinery significantly improves farming outcomes ($p = 0.0246$). But how farmers access machines matters—owning machinery leads to better utilization than renting ($p = 0.000$). Also, the way farmers learn about machinery (from dealers, government programs, etc.) strongly influences whether they adopt it ($p = 0.000$).
- Surprisingly, age and income don't have a big impact on mechanization choices. Just being aware of government subsidies isn't enough to push farmers toward adopting machinery ($p = 0.0785$). Also, whether a farmer uses machines for specific tasks doesn't seem to affect overall mechanization levels ($p = 0.1454$). Even factors like location, spare part availability, and preferred features don't play a major role in influencing decisions.

Variable Definition:

Independent Variable

- **X1=** Age
- **X2=** Income
- **X3=** Landholding
- **X4=** Which crops do you primarily cultivate?
- **X5=** What is your farming approach?
- **X6=** Do you use crop-specific machinery for your farming operations?
- **X7=** If yes, for which farming operations do you use machinery?
- **X8=** Do you own or rent machinery for crop-specific operations?
- **X9=** How did you learn about crop-specific machinery?
- **X10=** Are you aware of government subsidies or schemes for crop-specific mechanization?

Dependent Variable

- **Y1=** What percentage of your farming operations is mechanized?
- **Y2=** How much do you spend annually on crop-specific mechanization?
- **Y3=** What benefits have you observed from using crop-specific machinery?
- **Y4=** How frequently do you use crop-specific machinery?

Control Variable

- **X11=** Location (to account for regional differences in farming practices)
- **X12=** Are spare parts for your machinery easily available? (to control for availability of resources)
- **X13**= What features are most important to you in crop-specific machinery? (to control for preferences)

Correlation Analysis:

A correlation matrix [4]was used as a primary tool to explore pairwise linear relationships between variables. Pairwise 4relationships Among variables, pairwise linear relationships were initially explored using a correlation matrix [1]. It demonstrates which variables are or not in same directions, indicating which one can be used for later multivariate analyses. Indeed, this direct comparison drives possible patterns and modulates to support or complement the MANOVA test.

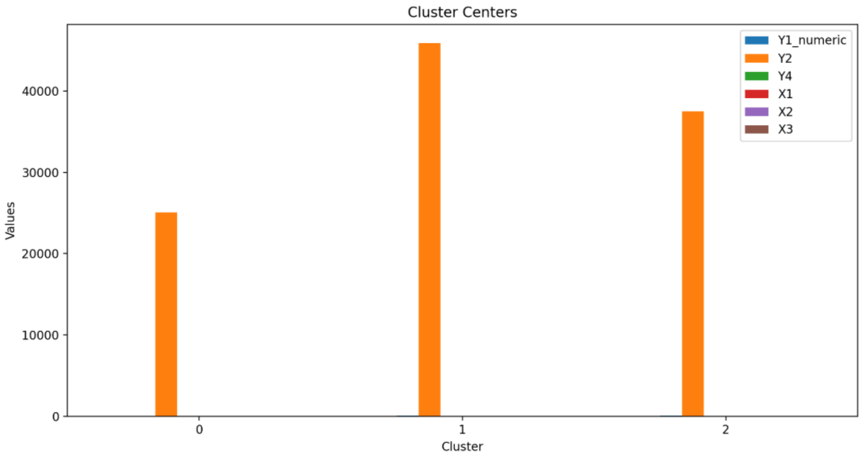
Key findings:

Y1	1	0.62	-0.32	-0.09	0.02	0.33	0.51	-0.02	-0.63	0.64	-0.02	-0.66	-0.89	0.42	0.1	0.45	-0.22
Y2	0.62	1	-0.5	-0.12	-0.04	0.47	0.64	-0.19	-0.51	0.5	0.09	-0.55	-0.6	0.34	0.17	0.19	-0.15
Y3	-0.32	-0.5	1	-0.38	-0.04	-0.36	-0.34	0.11	0.41	-0.37	-0.1	0.41	0.33	-0.26	0.01	-0.26	0.22
Y4	-0.09	-0.12	-0.38	1	-0.07	0.32	0.15	-0.15	-0.11	0.11	0.18	0.07	0.09	0.06	-0.05	0.09	0.05
X1	0.02	-0.04	-0.04	-0.07	1	0.11	0.06	-0.07	-0.01	0	0.04	-0.07	0.03	0.02	-0.1	0	-0.15
X2	0.33	0.47	-0.36	0.32	0.11	1	0.88	-0.29	-0.3	0.31	0.07	-0.2	-0.32	0.18	0.18	0.13	-0.16
X3	0.51	0.64	-0.34	0.15	0.06	0.88	1	-0.2	-0.37	0.37	0.03	-0.32	-0.51	0.22	0.25	0.12	-0.19
X4	-0.02	-0.19	0.11	-0.15	-0.07	-0.29	-0.2	1	0.15	-0.13	-0.45	0.05	0.07	0.06	0.01	-0.07	0.44
X5	-0.63	-0.51	0.41	-0.11	-0.01	-0.3	-0.37	0.15	1	-0.95	-0.08	0.94	0.5	-0.53	0.02	-0.52	0.3
X6	0.64	0.5	-0.37	0.11	0	0.31	0.37	-0.13	-0.95	1	0.08	-0.84	-0.52	0.5	-0.04	0.6	-0.26
X7	-0.02	0.09	-0.1	0.18	0.04	0.07	0.03	-0.45	-0.08	0.08	1	-0.01	0.08	0.04	0.11	-0.03	0.04
X8	-0.66	-0.55	0.41	0.07	-0.07	-0.2	-0.32	0.05	0.94	-0.84	-0.01	1	0.51	-0.49	0	-0.42	0.27
X9	-0.89	-0.6	0.33	0.09	0.03	-0.32	-0.51	0.07	0.5	-0.52	0.08	0.51	1	-0.26	-0.15	-0.36	0.23
X10	0.42	0.34	-0.26	0.06	0.02	0.18	0.22	0.06	-0.53	0.5	0.04	-0.49	-0.26	1	-0.04	0.6	-0.18
X11	0.1	0.17	0.01	-0.05	-0.1	0.18	0.25	0.01	0.02	-0.04	0.11	0	-0.15	-0.04	1	-0.22	-0.05
X12	0.45	0.19	-0.26	0.09	0	0.13	0.12	-0.07	-0.52	0.6	-0.03	-0.42	-0.36	0.6	-0.22	1	-0.22
X13	-0.22	-0.15	0.22	0.05	-0.15	-0.16	-0.19	0.44	0.3	-0.26	0.04	0.27	0.23	-0.18	-0.05	-0.22	1
	Y1	Y2	Y3	Y4	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13

- The MANOVA test shows significant multivariate effects for the intercept ($p < 0.001$)
- Most independent variables show weak to moderate correlations with dependent variables
- Control variables (X11, X12, X13) have varying degrees of influence on the relationships

[4] A correlation matrix shows how different factors are connected.

5.3 Cluster analysis[5]: -



1. We identified three distinct clusters of farmers:

- Cluster 0 (Low Adoption):
    - Lower Y1 percentage (~34%)
    - Lower investment (Y2 ~25,000)
    - Average farm characteristics
- Cluster 1 (High Tech-High Investment):
    - High Y1 percentage (~85%)
    - Highest investment (Y2 ~46,000)
    - Highest X2 and X3 values
- Cluster 2 (High Tech-Moderate Investment):
    - High Y1 percentage (~86%)
    - Moderate investment (Y2 ~37,500)
    - Moderate X2 and X3 values

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[5] Cluster analysis groups similar farmers based on their traits to uncover patterns in farming practices.

Governments seeking to support farming do so by realizing that all farmers are not the same: some are leaders in adopting technology, some are cautious, and some are still struggling to mechanize. Cluster analysis allows for understanding farmers' needs and providing suitable support by classifying them according to the level of technology adoption, income levels, and land size.

Interpretation:

1. **Cluster 0 – Low Adoption**
These farmers are lagging behind in mechanization, with only 34% using technology in their operations. Their investment in machinery is the lowest (₹25,000 annually), and while their income and land size are average, they may lack the financial flexibility to modernize. They need assistance-whether through subsidies, low-interest loans, or training-to enable their switch to better farming practices.

2. **Cluster 1 – High Tech, High Investment**
These remarkable set of farmers may be characterized as leading the world in agricultural modernization, having achieved 85% mechanization, and modern equipment investments nearly in excess of INR 46,000 per year. They are able to afford modern practices and possess the largest-sized farms and highest incomes. Instead of manual input, they can use AI tools and precision agriculture [6]for enhanced productivity. (Tolesa and Gejea, 2024)

3. **Cluster 2 – High Tech, Moderate Investment**
These farmers are just as advanced as Cluster 1 in terms of mechanization (86% adoption), but they are more cautious with spending, investing around ₹37,500 annually in machinery. Their income and land size are moderate, meaning they are financially stable but still mindful of costs. For them, affordable and efficient technology solutions could make a big difference, helping them balance cost and innovation.

- Not all farmers with smaller farms are lagging behind. Some (Cluster 2) are embracing technology despite having moderate resources.
- Investment levels matter. Some farmers can afford to invest more, while others hesitate, even if they have access to technology.
- Support needs to be targeted.
    - Cluster 0 needs financial aid and awareness programs to catch up.
    - Cluster 2 deserves affordable and good value-for-money technology.
    - Cluster 1 demands high-end innovation to further improve their efficiency.

The various concepts of clusters would allow policymakers, agribusinesses, and financing institutions to engage in products and services that are relevant to farmers' needs so that no one will be left behind on the way to modernized, efficient, and sustainable agricultural practices.

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[6] Precision agriculture is a farming approach using GPS, IoT, and data to optimize crop production through targeted actions.

5.4 Factor analysis: -

	Factors loading Heatmap		
Y1	0.73	-0.05	0.01
Y2	0.87	0.02	-0.04
Y4	-0.14	0.47	-0.07
X1	-0.01	-0.02	1
X2	0.52	0.85	0.12
X3	0.74	0.57	0.07
	Factor 1	Factor2	Factor3

The heatmap shows three main factors:
Factor 1 (Technology Adoption Factor):

- Strong positive loadings for Y1, Y2, X2, and X3
- Represents overall technology adoption and investment level

Factor 2 (Resource Intensity):

- Strong positive loading for X2
- Moderate positive loading for X3
- Related to resource utilization

Factor 3 (Size Factor):

- Very strong positive loading for X1
- Represents farm size characteristics

With factor analysis[7], we can decipher complex data dimensions within farming whereby interrelatedness among various parameters such as technology adoption, investment, income, and landholding is revealed. This gives a complementary view where instead of treating impact factors separately, related variables are grouped together for an easier understanding of what constitutes the rationale behind farmers' decisions. In doing so, the main purpose is to render farmers' decisions smoother, develop targeted support mechanisms, and plan strategies which cater to different segments of farmers.

Interpretation of the Data:

1. **Technology Adoption Factor**
Farmers with better income are largely capable of mechanizing and adopting modern farming technologies. This shows that finance plays an important role in the decision of a farmer to adopt technology.

2. **Resource Intensity Factor**
This factor indicates how financial resources affect farming decisions. The high-income farmer will tend to invest more in improved farming practices, landholding

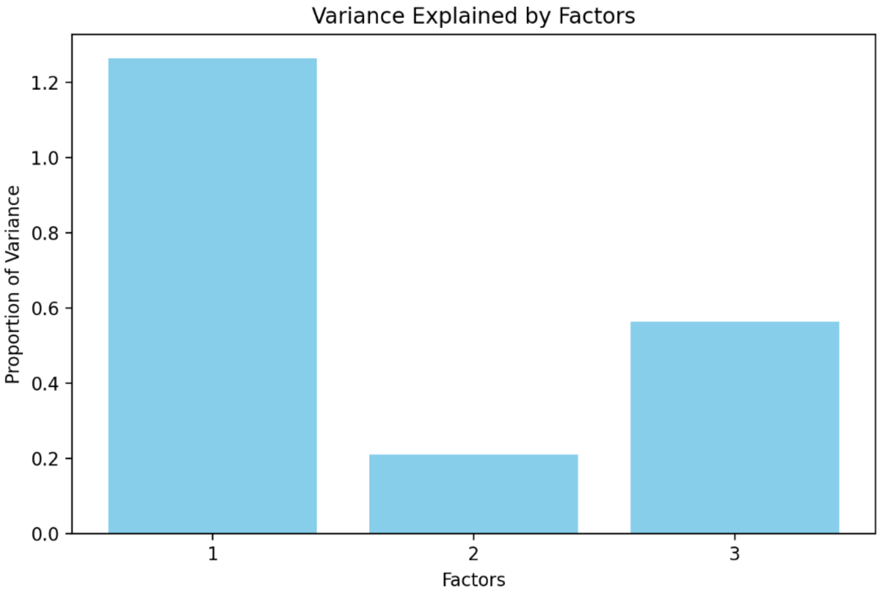
[7] Factor analysis is a technique that groups related variables together to reveal underlying connections.

size in this instance has only a little say. The decision is not only dependent on land but on reserves to make improvements.

3. **Size Factor**
Interestingly, farm size alone does not determine mechanization or investment. A farmer with a large piece of land may still rely on traditional methods, while a smaller farm might be highly mechanized. This shows that mechanization is influenced more by financial capability than just land area.

The analysis confirms that technology adoption is instead driven by levels of income and investment, not just farm size. This should establish the basis for agribusinesses and policymakers to create a durable financial product, training program, and technical solution suited for farmers based on their financial capacity, not so much on land size. These insights would go a long way toward establishing a more rational method of decision-making for the service of more productive and sustainable practices of the farmers.

5.5 Variance explained: -



- Factor 1 explains about 35% of the variance
- Factor 2 explains about 21% of the variance
- Factor 3 explains about 17% of the variance
- Cumulatively, these three factors explain about 73% of the total variance in the data

Key Insights:

- There's a clear segmentation between high and low technology adopters
- Investment levels (Y2) strongly correlate with technology adoption (Y1)
- Farm size (X1) operates independently of technology adoption
- The three-factor solution provides a good explanation of the variance in the data
- Resource intensity (X2, X3) plays a significant role in distinguishing between farmer groups.

Variance analysis helps us understand why some farmers adopt technology faster than others by breaking down the different factors influencing their decisions. Instead of looking at raw numbers, this method highlights the key drivers behind mechanization—such as income, investment, and farm size—so that support can be more effectively targeted.

Interpretation:

1. **Investment Drives Technology Adoption** (35% influence)
The biggest factor influencing mechanization is how much a farmer invests in technology**.** Farmers with higher financial capability and willingness to invest in modern tools are more likely to adopt mechanization.

2. **Farm Structure & Decision-Making** (21% influence)
The second major factor relates to farm size and structural differences among farmers. Interestingly, farm size operates independently of mechanization, meaning that having more land doesn't necessarily mean a farmer will invest in technology. Age and personal farming strategies might also play a role here.

3. **Resource Availability Matters** (17% influence)
The third factor focuses on income and landholding**,** which differentiate farmers based on financial and operational efficiency. Farmers with greater financial resources are more likely to mechanize, while those with limited resources may struggle to adopt new technologies.

Together, these three factors explain 73% of the variation in technology adoption, giving us a strong, data-backed understanding of what drives mechanization.

Key Takeaways

- **Farmers are not all the same** – There are clear differences between high and low technology adopters, mainly based on financial capability.
- **Investment matters more than farm size** – Even small landholders can mechanize if they have the right financial backing.
- **Financial support is key** – Since investment is strongly linked to adoption, providing subsidies, loans, or better financing options can encourage more farmers to modernize.

- **A reliable model for decision-making** – It means that since 73% of the data is explained by this analysis, the foundation for policy design and financial programs is strong.

Such information will be highly useful for policymakers, agribusinesses, and financial institutions that want to promote mechanization. Rather than a one-size-fits-all approach, strategies can be designed based on different levels of investment, financial capabilities, and the farm type so that a larger number of farmers will be able to access modern technology and improve productivity.

6. Discussion

It is very interesting to look into how mechanization can be made better for the future state of Haryana. The results conform to the literature already present relating mechanization with yield growth, labour cost-reducing, and efficiency enhancement. Even though these were benefits, the rate of adoption remains pathetically low as compared to global benchmarks because they were financially constrained and not trained.

A key empirical lesson includes the importance of mechanization solutions customized to their respective farm sizes and cropping types. While large-scale farmers are able to afford the purchase of machinery directly, rent services and custom hiring [8]centres (CHC) must be reinforced in order to be accessible to small-scale farmers. Further, public-private partnerships will go a long way to promoting farm mechanization.

As part of the study, the conscious knowledge and skill campaign are considered effective in the adoption of mechanization. Many farmers continue to rely on traditional practices since they are unaware of the available technology and the benefits derived from it. Knowledge gaps can be bridged by extension services, agricultural expos, and digital platforms.

Lastly, a study should to be led on long-term economic developmental and sustainability from mechanization, environmental impact and resource conservation. 'Precision farming and AI-based mechanisation are becoming popular and practical; hence further work to test the acceptability and feasibility of these approaches in the context of Indian agriculture will also help the policy makers and industry to move towards a more inclusive and effective mechanisation policy.' (Tolesa and Gejea, 2024)

7. Conclusion

Haryana has studied agricultural mechanization and found crop-specific machines become imperative for increasing productivity, efficiency, and profit. The study also reveals the extent of influence of various factors such as farm size, levels of income, credit access, or even awareness of technologies available towards the adoption of mechanization. Findings show that farmers who adopt advanced mechanized techniques yield more than those using traditional techniques.

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[8] Custom hiring refers to rental services of farm machinery, enabling small or marginal farmers to access advanced equipment without ownership.

The other classified groups of farmers from this research are: low adoption; high investment high tech; and high investment low tech. These three different clusters will show differences in the intensity of their mechanization and financial commitment. On the other hand, through our factor analysis, we have proved that there are three main factors concerning the adoption of mechanization: technology adoption, resource intensity, and farm size.

Mechanization indeed pronounces some advantages but is still marginal by high initial cost, inadequate skilled man power, or inaccessible advanced machinery. Additionally, government subsidies and financial support units play a major role in removing such barriers and will enable marginal and small farmers to take advantage of mechanization.

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