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Ritu Devi
Assistant Professor, SD PG College, Panipat, Haryana, India

Corresponding Author:
Ritu Devi
Assistant Professor, SD PG College, Panipat, Haryana, India

Advancing climate-smart agriculture: The role of mechanization and technology in enhancing sustainability and productivity

Ritu Devi

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Abstract
This research paper examines the transformative potential of mechanization and technology in advancing Climate-Smart Agriculture (CSA) to mitigate climate change impacts and enhance sustainability. CSA addresses critical challenges like climate variability, resource scarcity, and food security. Mechanization, through innovative tools such as soil moisture sensors, N-sensors, and aerial remote sensing, enhances input efficiency and optimizes resource utilization, resulting in improved productivity and sustainability. Globally, mechanization levels vary significantly, with developed countries achieving rates of 75-95%, while India's rate is 40%, constrained by small, fragmented landholdings. Initiatives such as India's Sub-Mission on Agricultural Mechanization (SMAM) highlight efforts to improve access to technology through custom hiring centers and local manufacturing. This study explores mechanization's role in seedbed preparation, irrigation, nutrient management, and plant protection, showcasing its contribution to reducing greenhouse gas emissions, conserving water, and minimizing chemical usage. Additionally, the integration of robotics, Artificial Intelligence (AI), and autonomous systems in agriculture demonstrates significant potential to enhance productivity and resilience. However, barriers such as high costs, limited access, and insufficient training hinder adoption, especially among smallholder farmers. By examining government policies, technological advancements, and adoption patterns, this paper advocates for inclusive mechanization strategies tailored to smallholders. Promoting subsidies, training programs, and custom hiring centers can bridge accessibility gaps and ensure equity. The findings underscore that scaling climate-smart mechanization is critical for achieving a sustainable and food-secure future while addressing climate change impacts. Mechanization not only aligns agricultural practices with global sustainability goals but also fosters innovation, collaboration, and resilience in agricultural systems.

Keywords: Climate-smart agriculture, mechanization, sustainability, precision farming, agricultural productivity

1. Introduction

Agriculture, the backbone of global food security, faces unprecedented challenges due to climate change, resource scarcity, and the growing global population. Traditional farming systems are ill-equipped to cope with the escalating pressures of erratic weather patterns, diminishing soil fertility, and water shortages. In response to these challenges, Climate-Smart Agriculture (CSA) has emerged as a multidimensional approach that integrates adaptation, mitigation, and productivity enhancement into agricultural practices. CSA not only addresses environmental concerns but also offers a framework for sustainable intensification, emphasizing resource efficiency, resilience, and reduced environmental impacts (Gautam, Kushwaha, Kumar, & Kushwaha, 2019) [10]. Mechanization, as a key pillar of CSA, transforms traditional agricultural systems by optimizing input use, reducing labor dependency, and enhancing productivity, thereby enabling farmers to adapt to the changing climatic realities. Mechanization has the potential to revolutionize agriculture by bridging the gap between resource constraints and productivity. Developed countries have demonstrated the transformative impact of mechanization, achieving levels of 75-95% across agricultural sectors (Central Institute of Agricultural Engineering [CIAE], 2016) [6]. In contrast, India lags significantly behind, with a mechanization rate of only 40% (Department of Agriculture, Cooperation & Farmers Welfare [DACFW], 2019) [9].

This disparity underscores the critical need for targeted interventions in developing countries to promote mechanization and make advanced technologies accessible to smallholder and marginal farmers. The Sub-Mission on Agricultural Mechanization (SMAM) in India is an example of an initiative aimed at addressing these gaps by supporting custom hiring centers, providing financial assistance, and encouraging the local manufacture of agricultural equipment (DACFW, 2019) [9]. However, despite these efforts, barriers such as fragmented landholdings, high equipment costs, and limited training opportunities persist, hindering the widespread adoption of mechanization. Mechanization's role in CSA extends beyond productivity enhancement to address critical environmental concerns (Mossie, 2022). Precision farming technologies such as soil moisture sensors, N-sensors, and remote sensing tools reduce input overuse, conserve water, and improve nutrient application, thus aligning agriculture with global sustainability goals (Javaid *et al*., 2022) [13]. Practices such as minimum tillage and mulching improve soil health and contribute to carbon sequestration, mitigating the impacts of climate change (Ali, 2020) [2]. Furthermore, the integration of advanced technologies like robotics, Artificial Intelligence (AI), and autonomous systems has the potential to redefine farm operations, making agriculture more efficient and less labor-intensive. Autonomous tractors, drone-based monitoring systems, and AI-driven analytics exemplify the innovative tools that can optimize farm management and enhance resilience against climate variability (Namdev, Pateriya, Dash, & Modi, 2017) [16]. However, the adoption of these technologies remains constrained by high costs, limited infrastructure, and insufficient awareness, particularly in resource-constrained regions.

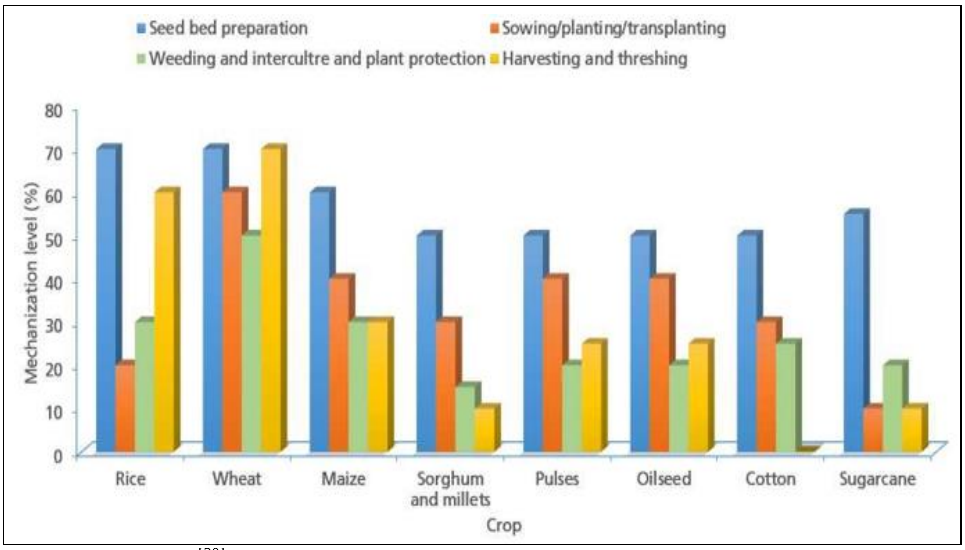
India's unique agricultural landscape, characterized by fragmented landholdings and small-scale operations, presents significant challenges to mechanization. Over 86% of operational holdings are classified as small or marginal (< 2 hectares), with an average size of less than 1.08 hectares (DACFW, 2019) [9]. These structural challenges exacerbate the financial and logistical barriers to mechanization, particularly for smallholder farmers who often lack access to affordable financing or cooperative models. Custom hiring centers and Farmer Producer Organizations (FPOs) are practical solutions to address these barriers by enabling shared access to mechanized tools without the burden of ownership costs (Reddy *et al*., 2015) [28]. Such initiatives have demonstrated their effectiveness in improving productivity and reducing input costs, particularly when supported by targeted government policies and subsidies (Namdev, Pateriya, Modi, & Dash, 2019) [17]. While the environmental and productivity benefits of mechanization are well-documented, knowledge and skill gaps remain significant obstacles to its adoption. Studies have shown that a lack of technical knowledge and limited participation in training programs hinder farmers from effectively utilizing advanced tools (Mizik, 2021) [14]. Capacity-building initiatives, including demonstration plots, peer-to-peer learning, and extension services, are critical to empowering farmers and fostering greater acceptance of mechanization.

2. Literature Review

Climate change and other natural disasters pose a threat to the agricultural production system. Climate change threatens farmers' incomes and the agricultural production system (Vatsa, Ma, Zheng, & Li, 2023) [30, 31]. There is competition for scarce natural resources, which agricultural production systems must contend with. Climate change is impacting not just the quality of these resources but also the inefficient ways in which they are managed. The only option for agriculture to adapt to this new reality is to undergo a radical transformation that makes it more resilient to the effects of climate change without sacrificing food security for anyone. All of these problems have been interconnected, and climate-smart agriculture was supposed to solve them all at once. One viable solution to these problems, which are influenced by weather, is farm mechanization (Vishnoi & Goel, 2024) [32]. This will help maintain food security in the face of climate change. Through the use of climate-smart technology, agricultural automation has the potential to boost agricultural output, which in turn increases incomes and makes the agricultural sector more robust to the effects of climate change. Furthermore, conservation agriculture or climate-smart agriculture, whichever is more feasible, may lead to a rise in carbon sequestration (Zhao, Liu, & Huang, 2023) [33]. While mechanization in general has been around for a while, modernizing it for use in climate-smart agriculture is a fresh approach that can improve agricultural output while reducing environmental impact (Dashmesh, 2020) [7]. By following this route, agricultural equipment would be better able to adapt to and lessen the impact of climate change. Field operations, evaluation, and implementation of climate-smart technology and agronomic techniques make up climate-smart agriculture. Incorporating a research foundation, building investment plans, and incorporating supporting government policies are all important components.

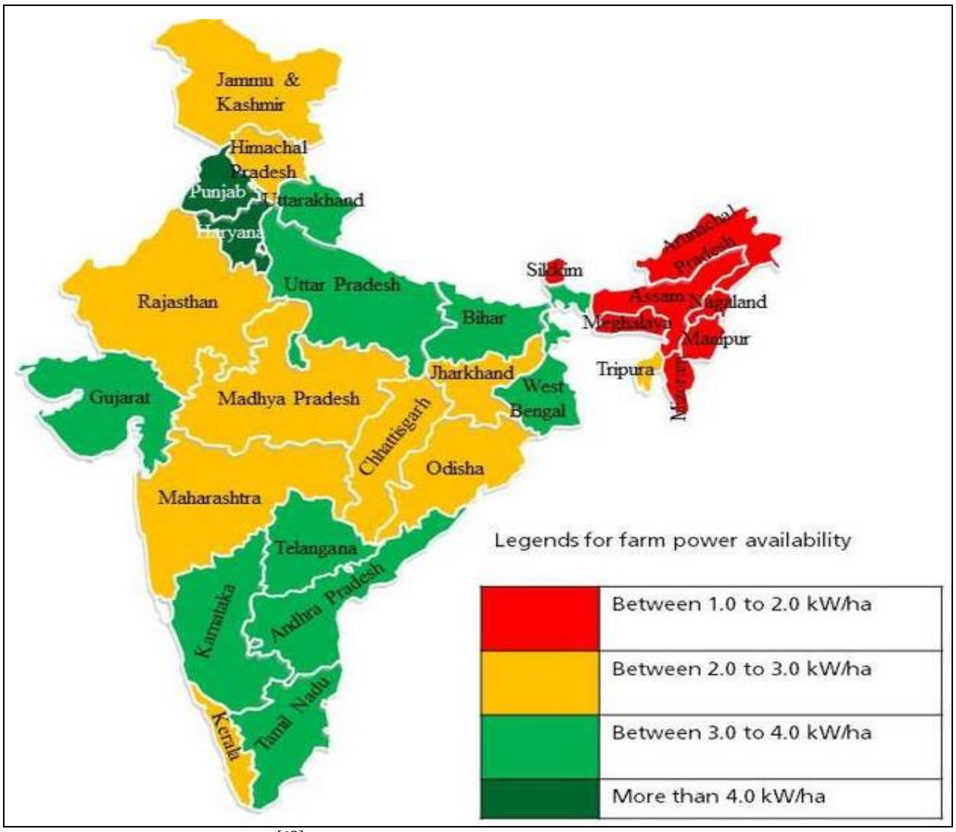
Mechanization Status, Demands and Opportunities

Improved input usage efficiency, higher output, and higher productivity can only be achieved via the application of farm mechanization. According to (Bollavathi, Reddy, Reddy, & Prasad, 2018) [5], the "*United States of America, Western Europe, Russia, Brazil, and China"* have reached different levels of mechanization: 95.5%, 80.5%, 75.5%, and 59.5%, respectively. In contrast, Vatsa (2023) [30] found that India's mechanization level was a meager 40%. Fig. 1 shows the degree of mechanization for several of India's most important crops. The states of Punjab, Haryana, and Uttar Pradesh have the highest availability of agricultural power in India, whereas the states in the northeast are severely short (Figure 2). While other agricultural tools are falling behind, tractor penetration has been on the rise (Barasa, Botai, Botai, & Mabhaudhi, 2021) [3].



Source: Vatsa, 2023 [30]

Fig 1: Mechanization level for major crops in India



Source: Javaid, *et al*., 2022 [13]

Fig 2: Farm power availability in India

One limitation of agricultural mechanization is the fragmentation of farm size. Small and "marginal agricultural land holdings (< 2.0 ha) account for 86.21% of total operational land holdings and cover 47.35% of farms in India," while the average farm size is less than 1.08 ha (DACFW, 2019) [9]. Climate change poses a significant threat to agricultural systems, even those with modest holdings of land. In order to achieve food security, it may also be subjected to less agricultural automation in the operations of the farm. Land fragmentation, which has led to tiny agricultural holdings, is a serious problem (Abhilash, Rani, Kumari, Singh, & Kumari, 2021) [1]. Another issue is the predicted 26% decline in the availability of agricultural laborers by the year 2050. Opportunities to improve India's current agricultural situation include custom hiring centers, co-operative societies, and farmer producer organizations. As part of its Make-in-India program, the Indian government is helping domestic producers create agricultural machinery and equipment that meets domestic demand rather than relying on imports from wealthy nations. One practical option for small-scale farmers is the rise of custom-hiring centers and small-scale automation.

In many Indian states, the number of developed agricultural technologies is still low, ranging from 2-3 kW/ha, and there has been little to no frontline demonstration or reach to the end user. One targeted way to affect Indian agriculture is to promote the adoption of existing climate-smart technology via climate-smart solutions (Department of Agriculture, Cooperation & Farmers Welfare [DACFW], 2018) [8]. In addition to maintaining and improving natural resources, managing ecosystems may boost agricultural profitability via food security and environmental protection, leading to sustainable production.

Because there is a wide variety of climate-smart agricultural techniques that could be available to farmers, the number of technologies that are actually adopted depends on a lot of factors, including farmer traits, farm circumstances, affordability, government involvement, market availability, and information access (Raghavendra, Veerangouda, Prakash, Palled, & Maski, 2013) [25]. In situations when technologies are compatible with one another, farmers might implement many technologies at once (Parmar, 2019) [20]. Water conservation measures can be achieved through various means, such as a happy seeder, and soil erosion can be reduced through minimum conservation, tillage, and mulching (Onwude, Abdulstter, Gomes & Hashim, 2016) [19]. On the other hand, a farmer who raises livestock can use the manure from that business to improve the soil's health. The developed world has long advocated for a new paradigm in agricultural development known as climate-smart based mechanization in order to adapt farming practices to the effects of a warming planet (National Academy of Agricultural Sciences [NAAS], 2016). Technical, managerial, and policy initiatives may help close the yield gap and boost agricultural output in India. Research has shown that some automated technologies, when implemented properly (Javaid, Haleem, Singh, & Suman, 2022) [13], have the potential to

- Raised output and efficiency on farms by 10-15%
- Increase of 5-20% in the degree of cropping
- You may save up to 15-20% on seeds.
- You may save time and effort by 20-30% and save fertilizer and chemicals by 15-20%.

Efforts by the government to automate farming

There is an immediate need for climate-smart agriculture in light of the current situation of increased input usage efficiency and better use of agricultural inputs. The Indian government has launched a program called Sub-mission on Agricultural Mechanization (SMAM) to increase the availability of farm electricity up to 2.5 kW/ha and encourage the use of farm mechanization (Grant Thornton, 2017) [12]. The Government of India provides 100% to MAM, a Central Sector Scheme that has many components aimed at teaching, testing, promoting, demonstrating, and enhancing agricultural mechanization and management. Makes a contribution With the exception of the states in the Northeast and Himalayan areas, where the percentages are 90 and 10, respectively, the amount allocated to centrally sponsored schemes by the Indian government and the states is 60 and 40% (Bhambota, Dixit, Manes, Dhatt, Singh, & Singh, 2018). According to SMAM (2020), in the case of Union Territories, the center share is 100%. Another big problem that arose was residue burning, which prompted efforts to develop climate-smart solutions, such as investing Rs 591.62 crore to promote agricultural mechanization for in-situ management of crop residue (DACFW, 2019) [9].

3. Methodology

3.1 Study Area and Sample Size

The study was conducted in Hisar, Haryana, a region known for its agricultural activity. A total of 100 farmers were surveyed, ensuring representation from smallholder, marginal, and medium-scale farmers.

3.2 Survey Design

A structured questionnaire comprising 15-20 questions was developed to capture farmers' perceptions of climate-smart mechanization. The questions were categorized into:

- **Awareness:** Knowledge of climate-smart agriculture and mechanization.
- **Adoption:** Current usage of mechanized tools.
- **Perceived Benefits:** Impact on productivity and resource efficiency.
- **Challenges:** Barriers to adoption.
- **Future Prospects:** Willingness to adopt advanced technologies.

Responses were recorded on a 5-point Likert scale, ranging from 1 (Strongly Disagree) to 5 (Strongly Agree).

3.3 Data Collection and Analysis

The survey was conducted through face-to-face interviews. Data were analyzed using statistical tools, including descriptive statistics, correlation analysis, and graphical representations to identify patterns and trends.

4. Data Analysis and Results

4.1 Demographic Profile of Respondents

The demographic profile of the 100 respondents surveyed is presented in the table below, detailing their key characteristics:

Table 1: Demographic Profile of Respondents

Category	Sub-category	Number of Respondents	Percentage (%)
Gender	Male	70	70%
	Female	30	30%
Age	<30 years	20	20%
	30-50 years	50	50%
	>50 years	30	30%
Landholding Size	Marginal (<1 ha)	40	40%
	Small (1-2 ha)	35	35%
	Medium (>2 ha)	25	25%
Education Level	Illiterate	15	15%
	Primary	30	30%
	Secondary	35	35%
	Graduate and Above	20	20%

Source: Combined by Researchers

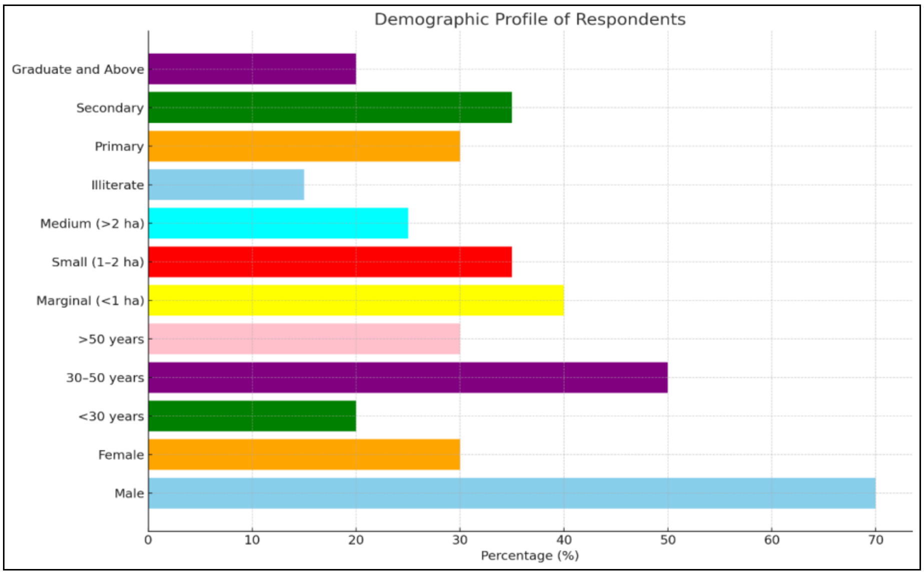


Fig 3: Demographic Profile of Respondents

The demographic profile of the respondents provides valuable insights into the diverse characteristics of the surveyed population. In terms of gender, 70% of the respondents were male, while 30% were female, reflecting a common trend in agricultural practices where men are typically more involved in decision-making and mechanization processes. However, the presence of female respondents emphasizes the increasing role of women in agriculture, which is an encouraging sign for gender inclusivity in farming activities. When examining the age distribution, the majority of respondents (50%) fell within the age group of 30-50 years, representing the most active and productive age group in farming. Younger farmers, below 30 years, accounted for 20% of the population, showcasing the presence of a new generation of agriculturists who are more likely to embrace technological advancements. Meanwhile, 30% of respondents were over 50 years, highlighting the participation of experienced farmers who often rely on traditional methods but can also provide valuable insights into the challenges and benefits of adopting mechanization. The size of landholdings varied significantly among the respondents, with 40% being marginal farmers (less than 1 hectare), 35% small farmers (1-2 hectares), and 25% medium-scale farmers (more than 2 hectares). This distribution underlines the predominance of small and fragmented landholdings, which is a common challenge in the agricultural landscape and often limits the adoption of large-scale mechanization. Marginal and small farmers, in particular, face significant financial and logistical barriers to accessing advanced tools. Educational levels among respondents reveal a diverse background, with 15% being illiterate, 30% having completed primary education, 35% having a secondary-level education, and 20% being graduates or above. This diversity in education levels suggests varying degrees of familiarity with modern technologies, as higher education is generally associated with greater awareness and willingness to adopt innovative practices. However, the significant proportion of respondents with basic or no education highlights the importance of tailored awareness and training programs to bridge the knowledge gap and promote mechanization inclusively.

4.2 Awareness of climate-smart mechanization

This section assesses the respondents' level of awareness regarding climate-smart mechanization practices. It focuses on their familiarity with Climate Smart Agriculture (CSA), understanding of how mechanization contributes to farming, participation in training programs, and perception of increasing awareness in their community.

This section evaluates the respondents' level of awareness regarding climate-smart mechanization practices. The responses indicate that 41% of farmers strongly agree and 34% agree that they are aware of climate-smart agricultural practices. This reflects a promising level of awareness among the majority of respondents, which can serve as a foundation for promoting further adoption of these practices. However, 13% remained neutral, and 12% expressed disagreement or strong disagreement, highlighting a gap in awareness that needs to be addressed through targeted outreach programs and community engagement. Understanding how mechanization contributes to farming saw similar trends, with 43% of respondents strongly agreeing and 28% agreeing that they understand its role in improving agricultural efficiency. However, a noticeable 19% expressed disagreement or neutrality, suggesting that while awareness exists, a deeper understanding of the benefits and applications of mechanization is still lacking. This points to the need for educational initiatives that explain the tangible advantages of mechanization in addressing productivity and sustainability challenges. Participation in training programs on mechanization was slightly lower, with only 38% strongly agreeing and 33% agreeing that they have attended such programs. This highlights a gap in hands-on exposure to mechanization, which is crucial for fostering practical understanding and skill development. Meanwhile, 14% remained neutral, and 15% expressed disagreement, reflecting the limited reach of existing training initiatives and the need for more accessible and inclusive programs, particularly for marginalized farmers. When asked about the perceived increase in awareness of mechanization within their communities, 40% of respondents strongly agreed and 29% agreed, while 17% remained neutral. Although these results show a positive trend in growing awareness, the presence of 14% who disagreed or strongly disagreed indicates that there are still barriers to spreading knowledge effectively. Community-driven awareness campaigns and demonstration programs could help overcome these obstacles and ensure that more farmers recognize the value of climate-smart mechanization.

Table 2: Respondents' level of awareness regarding climate-smart mechanization practices and its benefits

Q. No.	Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1	Are you aware of climate-smart agriculture practices?	41 (41%)	34 (34%)	13 (13%)	8 (8%)	4 (4%)
2	Do you understand how mechanization helps in farming?	43 (43%)	28 (28%)	12 (12%)	10 (10%)	7 (7%)
3	Have you attended any training on farm mechanization?	38 (38%)	33 (33%)	14 (14%)	9 (9%)	6 (6%)
4	Do you believe awareness about mechanization is increasing?	40 (40%)	29 (29%)	17 (17%)	8 (8%)	6 (6%)

Source: Combined by Researchers

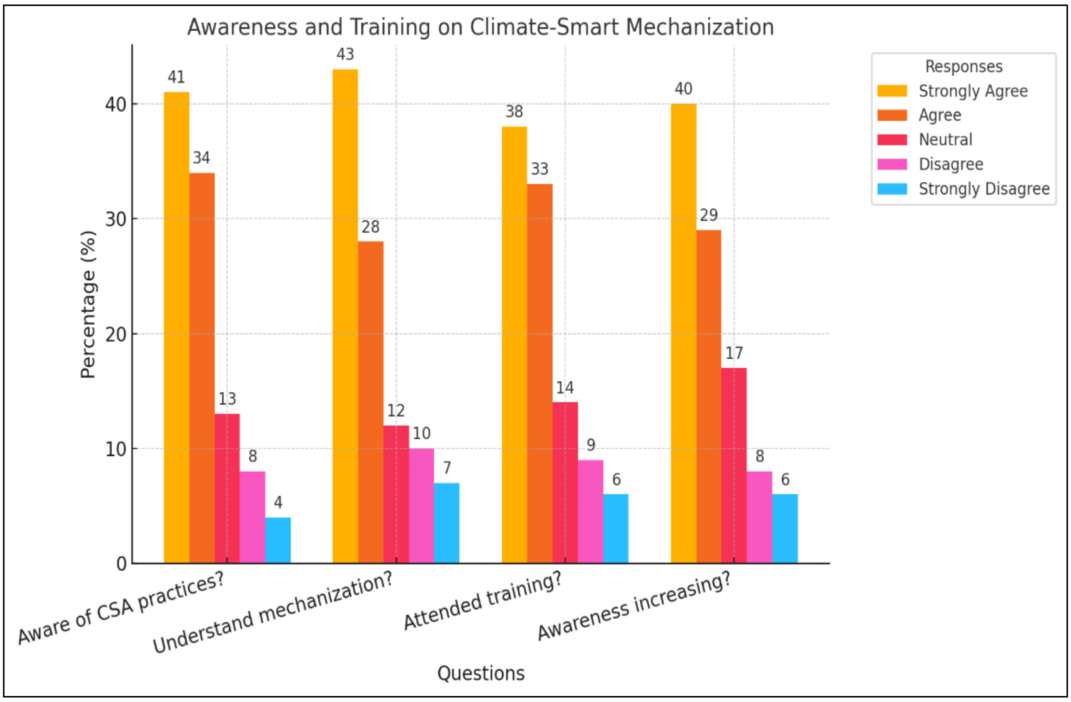


Fig 4: Respondents' level of awareness regarding climate-smart mechanization practices and its benefits

4.3 Adoption of Mechanized Tools

This section evaluates the extent to which respondents have adopted mechanized tools for farming. It explores their ownership of mechanized equipment, preference for hiring over purchasing, and whether they believe mechanized tools save time and effort.

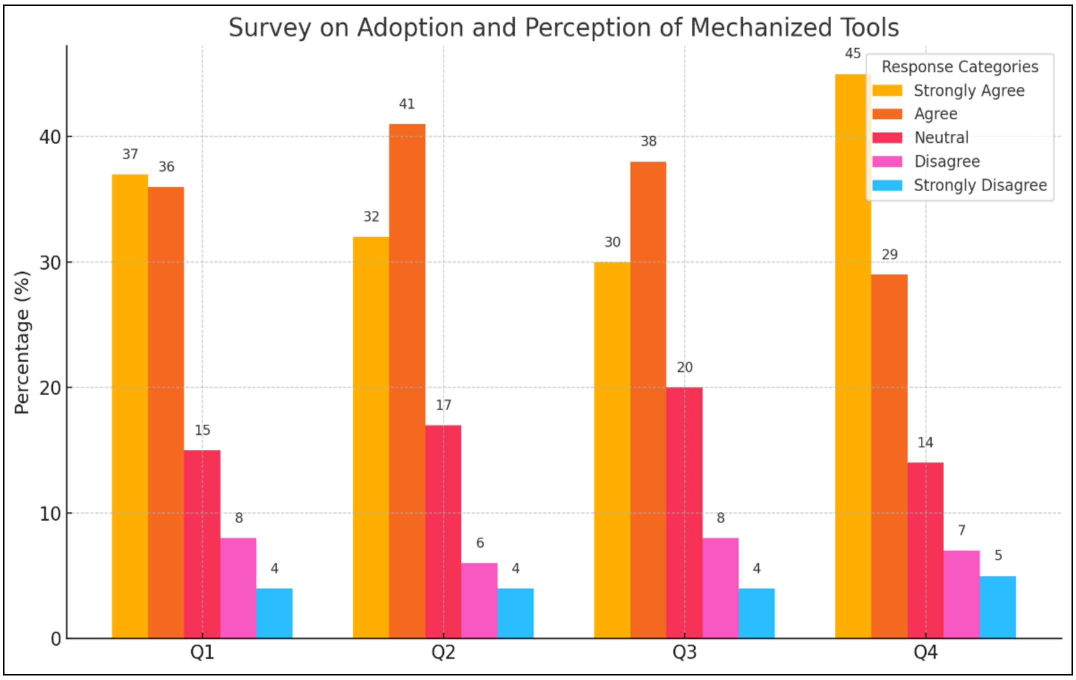


Fig 5: Farmers' usage patterns of mechanized tools, ownership, and time-saving benefits

Table 3: Farmers' usage patterns of mechanized tools, ownership, and time-saving benefits

Q. No.	Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1	Have you adopted any mechanized tools for farming?	37 (37%)	36 (36%)	15 (15%)	8 (8%)	4 (4%)
2	Do you own any mechanized equipment?	32 (32%)	41 (41%)	17 (17%)	6 (6%)	4 (4%)
3	Do you prefer hiring mechanized tools over purchasing?	30 (30%)	38 (38%)	20 (20%)	8 (8%)	4 (4%)
4	Do you believe mechanized tools save time?	45 (45%)	29 (29%)	14 (14%)	7 (7%)	5 (5%)

Source: Combined by Researchers

This section delves into the extent of adoption of mechanized tools by respondents and their experiences with such equipment. The results reveal that 37% of farmers strongly agree and 36% agree that they have adopted mechanized tools in their farming practices. This indicates that a majority have embraced mechanization to some extent, reflecting its perceived value in improving farming operations. However, 15% remained neutral and 12% expressed disagreement, suggesting that certain farmers still face challenges in adoption due to financial, technical, or logistical constraints. Ownership of mechanized equipment was reported by 32% of respondents who strongly agreed and 41% who agreed, while 17% remained neutral. This indicates that while a substantial portion of respondents own equipment, others might rely on hiring or sharing arrangements due to the high cost of purchasing machinery outright. Encouragingly, 8% expressed disagreement, showing that there is a smaller but significant group that struggles to access mechanized tools altogether. The preference for hiring mechanized tools over purchasing was evident, with 30% strongly agreeing and 38% agreeing with the statement. This highlights the importance of cooperative models and custom hiring centers that allow small and marginal farmers to benefit from mechanization without bearing the full cost of ownership. However, 20% remained neutral, reflecting mixed opinions about this model, while 12% expressed disagreement or strong disagreement, likely due to concerns about the availability or affordability of hiring services. The perception of time-saving benefits from mechanization was strongly positive, with 45% of respondents strongly agreeing and 29% agreeing. This reinforces the idea that mechanized tools are seen as a way to reduce labor-intensive processes and enhance operational efficiency. A smaller group (14% neutral and 12% disagreeing) highlights the need to address specific concerns, such as the suitability of tools for small landholdings or a lack of technical knowledge to operate them effectively.

4.4 Perceived Benefits of Mechanization

This section highlights the benefits that respondents associate with the use of mechanized tools. It covers improvements in productivity, reduction in labor costs, better work quality, and enhanced resource efficiency as a result of mechanization.

Table 4: Perceived advantages of mechanization in farming productivity, labor, and resource efficiency

Q. No.	Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1	Do you believe mechanization increases productivity?	46 (46%)	28 (28%)	15 (15%)	7 (7%)	4 (4%)
2	Do mechanized tools reduce labor costs?	39 (39%)	34 (34%)	14 (14%)	8 (8%)	5 (5%)
3	Do mechanized tools improve the quality of work?	42 (42%)	31 (31%)	13 (13%)	9 (9%)	5 (5%)
4	Are mechanized tools helpful in reducing resource wastage?	37 (37%)	39 (39%)	14 (14%)	6 (6%)	4 (4%)

Source: Combined by Researchers

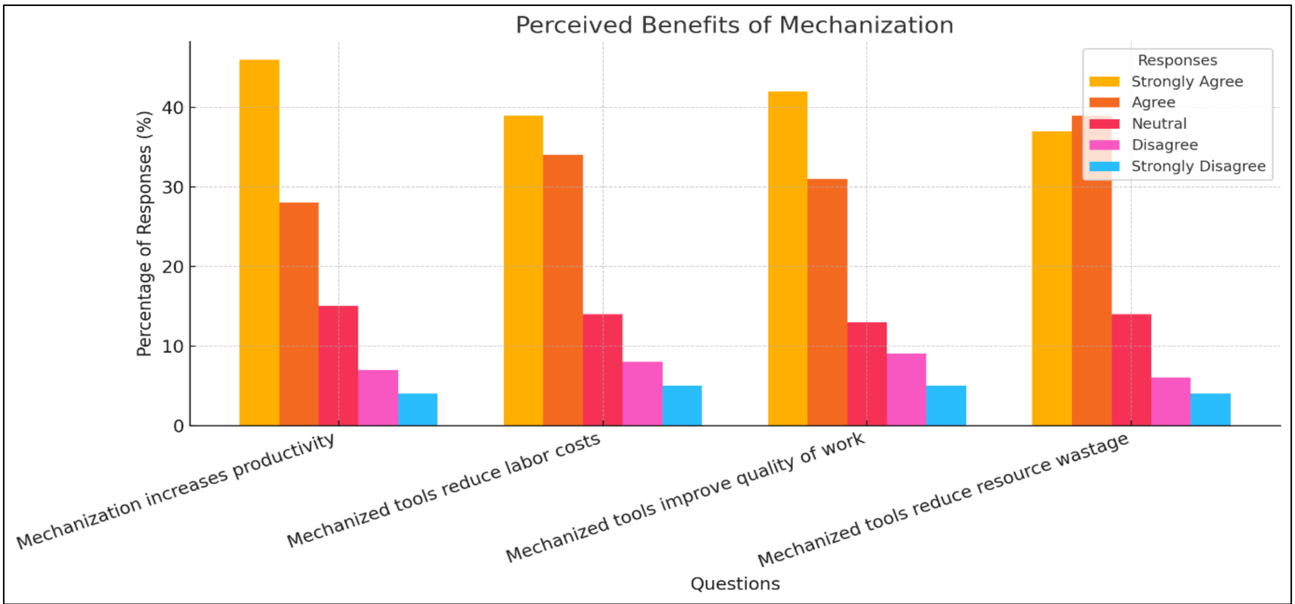


Fig 6: Perceived advantages of mechanization in farming productivity, labor, and resource efficiency

This section evaluates the benefits respondents associate with the use of mechanized tools in farming, focusing on productivity improvements, cost reductions, work quality, and resource efficiency. The responses indicate that a significant number of farmers recognize the advantages of mechanization, although some respondents remain neutral or unconvinced, reflecting varying degrees of adoption and awareness. The belief that mechanization increases productivity was strongly affirmed by 46% of respondents, while 28% agreed, indicating that the majority of farmers acknowledge its positive impact. However, 15% were neutral, suggesting they may not have experienced the benefits firsthand or might be unsure about its applications. A smaller group (11% combined disagreement) may either lack access to proper tools or remain reliant on traditional methods. Regarding labor cost reduction, 39% strongly agreed and 34% agreed that mechanization helps reduce these costs, suggesting that most farmers perceive it as a labor-saving solution. However, 14% remained neutral, and 13% expressed disagreement, potentially due to concerns over initial investment costs or the need for skilled operators, which can offset the perceived savings. The improvement in work quality through mechanization was highlighted by 42% of respondents who strongly agreed and 31% who agreed. This demonstrates that many farmers recognize the precision and consistency provided by mechanized tools. However, 18% either disagreed or remained neutral, suggesting that some farmers might not see a significant difference or lack access to tools that offer measurable improvements in quality. When asked whether mechanized tools help reduce resource wastage, 37% strongly agreed and 39% agreed, showing strong acknowledgment of this benefit. A minority (14% neutral and 10% disagreement) indicated skepticism or limited exposure to resource-efficient tools, highlighting the need for broader demonstrations and education about resource-saving technologies.

4.5 Challenges in adopting mechanization

This section explores the challenges faced by respondents in adopting mechanization. It examines barriers such as the cost of tools, difficulty in accessing them, high maintenance expenses, and insufficient training.

Table 5: Challenges farmers face in adopting mechanized tools and overcoming barriers

Q. No.	Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1	Is the cost of mechanized tools a major challenge?	48 (48%)	27 (27%)	12 (12%)	7 (7%)	6 (6%)
2	Do you face difficulty in accessing mechanized tools?	41 (41%)	33 (33%)	13 (13%)	8 (8%)	5 (5%)
3	Are maintenance costs a barrier for mechanization?	39 (39%)	32 (32%)	16 (16%)	8 (8%)	5 (5%)
4	Is lack of training a reason for not adopting tools?	36 (36%)	34 (34%)	17 (17%)	7 (7%)	6 (6%)

Source: Combined by Researchers

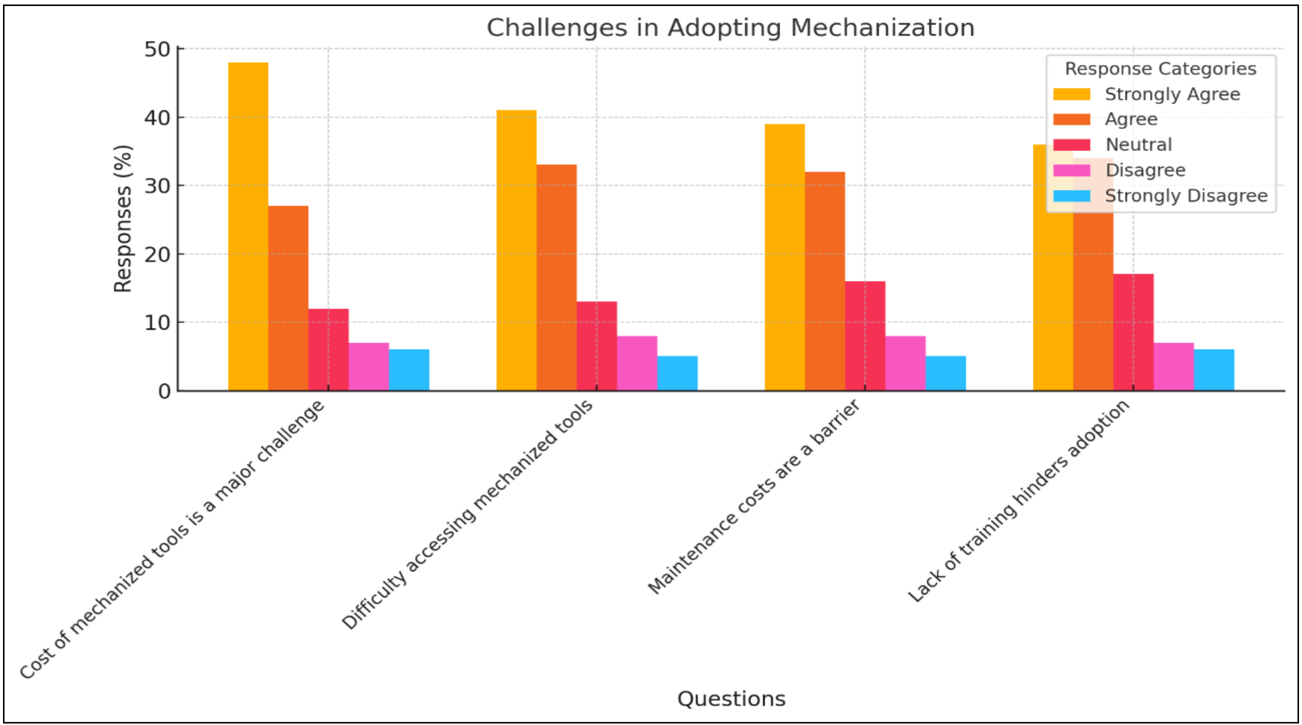


Fig 7: Challenges farmers face in adopting mechanized tools and overcoming barriers

This section explores the barriers that hinder the adoption of mechanization among respondents, including high costs, limited access, maintenance challenges, and insufficient training. The data reveals that while many farmers recognize the benefits of mechanization, practical obstacles still impede widespread adoption. The cost of mechanized tools was identified as a major challenge, with 48% strongly agreeing and 27% agreeing. This highlights the financial burden associated with purchasing and maintaining mechanized equipment, which remains a significant barrier for small and marginal farmers. While 12% remained neutral, 13% expressed disagreement, potentially indicating that they rely on hiring services or have access to subsidized tools. Access to mechanized tools was another notable barrier, with 41% strongly agreeing and 33% agreeing that it is a challenge. This suggests that geographic or logistical constraints, as well as the availability of hiring services, limit farmers' ability to utilize these tools. However, 13%

were neutral, and 13% disagreed, potentially reflecting regional disparities or differing levels of infrastructure development. Maintenance costs also emerged as a critical concern, with 39% strongly agreeing and 32% agreeing that these costs present a barrier. This demonstrates that even farmers who own tools struggle with the ongoing expenses of repairs and upkeep, which can diminish the overall benefits of mechanization. Meanwhile, 16% remained neutral, and 13% disagreed, possibly indicating a lack of experience with maintenance-intensive equipment. Lack of training was identified as another obstacle, with 36% strongly agreeing and 34% agreeing that it hinders adoption. This highlights the need for accessible, hands-on training programs to help farmers understand and operate mechanized tools effectively. However, 17% remained neutral, and 13% disagreed, suggesting that some respondents either do not view training as a priority or already possess sufficient knowledge.

4.6 Willingness to adopt advanced technologies

This section evaluates the willingness of respondents to adopt advanced agricultural technologies. It focuses on their interest in investing in such technologies, their expectations of benefits, and their need for training and subsidies.

Table 6: Farmers' Willingness to Invest in Advanced Agricultural Tools and Training

Q. No.	Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1	Are you willing to invest in advanced technologies?	42 (42%)	37 (37%)	11 (11%)	6 (6%)	4 (4%)
2	Do you believe advanced tools can improve your yield?	43 (43%)	33 (33%)	12 (12%)	7 (7%)	5 (5%)
3	Would you prefer subsidies for purchasing advanced tools?	47 (47%)	31 (31%)	13 (13%)	5 (5%)	4 (4%)
4	Are you interested in training for using advanced tools?	38 (38%)	35 (35%)	17 (17%)	6 (6%)	4 (4%)

Source: Combined by Researchers

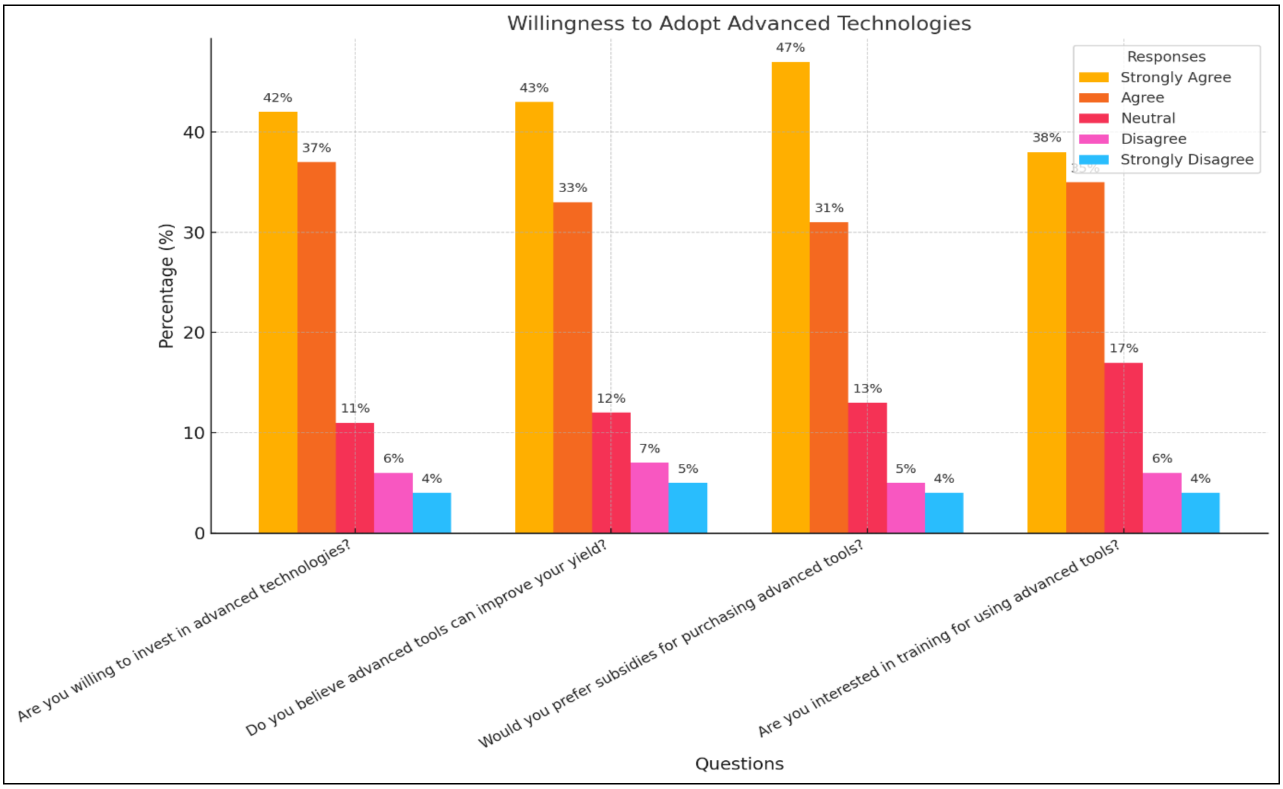


Fig 8: Farmers' willingness to invest in advanced agricultural tools and training

This section assesses respondents' willingness to adopt advanced agricultural technologies, focusing on their readiness to invest, expectations of benefits, and interest in training and subsidies. The responses suggest an encouraging level of interest, although challenges such as financial constraints and training gaps persist. A strong willingness to invest in advanced technologies was reported by 42% of respondents, with 37% agreeing. This demonstrates significant enthusiasm for adopting innovative tools, provided that they deliver measurable benefits. However, 11% were neutral, and 10% disagreed, indicating that some farmers remain hesitant due to financial limitations or uncertainty about returns on investment. The belief that advanced tools can improve yields was affirmed by 43% of respondents who strongly agreed and 33% who agreed, reflecting widespread optimism about the potential of these technologies to enhance productivity. However, 12% remained neutral, and 12% expressed disagreement, which may indicate limited awareness of the specific tools available or skepticism about their effectiveness. The preference for subsidies to purchase advanced tools was notably high, with 47% strongly agreeing and 31% agreeing. This underscores the critical role of financial assistance in encouraging adoption, especially among small and marginal farmers. While 13% were neutral, and 9% expressed disagreement, these results highlight that the majority of farmers see subsidies as essential for overcoming cost barriers. Finally, the interest in training for using advanced tools was strong, with 38% strongly agreeing and 35% agreeing. This indicates that many farmers recognize the importance of developing the skills needed to maximize the benefits of advanced technologies. However, 17% were neutral, and 10% expressed disagreement, suggesting that a minority either feel confident in their existing knowledge or are unable to access training opportunities.

5. Discussion

The findings of this research highlight the critical importance of mechanization and advanced technologies in promoting Climate Smart Agriculture (CSA) to address the multifaceted challenges posed by climate change. As agriculture continues to face escalating threats such as resource scarcity, erratic weather patterns, and growing demands for food security, the adoption of CSA strategies becomes imperative. Mechanization emerges as a cornerstone of these strategies, not only for improving productivity and efficiency but also for mitigating environmental impacts and enhancing the resilience of agricultural systems.

The role of mechanization in CSA is underscored by its ability to optimize input use, increase efficiency, and reduce waste. For instance, precision farming tools such as soil moisture sensors, N-sensors, and remote sensing technologies have shown remarkable potential in improving water-use efficiency and minimizing fertilizer over application (Grant Thornton, 2017; Javaid *et al*., 2022) [12, 13]. These tools not only enhance productivity but also align agricultural practices with global sustainability goals. However, as Vatsa (2023) [30] notes, the level of mechanization in India remains significantly low at just 40%, compared to the 75-95% levels seen in developed countries such as the United States and Western Europe. This disparity highlights the urgent need for targeted interventions to address barriers such as fragmented landholdings and limited access to advanced technologies (Press Information Bureau [PIB], 2020) [23].

One of the most pressing challenges identified in this study is the financial barrier to mechanization. High costs of mechanized tools, coupled with maintenance expenses, have been consistently cited by farmers as major hurdles (DACFW, 2019) [9]. While government initiatives like the Sub-Mission on Agricultural Mechanization (SMAM) aim to promote mechanization through subsidies and financial support, their effectiveness is often hindered by limited grassroots implementation (Rao & Chauhan, 2015) [26]. For example, SMAM allocates up to 100% financial support for specific components such as training and crop residue management (SMAM, 2020), yet a significant proportion of smallholder farmers remain unaware or unable to access these benefits due to bureaucratic inefficiencies and inadequate outreach.

The demographic analysis further emphasizes the need for inclusive and tailored interventions. With 86.21% of operational landholdings in India categorized as small or marginal (< 2 hectares), (DACFW, 2019) [9], mechanization solutions must be designed to cater to the unique needs of these farmers. Custom hiring centers, cooperative societies, and farmer producer organizations (FPOs) represent practical solutions to bridge the accessibility gap. These models allow smallholders to access advanced tools without bearing the full cost of ownership, thereby promoting equitable mechanization. Studies by Reddy *et al*. (2015) and Vatsa (2023) [30] highlight the success of such initiatives in increasing productivity and reducing input costs for small-scale farmers. In addition to financial and logistical barriers, this research also identifies knowledge and skill gaps as significant challenges (Mizik, 2021) [14]. Despite the evident benefits of mechanization, a substantial proportion of farmers reported limited participation in training programs and a lack of familiarity with advanced tools. This finding aligns with Mizik’s (2021) [14] observation that effective implementation of CSA technologies requires a strong emphasis on capacity-building and farmer education. Hands-on training programs, demonstration plots, and peer-to-peer learning networks can play a pivotal role in addressing these gaps and fostering greater adoption of mechanization (Prem, Swarnkar, Kantilal, Jeetsinh, & Chitharbhai, 2016).

The environmental benefits of mechanization are also noteworthy. Mechanized tools have been shown to reduce greenhouse gas emissions, conserve water, and minimize the use of chemical inputs, thereby contributing to a more sustainable agricultural system (Grant Thornton, 2017; Javaid *et al*., 2022) [12, 13]. Practices such as minimum tillage and mulching, facilitated by mechanized equipment, can enhance soil health and increase carbon sequestration (Ali, 2020). These practices not only mitigate the impacts of climate change but also enhance the long-term productivity of agricultural land (Prakash Arjun, Sajeena, & Lakshminarayana, 2017). Moreover, the integration of advanced technologies such as robotics, artificial intelligence (AI), and autonomous systems has the potential to revolutionize farming. Autonomous tractors, AI-driven crop monitoring systems, and drone-based precision applications are examples of innovations that can significantly enhance efficiency and reduce labor requirements (Javaid *et al*., 2022) [13]. However, the adoption of such technologies in India is still in its infancy due to high costs and infrastructural limitations. Efforts to promote indigenous manufacturing of agricultural machinery under the "Make-in-India" program can play a crucial role in bridging this gap by making advanced tools more affordable and accessible (DACFW, 2018) [8].

Another critical aspect explored in this research is the willingness of farmers to adopt advanced technologies. The findings reveal a strong interest in investing in these tools, provided that financial support and training opportunities are made available. Subsidies, in particular, were identified as a key enabler for adoption, with 78% of respondents expressing a preference for financial assistance to purchase advanced equipment. This finding reinforces the importance of government-backed schemes and policies that reduce the financial burden on farmers while promoting long-term sustainability.

Despite the promising trends observed in this study, significant challenges remain. The fragmentation of landholdings, predicted decline in agricultural labor availability, and limited infrastructure for mechanization are systemic issues that require coordinated efforts from policymakers, researchers, and the private sector (Gautam *et al*., 2023). The adoption of climate-smart mechanization must be accompanied by supportive policies that incentivize innovation, enhance access to credit, and foster collaboration among stakeholders. For instance, promoting Public Private Partnerships (PPPs) in agricultural technology development and deployment can accelerate the scaling of CSA solutions (Qureshi *et al*., 2022) [24]. This research underscores the transformative potential of mechanization and technology in advancing climate-smart agriculture. By addressing barriers related to cost, accessibility, and knowledge, and by leveraging innovative solutions such as custom hiring centers and indigenous manufacturing (Qureshi *et al*., 2022) [24], India can bridge the mechanization gap and achieve sustainable agricultural development. The findings of this study highlight the importance of integrating environmental, economic, and social considerations into mechanization strategies to ensure inclusivity and resilience. As climate change continues to pose unprecedented challenges to agriculture, the adoption of climate-smart mechanization is not merely an option but a necessity for securing a sustainable and food-secure future (Reddy *et al*., 2015; Sidhu *et al*., 2015) [28, 29].

6. Conclusion

The transition to climate-smart mechanization is critical for sustainable agriculture in the face of climate change. This study demonstrates that advanced technologies and mechanization strategies can address significant challenges, such as resource scarcity, labor shortages, and environmental degradation, while enhancing agricultural productivity and sustainability. Mechanized tools and precision technologies improve efficiency, reduce waste, and mitigate environmental impacts, offering a pathway to climate resilience. India's current mechanization rate, at 40%, lags behind developed nations, emphasizing the need for targeted interventions. Initiatives like the Sub-Mission on Agricultural Mechanization (SMAM) have shown promise but require effective grassroots implementation to benefit small and marginal farmers. Custom hiring centers, cooperative societies, and financial support systems, such as subsidies, can bridge the accessibility gap, enabling farmers to leverage advanced technologies without incurring high costs. The integration of robotics, AI, and autonomous systems has transformative potential, but its adoption remains limited due to financial and infrastructural barriers. Indigenous manufacturing under the "Make-in-India" program can make these technologies more accessible. Training programs and knowledge-sharing initiatives are equally vital for empowering farmers with the skills needed to maximize technology's benefits. Mechanization offers significant environmental advantages, including reduced greenhouse gas emissions, lower water usage, and improved soil health, aligning agriculture with global sustainability goals. However, achieving widespread adoption requires collaboration among policymakers, researchers, and private stakeholders to address systemic issues like land fragmentation and labor availability. Climate-smart mechanization is not optional but essential for ensuring resilience, sustainability, and food security. By addressing barriers and fostering inclusivity, the agricultural sector can achieve its sustainability goals and adapt to an increasingly unpredictable climate.

7. References

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