

Mechanization policies and strategies: a pathway to smart agriculture for rice production

Bidhan Chandra Nath^{1*}, Haimonti Paul¹, Md Moudud Ahmmed², Subrata Paul¹, Md Durrul Huda¹, Md Golam Kibria Bhuiyan¹, Md Monirul Islam¹, Md Anwar Hossen¹, Md Mizanur Rahman¹, Arafat Ullah Khan¹

(1. Farm Machinery and Postharvest Technology Division, Bangladesh Research Institute, Gazipur-1701, Bangladesh;
2. Workshop Machinery and Maintenance Division, Bangladesh Research Institute, Gazipur-1701, Bangladesh)

Abstract: Mechanization is a vital component of modern agriculture, and this review explores its role in advancing smart and sustainable rice production practices in Bangladesh. It highlights the nation's progress in adopting mechanized solutions, particularly irrigation and tillage, while acknowledging that many farm operations remain labor-intensive. The review suggests significant rice planting and harvesting mechanization to promote sustainability. Government initiatives, collaborations, and technological advancements are examined, focusing on precision farming and IoT-based decision-making. The adoption of rice transplanters and combined harvesters over the past decade is recognized as a strategic government success, with a notable shift toward entrepreneurial models driving mechanization. Challenges, digital interventions, and recommendations for engaging rural youth in long-term mechanization efforts are explored. The review emphasizes the transformative potential of mechanization for smart agriculture and underscores the importance of supportive policies and legislation in facilitating mechanization. These efforts are significant and urgent in ensuring food security and fostering sustainable development in Bangladesh. The review concludes with recommendations to enhance mechanization efforts further, contributing to the sustainable growth of rice production and the overall well-being of the nation's population.

Keywords: Mechanization potential, Government mechanization policy, Mechanization budget, Smart agriculture, Challenges.

Citation: Nath, B. C., H. Paul, M. Ahmmed, S. Paul, D. Huda, G. K. Bhuiyan, M. Islam, A. Hossen, M. Rahman, and A. U. Khan. 2025. Mechanization policies and strategies: a pathway to smart agriculture for rice production. *Agricultural Engineering International: CIGR Journal*, 27(4):168-188.

1 Introduction

Bangladesh has experienced a significant change in its farming methods in recent years (Hasan and Kumar, 2022). This change entails utilizing machines and specific plans to make agriculture smarter and more sustainable. Bangladesh has realized that technology can significantly improve traditional

farming, so the country is now focused on using machines to increase productivity, efficiency, and overall economic development in agriculture (Mada and Mahai, 2013). This paper explores the goal of thoroughly examining and critically analyzing the efforts shaping the country's path in agriculture.

Received date: 2025-02-15 **Accepted date:** 2025-07-27

***Corresponding author:** Bidhan Chandra Nath, Ph.D. Farm Machinery and Post-Harvest Technology Division, Bangladesh Research Institute, Gazipur, Bangladesh. Email: bidhanbrri@gmail.com.

Using machines in farming has been challenging, like dealing with more people, adjusting to changing weather, and ensuring enough food for everyone (Karim et al., 2024; Rakhra et al., 2022). Bangladesh aims to become a "Smart Nation" by 2041, where agriculture plays a vital role in this transformative plan (Ahmed et al., 2023). Mechanized farming is not just about producing more crops efficiently and at a lower cost; it is also a key driver for developing rural areas, creating jobs, and reducing poverty (Giller et al., 2021). In the Bangladeshi context, "mechanized farming" specifically means using machines for growing rice (Kabir et al., 2015; Hossen et al., 2022; Paul et al., 2024). This focus on rice is significant because it is a politically important crop (Karim et al., 2024). In Bangladesh, ensuring enough rice is considered sufficient food for the population (Hossen et al., 2022).

Figure 1 shows the trends in rice production from 1971 to 2023. Bangladesh's rice production area (11.70 million hectares) and productivity has seen remarkable growth, from 9.77 million metric tons in 1971-72 to 41.30 million metric tons, a fourfold rise despite a slight decline in agricultural land. With a population of around 174 million, the country has achieved self-sufficiency in rice production (Kabir et al., 2020). However, the food supply remains vulnerable to climate fluctuations such as floods, droughts, and excessive rainfall. Rice is cultivated in three main seasons: Aus (pre-monsoon), Aman (monsoon), and Boro (dry winter, with irrigation support) (Islam, 2018). Boro cultivation has expanded in recent decades due to its higher yield potential, supported by irrigation and advanced farming techniques (Mainuddin et al., 2021; Pradhan et al., 2022). However, significant challenges persist, including the reliance on manual labor for key tasks, unpredictable weather patterns, and limited mechanization in rural areas. Additionally, the growing impact of climate change, particularly rising temperatures and erratic rainfall, threatens rice production, highlighting the urgent need for adaptive measures and increased mechanization to secure the nation's food supply.

Rice is the primary source of daily calories for

Bangladeshis, constituting a significant portion of their diet (De Brauw et al., 2020; Rahaman et al., 2022). Individuals consume approximately 400-500 grams of rice daily, making it the predominant energy source and nutrients (De Brauw et al., 2020). This dependence is especially pronounced in rural areas, where rice provides nearly 78% of the population's daily calorie intake, highlighting its central role as the primary carbohydrate source. However, this reliance raises concerns about nutritional balance, as excessive rice consumption can result in deficiencies in essential vitamins and minerals. To address these challenges, there is an increasing emphasis on diversifying diets and promoting cultivating other nutritious crops alongside rice. Recognizing the importance of rice for national food security, the government of Bangladesh has prioritized rice production and implemented policies to boost its output. Since 2018, special budget allocations have been made to support rice cultivation and mechanization, aiming to sustain the rising trend in production in response to the country's growing population (Husain and Hossain, 2022).

In Bangladesh, the population is growing, but the amount of land available for farming decreases by 1% each year (Abdu Abdullah et al., 2019). We need to produce more crops to feed the increasing number of people. One way to achieve this is by using machines in agriculture, a sustainable approach known as mechanization (Sims and Kienzle, 2017). This involves adopting smart farming practices. This article explores the various aspects of mechanized agricultural policies and their effects on different groups engaged in smart farming. This includes small-scale farmers, big agricultural businesses, policymakers, and technology providers. The impact of these strategies extends throughout the entire process of producing and selling crops. By studying the current policies and their implementation, as well as their results, we aim to understand what has worked well, what challenges exist, and how we can improve to create a more intelligent and resilient agricultural sector in Bangladesh.

The review also underscores the importance of aligning mechanization efforts and potential areas with sustainability goals. Striking a balance between the imperative for increased agricultural output and the responsible utilization of digital agriculture, particularly IoT-based practices, is essential for ensuring the long-term sustainability of farming methods. This paper thoroughly analyzes the challenges and outlook of mechanized agriculture, delving into strategies for current intervention and practices that contribute to enhanced productivity and

advancing a smart nation initiative.

In the following sections, we will explore the historical background of mechanized agriculture in Bangladesh, the policy frameworks that have shaped its development, and the technological innovations that define its current landscape. By comprehensively examining these aspects, we aim to provide a detailed understanding of the status of mechanized agriculture in Bangladesh. We will delve into its challenges and identify potential avenues for advancing toward a more intelligent and sustainable future.

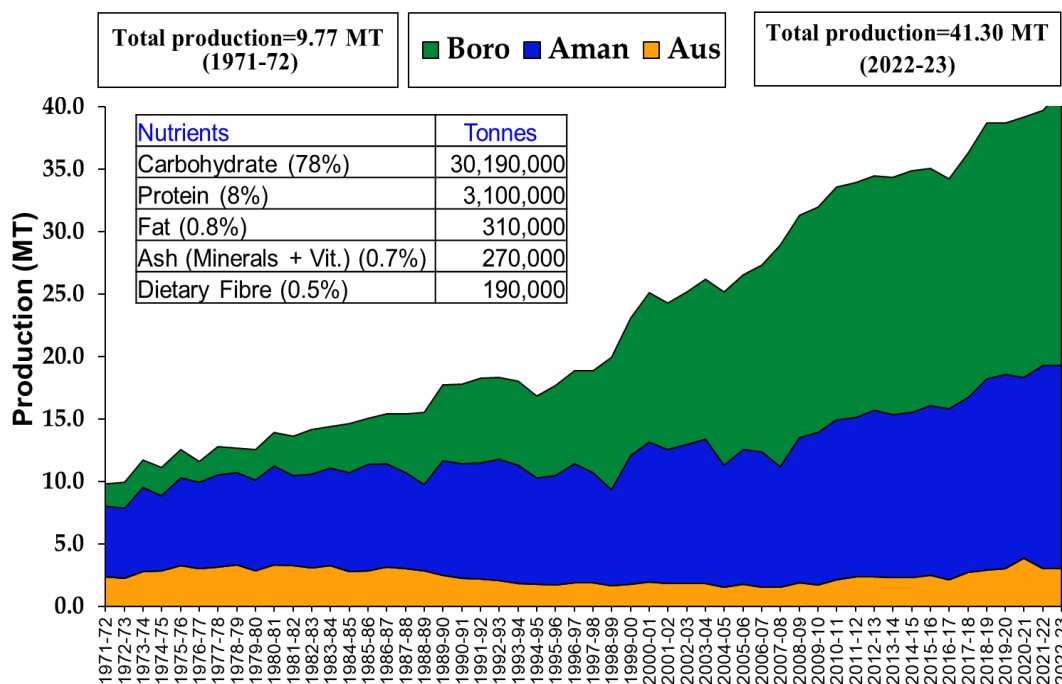


Figure 1 Rice production up from 1971-72 to 2022-23

Source: Department of Agricultural Extension-DAE, Bangladesh Rice Research Institute and (Statistics, 2018)

2 Methods

2.1 Initial step of mechanization and the government's way forward

Agricultural mechanization involves using engines or motorized equipment to facilitate energy transfer within farm production systems (Diao et al., 2016; Nath et al., 2023; Scolaro et al., 2021). This approach simplifies tasks, reduces strenuous labor, addresses workforce shortages, enhances productivity, and holds the potential for mitigating climate-related challenges (Negrete, 2018). In the context of Bangladesh, the origins of agricultural mechanization can be traced back to the early 1960s with the introduction of deep tube wells (DTWs) for irrigation (Hossain, 2018;

Razzak et al., 2017). After gaining independence in 1971, there was a notable change in the irrigation policy, favoring the adoption of shallow tube wells (STWs) and low lift pumps (LLPs) (Biggs and Justice, 2015; Paul et al., 2010a, 2010b). However, when considerable import barriers were lifted for several agricultural equipment's, with two-wheeled tractors (2WTs), a broader mechanization drive started in 198 (Amjad et al., 2024; Nath et al., 2024). This policy shift resulted in a notable increase in imports, mainly sourced from China, leading to a considerable reduction in the cost of agricultural machinery (Mottaleb et al., 2016), minimizing the postharvest losses (Nath et al., 2025), and a subsequent upsurge in

sales. The import of 2WTs was fully duty-free six years later (in 1994), encouraging more private-sector participation in agricultural mechanization (Rahman et al., 2020).

In Bangladesh, small-scale industries gradually transformed from local workshops due to a boom in the demand for farm equipment in the 1990s (Fuad and Flora, 2019). Government assistance in the form of loans and tax cuts made available by the 1999 National Agricultural Policy further contributed to this development (Alam et al., 2017; Chowhan et al., 2024). Consequently, Bangladesh became a leader in farm machinery use in South Asia, with a constantly growing market emphasizing quality products. However, a drawback surfaced as some local entrepreneurs produced substandard machinery, selling it to farmers at the lowest prices, thus negatively impacting the farming community. Consequently, with the rapid expansion of the agricultural machinery sector in Bangladesh, ensuring a rigorous and precise manufacturing process emerged as a significant challenge.

2.2 Status of farm mechanization

Currently, Bangladesh needs a complete inventory of its farm machinery. To paint a picture of the sector, this study gathers data from various sources, including annual reports, surveys conducted by different government agencies and organizations, sales records from importers, and information from major domestic farm machinery manufacturers (see Table 1). Regarding quantity, diesel engines appeared as the preferred power source among farmers, primarily active for running irrigation pumps (Chowdhury et al., 2020). They also find application in a diverse range of other agricultural tasks. For example, Bangladeshi ingenuity is the widespread use of small, diesel-powered boats and trolleys for transporting agricultural goods in rural areas. This popularity can be traced back, at least in part, to the significant subsidies the Bangladeshi government provides for diesel fuel, making it a more affordable option for powering these vehicles (Hossain et al., 2024; Rahman et al., 2022).

Bangladesh, the total number of power tillers (2WT) is 745,000. A diesel-powered agricultural tool is the unchallenged leader in land preparation. Because of their low cost and ease of moving in confined locations, these agile workhorses outweigh their four-wheeled counterparts, with an astounding 185,000 operational units (see Table 1). Additionally, Bangladeshi technicians nationwide have gained expertise in repairing and maintaining 2WTs, encouraging farmers to invest in these machines. Approximately 83% of the country's land is cultivated using 2WTs, while tractors cover the remaining 15% of the land (Sayed et al., 2022) (Figure 2).

A total of 1.57 million STWs, DTWs, and LLPs (Hossain et al., 2022) are used to irrigate about 88% of all agriculture (see Figure 2). The country's pesticide and herbicide spraying mechanization has also surpassed 92%. Despite these noteworthy accomplishments, there is still a slow uptake of other agricultural equipment, including bed builders, weeders, winnowers, seeders, and rice transplanters (Islam and Shirazul, 2009; Paul et al., 2019).

Bangladesh's necessary rice production operations, involving combine harvesters and rice transplanters, currently stand at 400 and 3,064, respectively (Table 1). These sectors exhibit promising potential, signaling the need for increased government investment. Machine transplanting accounts for only 5%, while combine harvesters cover 12% of the rice production operations (Figure 2).

A promising shift is stirring in Bangladeshi agriculture - the rise of mechanized transplanting and harvesting (Titumir, 2021). Spurred by labor shortages during peak seasons, the government has taken a proactive stance since 2016, offering subsidies on transplanting and harvesting machines like the one pictured above. This timely intervention ensures that important agricultural tasks are completed before the monsoon's wrath descends, safeguarding precious crops and farmer livelihoods. This strategic approach addresses labor shortages and serves as a proactive measure against the impacts of climate change through agricultural mechanization in Bangladesh.

Table 1 Status of agricultural machinery in Bangladesh until 2022

Activities	Machinery	Quantity (Nos.)	Sources
Cultivations	Power tiller (2WT)	745,000	Bangladesh Rice Research Institute (BRRRI); Bangladesh Agricultural Research Institute (BARI); Bangladesh Agricultural Development Corporation (BADC); Department of Agriculture Extension (DAE)- Bangladesh; Ministry of Agriculture of Bangladesh; Alim Industries Limited (https://alim.com.bd/); ACI Motors Limited (https://acimotors-bd.com/)
	Tractor (4WT)	158,000	
	Rotary tiller	7,000	
Transplanting	Rice Transplanting	400	
Seeding	Power operated	1,100	
Weeding	Hand operated weeder	2,50,000	
	Power weeder	50	
Spraying	Knapsack Sprayer	20,00,000	
	Reaper	1434	
Harvesting	Whole feed Combine harvester	1230	
	Head feed Combine harvester	400	
Threshing	Rice thresher	3,90,000	
	Maize sheller	23,500	
Cleaning	Winnower	3,000	
	Low Lift Pump	1,81,469	
Irrigation	Shallow Tube well	13,55,852	
	Deep Tube well	37,538	
	Diesel engine	37,00,000	
Power sources	Petrol Engine	25,000	
	Renewable energy	Undefined	

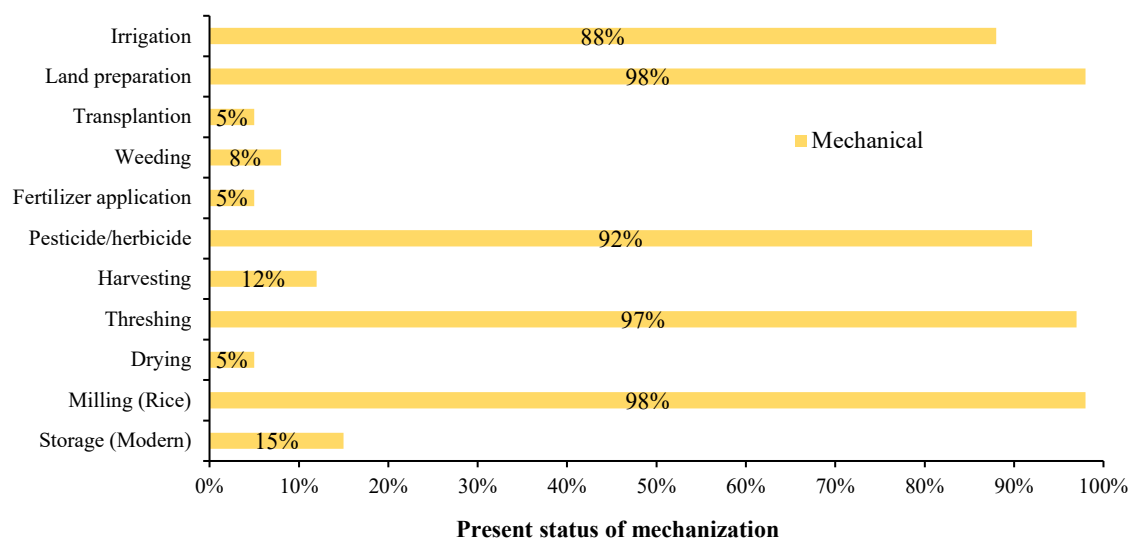


Figure 2 Agricultural mechanization measured in terms of field operations

Source: (Hossen, 2019; Paul et al., 2019; Paul et al., 2021); <https://www.thedailystar.net/country/news/agricultural-machinery-where-bangladesh-heading-1927969>; and BRRI:2023-Ayear in Review (<https://bitly.ws/3arxw>)

2.3 Farm power used in the agricultural production system in Bangladesh

The energy required for farm work can be derived from traditional or modern methods (Chel and Kaushik, 2011). To assess the level of agricultural mechanization in Bangladesh, it is essential to examine the number of power farms and the amount of machinery in use. Between 1960 and 2020, the average agricultural power in Bangladesh increased significantly from approximately 0.3 kW ha⁻¹ to 1.9 kW ha⁻¹ (Figure 3). While farm power was limited in the early 1990s, it experienced an 8% increase in

subsequent years, primarily due to the implementation of new government policies, such as tax incentives.

2.4 Allocation of the government's agricultural budget

The comprehensive budget for agriculture over the last seven fiscal years is depicted in Figure 4. Notably, the Bangladesh government has recently accorded high priority to the agriculture sector, leading to a gradual increase in budget allocations. Much of this augmented budget is earmarked for mechanization, notably the purchase subsidy for selected machinery. The economic challenges stemming from COVID-19

have accentuated the pivotal role of agriculture in securing food production for the nation. The fiscal year 2021 assumes particular importance in safeguarding food security amidst and beyond COVID-19. The agriculture sector serves as a lifeline for newly emerged urban poor communities and a vital source of employment for those affected by job losses.

In response to these challenges, the Bangladesh government has committed a significant financial package, providing US\$ 581 million in soft loans to farmers within a single fiscal year, with a noteworthy portion (US\$ 351 million) explicitly allocated for

mechanization. According to the most recent data provided by Bangladesh Bank in June 2022, the mechanization finance scheme has been successfully executed, with a practical implementation rate of 84.1%. This extraordinary effort, unparalleled in Bangladesh's history, involves utilizing funds to offer substantial subsidies, up to 70%, to farmers investing in machinery. Ensuring the seamless integration of machinery into Bangladesh's agricultural sector necessitates a continued commitment to such resource allocations in the years to come.

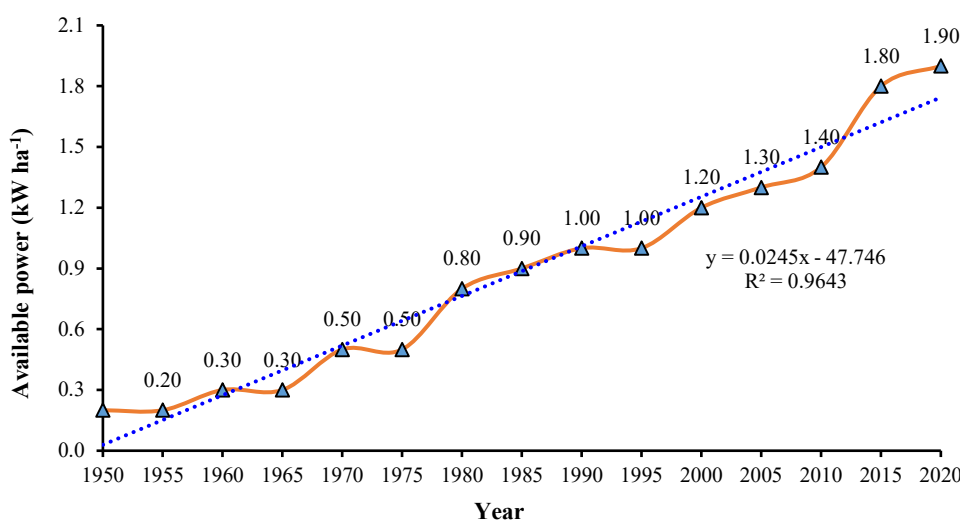


Figure 3 Amount of farm power (kW ha⁻¹) utilized in the agricultural sector in Bangladesh

Source: (Islam, 2018; Kabir et al., 2020)

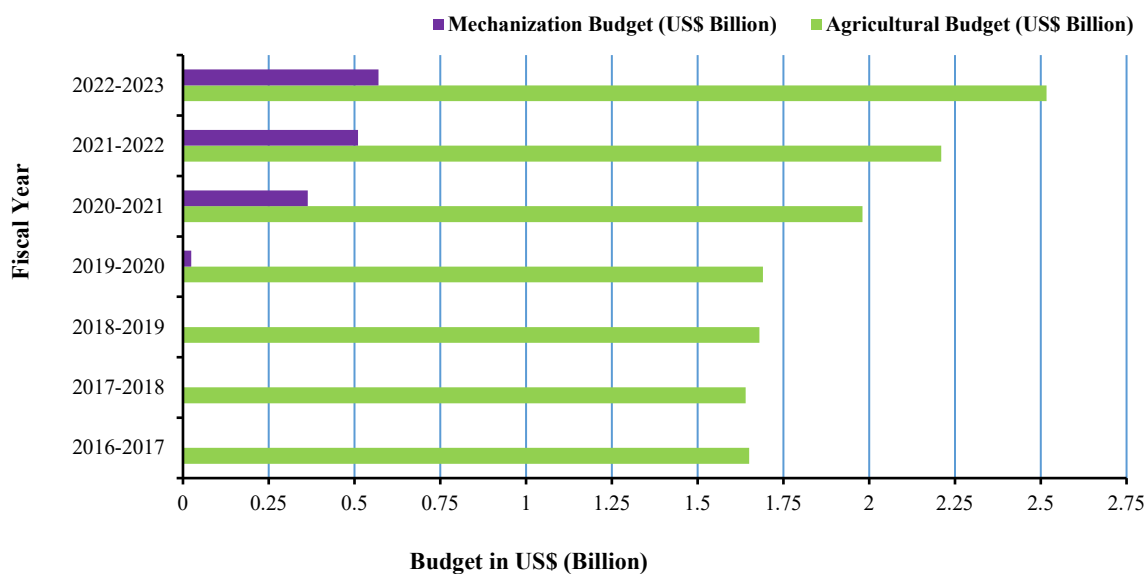


Figure 4 Allocation of government budget designated for the agriculture sector

Source: MoF, Budget in Brief (2016-17 to 2022-23), Finance Division, Ministry of Finance, Government of the People's Republic of Bangladesh, 2022, https://mof.gov.bd/site/budget_mof/2fbdbbbe-e514-4f14-a2a3-fd819e088f4 and MoA, Ministry of Agriculture Bangladesh, <https://moa.gov.bd/site/page/08e59783-6c7a-4a10-8daf-3954c4fc349a>

2.5 Entrepreneurship models

A significant challenge to mechanization in Bangladesh is the limited financial capacity of farmers (Aryal et al., 2019). However, in recent decades, creative approaches like the entrepreneurship model and custom hiring, adopted by communities and individuals, have effectively overcome this hurdle (Neumeyer et al., 2020). This method allows those who can afford machinery to invest in it. At the same time, smaller farmers can rent the services (Figure 5). The entrepreneurship models have been implemented

to ensure the proper use of farm machinery and increase farmers' access to it: group, cooperative, and individual ownership (Hinnou et al., 2022). Notably, the fees and interest often do not reflect ownership costs, such as yearly depreciation and goods, when farmers or cooperatives use their savings to invest. Despite the practical success of these models, scientific documentation regarding their profitability is scarce in the existing literature. This gap highlights the need for further studies to comprehensively assess and document the financial viability of these innovative ownership models.

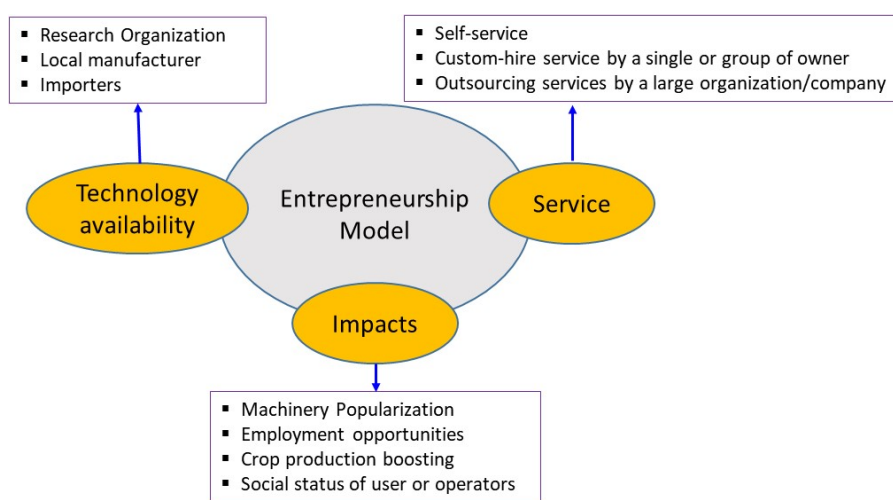


Figure 5 Benefits of the entrepreneurship model: inspiration of mechanization

1960	1988	1999	2012	2020	2021	2022
<ul style="list-style-type: none"> Introduce Deep tube wells 	<ul style="list-style-type: none"> Import Tariffs Withdraw 	<ul style="list-style-type: none"> National Agricultural Policy Minor Irrigation Policy 1999 	<ul style="list-style-type: none"> Agricultural Extension Policy SDG 2012 	<ul style="list-style-type: none"> National Agricultural Mechanization Policy 2020 Perspective Plan Bangladesh: 2021-2041 8th Five-Year Plan 	<ul style="list-style-type: none"> Bangladesh Delta Plan 2100 	<ul style="list-style-type: none"> National Adaptation Plan Bangladesh: 2023-2050 4IR Work Plan

Figure 6 Key policy steps towards mechanization as well as smart agriculture

3 Recent Initiatives

Bangladesh initially focused on small-scale farming equipment that suited its economic situation for agricultural mechanization. The next phase involved introducing foreign machinery and producing domestic spare parts. By 2020, the third stage of agricultural mechanization emerged through

collaboration between the public and private sectors, guided by the “National Agricultural Mechanization Policy” (<https://bitly.ws/3arMU>). This policy provides technical support for developing agricultural machinery at various levels, emphasizing the importance of appropriately sized mechanization in the country. Additionally, it recognizes the necessity of

establishing service providers of farming machines as a viable business model.

Recently, Bangladesh has actively embraced smart agriculture through various initiatives, including pilot projects and policies heading toward smart agriculture (Figure 6). The associated policies such as the National ICT Policy 2020, Minor Irrigation Policy 1999, Krishi Vision 2025, National Strategy for Robotics 2020, Drone Registration and Flying Policy 2020, and the National Blockchain Strategy: Bangladesh 2020 also boosting the crop production through machinery used in the agricultural domain (Karim et al., 2023). Therefore, Bangladesh has also significantly emphasized precision agriculture, incorporating the Internet of Things (IoT), machine vision, etc.

Through diverse institutes and ministries, the government has implemented various rules,

regulations, and strategies to enhance crop postharvest operations. These efforts prioritize research and development in essential areas like harvesting, processing, transportation, packaging, and storage (Nath and Nam, 2013). A key focus is advancing sustainable farm mechanization technologies to boost energy efficiency and integrate renewable sources (Majeed et al., 2023). The policy, mindful of farmers' socio-economic conditions, aims to adopt affordable technologies. Additionally, it supports local enterprise development for farm mechanization services and encourages environmentally friendly equipment. The dynamic nature of policy implications, responsive to various situations, is evident, emphasizing the nuanced implementation and adaptation of strategies outlined in Table 2 to ultimately strengthen agricultural production.

Table 2 Potential work/research area and policy implications

Overall goal	Issues/Problems	Research areas/ Actions needed	Policy implications
Strengthening farm mechanization	Insufficient machinery poses challenges in crop production, irrigation, agro-processing, oil extraction, juice extraction, gur-processing, rice drying, parboiling, etc.	Develop suitable machinery related to crop production like a tiller, seeder, planter, weeder, fertilizer applicator, harvester, etc. Machinery for threshing, sorting, cleaning, storage, drying, rice parboiling, milling, oil extraction, juice extraction, gur processing, etc. Impact study of mechanization in rural livelihood and environment	A, C, D, E, F, G, H, M
	Limited utilization of available machinery		
	Policy issues persist regarding the quality and standardization of agricultural machinery	Design and manufacture of irrigation equipment	A, D, K
Postharvest management	High percentages of losses occur in the supply chain from production to consumption	Postharvest losses assessment of different commodities Develop techniques to reduce losses through pre- and postharvest operations.	A, C, D, E, F, G, L
	Inefficient and unorganized marketing system	Safe technique advancement for fruit ripening and shelf-life extending Standardize maturity indices for major fruits Standardize postharvest handling, packaging, transportation and storage techniques for different commodities	
	Lack of low-cost improved technologies	Searching sources of renewable energy Development of biofuel without hampering food security	
Management of agricultural waste and energy generation	Crisis of energy in agricultural operation	Explore the biological source of ethanol	A, C, D, E, F, G
	Absence of a program for exploring renewable energy	Effective use of huge Agri-waste Conversion to biofuel from wastes leftover after refinement of crude oil for edible oil	
	Under-utilization of agricultural waste	Develop machinery and equipment for efficient use of renewable sources of energy Prospect and process for using renewable energy like solar, wind, biofuel, biogas, etc., in farm machinery	

Note: A= National Agricultural Mechanization Policy 2020; C = 8th Five-Year Plan; E= Krishi Vision 2025; G= Fourth Industrial Revolution (Draft); I= National ICT Policy 2020; K= Minor Irrigation Policy 1999; M= National Strategy for Robotics 2020; B= National Strategy for Artificial Intelligence 2020; D= National Agriculture Policy 2018; F= Agricultural Extension Policy 2020; H= National Strategy for Artificial Intelligence 2020; J= National Blockchain Strategy: Bangladesh 2020; L= Drone Registration and Flying Policy 2020

3.1 Plan for fourth industrial revolution: smart agriculture and mechanization

Bangladesh's government, especially the Ministry of Agriculture, is trying wholeheartedly to modernize the agricultural production system. Hence, a proposal to develop an actionable plan to adopt Fourth Industrial Revolution (4IR) indicators for smart agriculture is needed in Bangladesh. IOT-based digital technologies are the primary foundation of 4IR (Datta, 2022).

In agriculture, particularly in Bangladesh, digital technologies are poised to revolutionize the enhancement of yields, minimize wastage, and foster economic growth (Abiri et al., 2023). Aligned with the original Digital Bangladesh Vision 2021, the government has adopted Vision 2041, aiming to eliminate extreme poverty, attain upper middle-income country (UMIC) status by 2031, and achieve high-income country (HIC) status by 2041 (Hasan and Irfanullah, 2022). This transformative revolution incorporates innovative input sourcing, precise tilling, data-driven guided planting, drone-assisted irrigation (McLennon et al., 2021), and IoT-enabled crop readiness sensing to optimize the harvesting process. Digital marketplaces with analytics are revolutionizing agricultural trade, robotics, and blockchain technology are integrated into processing, and IoT tracking enhances logistics visibility. These interventions

promise to revolutionize the entire agricultural value chain, foster efficiency, and drive innovation (Table 3).

3.2 Present efforts aim to boost mechanization through the promotion of IoT

The government invests in various modern digital solutions to effectively tackle agricultural challenges. These solutions aim to enhance efficiency, accessibility, and knowledge dissemination within the farming sector (Fabregas et al., 2019) (Table 4). Present efforts are concentrated on optimizing machine performance by utilizing smart technology known as the Internet of Things (IoT). This strategic emphasis on IoT stems from its potential to revolutionize practices in diverse sectors such as farming and industry (Ayaz et al., 2019). Through IoT, machines can be linked to sensors and devices, enabling them to operate more efficiently (Bansal and Kumar, 2020). For instance, farmers can monitor their crops and environmental conditions in agriculture in real time, facilitating informed decision-making and sustainable agricultural practices. Additionally, IoT enables remote monitoring and control of machines, ensuring seamless operations (Raj et al., 2021). By fostering collaboration and knowledge sharing, stakeholders can maximize the potential of IoT, leading to innovation, environmental sustainability, and economic prosperity for all involved (Allioui and Mourdi, 2023).

Table 3 Benefits of IoT-based technique applications in agricultural mechanization in Bangladesh (Karim et al., 2023)

Opportunity	Remarks
Crops, soil, and livestock monitoring	Discover opportunities for implementing IoT in agriculture through collaboration with agricultural experts and farmers, and formulate strategic initiatives.
Sowing advisories	
Diseases forecasting system for crops	
Dynamic soil topology map	Adopt precision agriculture and automation solutions to narrow yield gaps and mitigate environmental damage.
Picture-based diseases prediction and medication	
Agricultural robots	Utilize data intelligence to enhance food inspection processes, address food waste challenges, and improve early warning systems for post-harvest plant diseases and pest outbreaks.
Herbicide optimization	
Reducing farm workload	
Precision farming	Create strategies to decrease trade intermediation between small farmers and buyers to reduce inefficiencies and enhance farmers' profitability.
AI sensors to detect and target weeds while deciding which herbicides to apply within the right buffer	
AI solutions to monitor and suggest for measurements for crops, soil, and livestock	Predictor for agro-business and marketing
Predictive analysis using ai for real-time advisories to farmers	Production in a controlled environment

Table 4 Government initiatives paving the way forward for smart agriculture (Alam, 2023; Chowhan et al., 2024; Karim et al., 2023).

	Initiatives	Targeted services
1	Krishoker Janala	Serves as a database for plant diseases and samples
2	Krishoker Digital Thikana	Provides information on crop-specific production techniques
3	Pesticide Prescriber	Enables extension officers to recommend suitable pesticides, while SMS-based livestock services provide complimentary access to essential veterinary services via text messages
4	Toll-free call service "Agri Call Service 16123."	Allows farmers to seek expert advice on agriculture
5	Agricultural Information and Common Center	Serves as a farmer-run agricultural information dissemination service
6	National Agricultural Portal	Acts as a one-stop platform for accessing information on crops
7	Climate IMS	Provides a dashboard logging prevailing weather conditions
8	E-Marketing Portal	An effort concentrated on distributing market information to farmers, traders, and other participants in the agricultural value chain

3.3 Current initiatives are directed towards enhancing mechanization by advocating for the widespread adoption of ICT

Information and communication technology (ICT) is pivotal in transforming mechanization in Bangladesh, leading to enhancements in effectiveness, precision, and sustainability (Ahsan et al., 2022). By collecting information on soil conditions, crop health, and weather patterns, ICT facilitates precision agriculture, enabling farm equipment such as tractors and harvesters to operate efficiently with optimal resource usage. State-of-the-art machinery equipped with sensors and controllers utilizes real-time data to automate tasks like harvesting and milking, ensuring higher precision and reducing reliance on human intervention (Amertet et al., 2023). ICT enables remote monitoring and control through mobile apps and web interfaces, empowering farmers to track progress, monitor equipment, and manage functions remotely. Sensors can detect potential equipment malfunctions, enabling proactive maintenance to minimize downtime. ICT is revolutionizing mechanization, making it more efficient, productive, and environmentally sustainable.

3.4 Recent endeavors are focused on augmenting mechanization through the advocacy and implementation of Artificial Intelligence (AI) technologies

In Bangladesh, the use of artificial intelligence (AI) in farming machinery is growing rapidly (Babu, 2021). This push aims to make agriculture more efficient by incorporating AI into different farming methods (Ferdous et al., 2021). AI empowers machines to become more innovative and adaptable, offering

numerous benefits. These include optimizing resource utilization, automating repetitive tasks, and making data-driven decisions. By integrating AI, Bangladesh's agriculture can significantly improve efficiency, productivity, and crop yields.

3.5 Blockchain to enhance transparency and efficiency of Bangladesh's agricultural mechanization

Bangladesh's mechanization sector is adopting an advanced technology: Blockchain (Rahman and Abedin, 2021). This innovative approach enhances the agricultural supply chain by ensuring transparency, traceability, and efficiency. Blockchain technology enables the secure recording and tracking of critical data, such as equipment maintenance, land ownership, and crop origin (Kamble et al., 2020). This transparency benefits all stakeholders, empowering farmers to access loans more efficiently and obtain fairer prices for their produce. Consumers can trust that their food is high quality and sourced responsibly. Additionally, Blockchain could make the process of getting products from farms to consumers smoother and more efficient, which would help the whole agricultural sector in Bangladesh (Tasnim et al., 2022).

3.6 Present status of agricultural mechanization and the prospects for enhancing farm production

Bangladesh became a middle-income country in 2020, marking a significant milestone (WHO, 2017). However, this achievement has been accompanied by a notable trend of rural labor migration to urban centers over the past three decades. More unskilled workers from agriculture are now working in the ready-made garments industry because there's a growing need for

affordable unskilled labor there. This change has led to a shortage of agricultural labor in rural areas, especially during crucial times like planting and harvesting seasons when fulfilling the seasonal targets is essential. The upcoming phase of agricultural mechanization in Bangladesh is anticipated to address these shortages, particularly in the transplanting and harvesting sectors. Nevertheless, there is also a growing need to mechanize tillage, weeding, and crop protection technologies in the foreseeable future (Nath et al., 2021).

3.6.1 Land cultivation and preparation

The power tiller (PT) has emerged as a revolutionary machine in Bangladesh, significantly revolutionizing tillage operations across the country. Moreover, land cultivation services facilitated by PT-operated ladders are available on a custom-hire basis (Islam, 2018). However, implementing moldboard or disc plows for large-scale farming in regions with dense clayey loam soil is still pending. The dominant tillage practice in Bangladesh involves tractors equipped with mounted rotavators, leading to widespread shallow tillage. Enhancing cultivation mechanization is possible by introducing tractor-drawn moldboard or disc plows. Furthermore, aligning with the fourth industrial revolution (4IR) goals, a four-wheel drive tractor has a significant potential for achieving 100% machine-operated cultivation.

As the use of farming machinery has increased significantly, there is a clear need for regulations in the service industry. Several reports suggest that mechanics charge higher fees for repairs and maintenance without clear explanations (Majumder and Dey, 2020). Local authorities might establish on-demand mobile repair and maintenance services to address this issue, particularly during the pandemic. This would eliminate the necessity of visiting crowded workshops, thus minimizing the risk of infection.

3.6.2 Rice seedling raising and transplanting

In Bangladesh, rice is a staple food and undergoes predominantly manual seedling, raising, and transplanting processes. This manual approach is time-consuming, costly, and frequently results in crop

transplanting shock (Sangeetha and Baskar, 2015). Mechanical solutions offer a practical way, allowing the transplantation of infant seedlings and eliminating the risk of shock (Singh et al., 2023). Labor shortages frequently result in delays in transplanting within the paddy farming industry, with studies indicating significant yield reductions for delayed transplanting (Islam, 2016).

In Bangladesh, manual rice planting takes around 123~150 person-hours/ha, whereas mechanical transplanters reduce it to 9-11 person-hours ha⁻¹ (Islam et al., 2016). Currently, most seedling raising relies on manual labor, but some forward-thinking farmers are adopting transplanters for both seedling raising and field transplanting (Huda et al., 2024; Kamruzzaman et al., 2014). However, these machines are often used for demonstrations to raise farmers' understanding of the benefits of mechanized transplanting (Hossen et al., 2022; Paul et al., 2016). Public and private organizations are collaborating to train local entrepreneurs in mechanical transplanting services, with a government initiative offering a 70% subsidy on the market prices of transplanting machines (Sarkar et al., 2024). To support these efforts, the study suggests: a) establishing repair and maintenance services for rice transplanters in each upazila by agricultural extension services, b) creating training facilities and programs for machine operators in key locations nationwide, focusing on educating owners and operators about machine calibration based on various factors, and c) hiring agricultural engineers with technical knowledge to oversee and advise transplanting activities at the upazila level.

Rice transplanting is a significant sector within rice production, holding considerable potential for the future (Kabir et al., 2020). In Bangladesh, common rice transplanters include 4-row walking and 8-row riding models. Based on their potential, annual area coverage is estimated at approximately 45 hectares for walking-type transplanters and 80 hectares for riding-type transplanters. Projections suggest that in 2030, 2035, and 2040, four-row walking-type transplanters will cover 95%, 93%, and 90% of the total rice area to

be transplanted, respectively. 8-row transplanters will cover the remaining area. Assuming 95% mechanical transplanting, the estimated demand for rice

transplanters is 19,720, 53,410, and 101,500 units for 2020, 2030, and 2040, respectively (Figure 7).

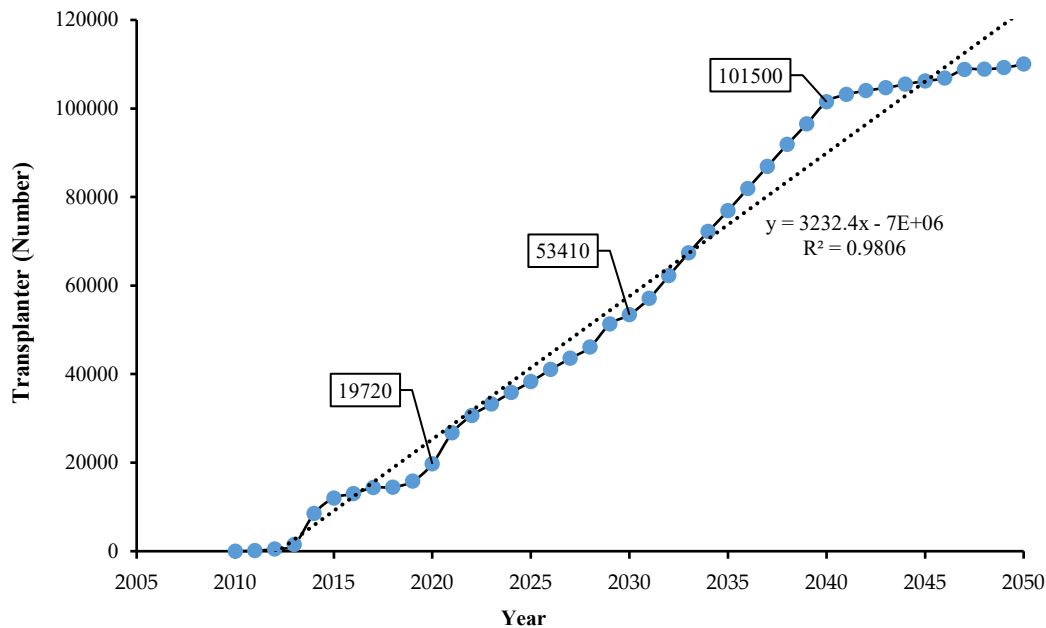


Figure 7 Demand for rice transplanters for 95% mechanized transplanting is projected by the year 2050; Source: (Kabir et al., 2020) and estimated by the author

3.6.3 Seeder

In Bangladesh, machines called seeders are beneficial for directly planting crops during dry seasons, like winter. These devices are great for sowing wheat, maize, rice, beans, and seeds (Islam and Shirazul, 2009). The government should focus on supporting local companies that design and make high-speed tillers, seeders, and planters. Bangladesh only has about 1,100 of these machines (Hossen et al., 2022; Huda et al., 2024). Instead of buying them from abroad, it's better to help local workshops grow their production capacity by providing loans and other resources (Pokharel et al., 2018). This will help them turn into successful small businesses.

3.6.4 Irrigation

In Bangladesh, half of the total irrigable land, 15.12 million hectares, is now irrigated, while the other 12% of land depends on rain or is left unused during dry periods (<http://en.banglapedia.org/index.php?title=Irrigation>). The country employs both shallow and deep tube well irrigation methods, with 37,538 DTWs, 1,355,852 STWs, and 181,469 LLPs for water lifting (Hossain et

al., 2022). STWs are famous for their mobility and cost-effectiveness, often powered by a centrifugal pump driven by a diesel engine or electric motor. Despite the heavy diesel fuel subsidies, the widespread availability of electricity (99%) suggests a potential shift away from diesel reliance in the future (Amin et al., 2022) Adequate preparations are crucial to ensure a smooth transition without negatively impacting marginal farmers who depend on Bangladeshi water vendors using tube well systems.

Another potential challenge for Bangladesh is extracting groundwater for irrigation, causing arsenic contamination in aquifers in various parts of Bangladesh (Ahmad et al., 2018). Additionally, Bangladesh is facing the effects of global climate change, which is affecting the availability and distribution of rainfall. To tackle these issues, the government is promoting the storage and use of surface water in irrigation projects (Krupnik et al., 2017). This emphasizes the need to efficiently use limited surface and groundwater resources in the coming years. However, with the current irrigation efficiency at only 30% in Bangladesh (Mainuddin et

al., 2021), introducing precision irrigation systems is necessary to meet future challenges.

3.6.5 Weed control and plant protection

In many areas, the traditional method of weeding relies on manual labor, and the amount of work needed depends on factors like weed infestation severity, the weeding frequency, and herbicide use (Paul et al., 2023). About 250,500 manual weeders are used in the country (Paul et al., 2025) Manual weeding requires around 86 person-hours/ha, but using mechanical weeders reduces this to only 22 person-hours/ha (Hossen et al., 2011; Hossen et al., 2010; Islam et al., 2017), indicating a significant potential for mechanization in this sector. Farmers commonly use knapsack sprayers for chemical spraying due to their affordability, with application costs ranging from BDT 300 to 330 per acre. Tractor-mounted sprayers are not widespread in Bangladesh, but there are approximately 2,000,000 knapsack sprayers (Rahman et al., 2021).

Despite their widespread use, concerns have been raised by the scientific community regarding farmers' reluctance to adopt safety measures while using knapsack sprayers, leading to potential health risks. Researchers from the most prominent medical university in Bangladesh (BSMMU) have raised concerns (Billah et al., 2023; Khatun et al., 2023) about a significant number of cancer patients having a farming background, indicating a potential connection to farmers' unsafe use of agrochemicals. To address this problem and reduce the health risks associated with agrochemicals, it's crucial to promptly educate farming communities about the importance of wearing protective gear when spraying these chemicals. Many of them are known to be cancer-causing, so taking precautions is essential.

3.6.6 Harvesting

Harvesting is recognized as the costliest and most labor-intensive activity in crop production (Amponsah et al., 2020; Huda et al., 2019b). For example, a sickle to harvest paddy can take up to 240 man-hours ha⁻¹ (Kaur et al., 2023), this high demand for labor results in a significant shortage during the harvest season. However, the country's adoption of mechanized

harvesting has been minimal, accounting for less than 5% (Hasan et al., 2019). The peak paddy harvest in Bangladesh usually arises just before the heavy monsoon (April–May) (Huda et al., 2019a). A slight harvest delay can lead to significant losses of ripened paddy because of flash floods (Baishakhy et al., 2023) Traditionally, thousands of laborers from different parts of the country migrate to rice-growing areas during this time to participate in manual harvesting (Nath et al., 2022). This was the usual scenario in Bangladesh agriculture until the onset of the pandemic, which significantly reduced internal labor migration from one area to another (Naivinit et al., 2010; De Brauw et al., 2020; Nath et al., 2016; Sarker et al., 2024).

Recognizing the upcoming challenges, the Bangladesh government launched a comprehensive mechanization plan for the agricultural sector, starting with the subsidized introduction of harvesters with discounts of up to 70% (Hossen et al., 2020). As a result, essential grains were preserved, and Bangladesh achieved a GDP growth of over 3% even during the pandemic. In the coming years, machine-based harvesting is expected to replace manual rice harvesting across the country largely (Nath et al., 2017). Despite these government initiatives, leading agro-machinery importers in the country raised concerns about the limited number of machines eligible for subsidies. They also criticized the current situation, identifying the lack of access to finance as a "significant barrier to farm mechanization.

Experts and consultant agencies suggest that Bangladesh would need around 30,000 standard-sized combine harvesters to enable mechanical harvesting of the entire cultivated area. However, Bangladesh operates only about 3021 combine harvesters (<https://alim.com.bd/>). It is worth noting that until 2018, Bangladesh had only about 750 combine harvesters. From 2019 to 2021, a total of 3021 combined harvesters were delivered. While the increasing adoption of combine harvesters is a positive sign, there is a need for additional attention to ensure sustainability (Akter et al., 2024; Huda et al., 2019a;

Paul et al., 2024; Hossain et al., 2013). The primary measure needed for this objective is initiating a training program to develop skilled mechanics and operators in rural areas (Nath et al., 2021).

The demand projection for a combine harvester assumes that the yearly harvesting capacity of a

combine harvester is 70 ha (Akter et al., 2024). The estimated demand for the combine harvester to achieve 95% mechanized harvesting in rice cropping areas in Bangladesh is 7,640, 28,980, and 55,200 in 2020, 2030, and 2040, respectively (Figure 8).

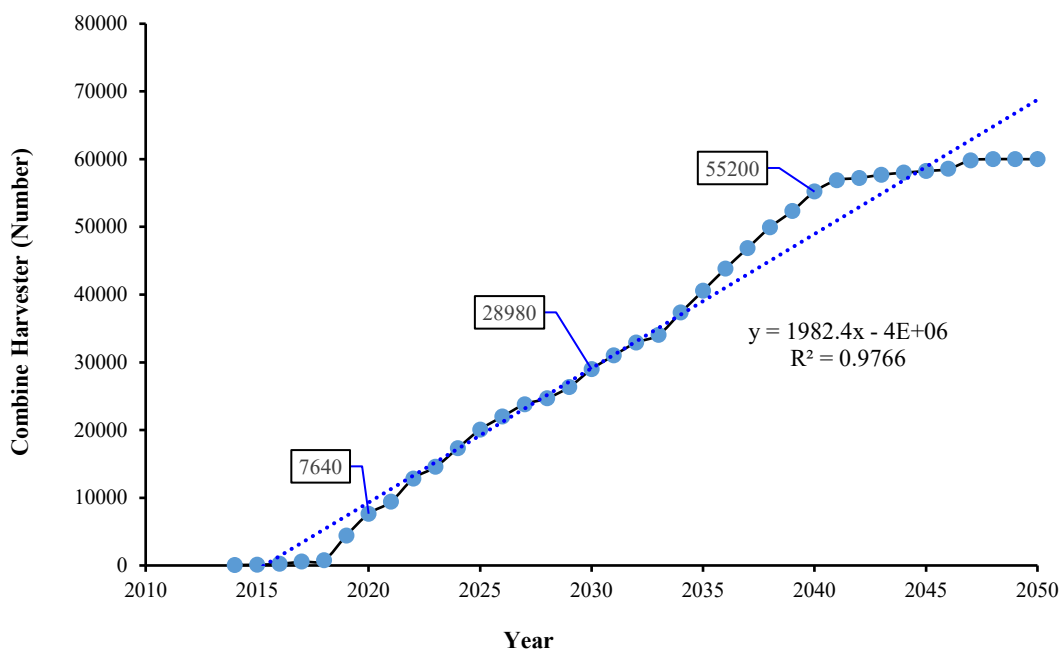


Figure 8 Demand for combine harvesters for 95% mechanized harvesting is projected by 2050. Source: (Kabir et al., 2020) and estimated by the author

3.7 Major barriers/challenges in adopting mechanized agriculture and smart agriculture

Farm mechanization's extent and its suitable selection directly impact farm productivity (Fuad and Flora, 2019). Despite the proven advantages, farm mechanization adoption in Bangladesh could have been more active, mainly due to various constraints.

One significant obstacle to mechanization is the prevalence of small and fragmented land holdings, where large machinery cannot be effectively used (Vortia et al., 2021). The challenge intensifies when fragmented lands are cultivated with diverse crops, hindering the efficient use of specialized machinery for specific tasks in each area. The varying equipment needs across seasons further impede the mechanization process. Moreover, Bangladeshi manufacturers frequently rely on outdated techniques and are reluctant to invest in precision manufacturing technology (Talukder and Jahan, 2017). Inadequate government incentives in this sector further compound

the slow progress (Khan et al., 2024; Raihan and Bourguignon, 2020; Faruque, 2012), leading the scientific community to advocate for support to local entrepreneurs.

Even with increased access to banking services for farmers in the past decade, there has remained a substantial increase in investments in new machines (Hossain, 2023; Hunt, 2022; Mottaleb et al., 2016). This highlights the need for motivational extension efforts within the farming community to accelerate adoption. The lack of adequate financial resources poses a significant obstacle, particularly for small-scale and resource-constrained agricultural operations. Furthermore, the literacy status of farmers plays a crucial role, as unfamiliarity with technology and digital tools can impede adoption (Malhotra, 2022). Inadequate telecommunications infrastructure and data management exacerbate these challenges. Connectivity issues, limited resources and content, and a lack of technological literacy create additional

barriers.

Research and development efforts and motivation to adapt and invest in innovative technology are essential to addressing these challenges. Ensuring the availability of necessary infrastructure and devices and addressing import obstacles are critical steps in facilitating the widespread adoption of precision agricultural technologies (Guan et al., 2023).

3.8 Future perspective of agricultural mechanization

Bangladesh's national agricultural mechanization policy recognizes that mechanized farming is the future of the country's agriculture (Islam et al., 2022). The government acknowledges farm mechanization as necessary for achieving sustainable development goals (SDG) (Asrafuzzaman, 2022). With this vision, initiatives like Smart Bangladesh 2041 and 4IR emphasize IoT-based digital agriculture to enhance crop/product quality and quantity through optimal human labor and resource utilization (Kittichotsatsawat et al., 2023; Quy et al., 2022).

Future efforts need reinforcement to establish mechanized farming as a future business model. Our comprehension of mechanization trends suggests specific measures to ensure the sustainability of upcoming farming practices:

Engage the youth workforce actively in the mechanization process and provide them access to the necessary funds for support.

To reduce the impact of rural labor migration, prioritize labor-intensive agricultural operations, like transplanting, in the mechanization route.

Implementing a machine-based grain harvesting system is crucial to minimizing postharvest losses. It enhances efficiency and contributes to the formation of entrepreneurship for profitable agriculture trading.

Implementing water-saving irrigation technologies and gradually replacing fossil fuel (diesel) pumps with solar-powered irrigation systems nationwide is advisable. This shift would decrease carbon emissions in the irrigation sector, lower production costs, and ease the financial burden on the national economy, considering the substantial government subsidies on

diesel fuel.

The right of entry to credit facilities should be facilitated. Still, a strengthened monitoring mechanism must ensure that the allocated credit is utilized within the farming sector and not diverted elsewhere.

The machinery purchase subsidy program must continue to ensure widespread mechanization.

The global economic crisis (COVID-19) has presented a significant challenge in importing agricultural equipment and raw materials. Consequently, there is a pressing need to bolster local manufacturers and prioritize local production.

Social media groups and mobile applications have effectively connected agricultural machinery service providers and commercial farmers. The ministry should actively encourage and promote these innovations to foster the growth of the national agricultural market.

4 Conclusion

Agriculture has consistently been a top priority in Bangladesh. Since 2018, the country has allocated specific funds for agricultural mechanization in its national budget to ensure food security through rice production. This review comprehensively analyzes Bangladesh's status and potential for farm mechanization in rice production. It highlights the country's progress in adopting mechanized solutions, particularly irrigation, and tillage while acknowledging that many farming tasks still depend heavily on manual labor. The review emphasizes the need for financial support and modernization in rice planting and harvesting to improve sustainability.

The paper discusses government initiatives, collaborations, and technological advancements, focusing on precision farming and IoT-based decision-making. The government's adoption of rice transplanters and combined harvesters over the past decade is commended as a strategic initiative, and the growing trend of entrepreneurial models for mechanization is noted. The paper also explores challenges and digital interventions and recommends engaging rural youth in long-term mechanization

efforts.

The review underscores the transformative potential of mechanization in advancing smart agriculture and highlights the current policies and legislation that support this transition. These efforts are vital for ensuring food security and fostering sustainable development in Bangladesh. Finally, the review offers recommendations to enhance the country's mechanization initiatives further and promote sustainable rice production, ultimately contributing to the overall well-being of Bangladesh's population.

Statements and Declarations

Competing Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

No funding was received.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

References

- Abdu Abdullah, H. M., M. Muraduzzaman, I. Islam, M. G. Miah, M. M. Rahman, A. Rahman, N. Ahmed, and Z. Ahmed. 2019. Spatiotemporal dynamics of new land development in Bangladesh coast and its potential uses. *Remote Sensing Applications: Society and Environment*, 14: 191-199.
- Abiri, R., N. Rizan, S. K. Balasundram, A. B. Shahbazi, and H. Abdul-Hamid. 2023. Application of digital technologies for ensuring agricultural productivity. *Heliyon*, 9(12): e22601.
- Ahmad, S. A., M. H. Khan, and M. Haque. 2018. Arsenic contamination in groundwater in Bangladesh: implications and challenges for healthcare policy. *Risk Management and Healthcare Policy*, 11: 251-261.
- Ahmed, T., N. Hasan, and R. Akter. 2023. Journey to smart Bangladesh: Realities and challenges. *International Journal of Qualitative Research*, 3(2): 178-187.
- Ahsan, M. B., L. Guo, F. M. Safiul Azam, B. Xu, S. J. Rayhan, A. Kaium, and W. Wang. 2022. Barriers, challenges, and requirements for ICT usage among sub-assistant agricultural officers in Bangladesh: Toward sustainability in agriculture. *Sustainability*, 15(1): 782.
- Akter, H., M. R. Ali, M. S. Alam, T. R. Sarker, S. Ahamed, and C. K. Saha. 2024. Estimation of economic life and feasibility of combine harvesters in Bangladesh deploying a unique web-based app. *Smart Agricultural Technology*, 7: 100378.
- Alam, M. M., C. K. Saha, A. Rahman, and M. G. K. Bhuyian. 2017. Manufacturing of agricultural machinery in Bangladesh: opportunities and constraints. *CIGR Journal*, 19(1): 122-135.
- Alam, N. 2023. Opportunity assessment and feasibility study of IoT-based smart farming in Bangladesh for meeting sustainable development goals. In *The Fourth Industrial Revolution and Beyond: Select Proceedings of IC4IR+*, eds. M. S. Hossain, S. P. Majumder, N. Siddique, and M. S. Hossain, ch. 52, 723-736. Singapore: Springer.
- Allioui, H., and Y. Mourdi. 2023. Exploring the full potentials of IoT for better financial growth and stability: A comprehensive survey. *Sensors*, 23(19): 8015.
- Amerttet, S., G. Gebresenbet, H. M. Alwan, and K. O. Vladimirovna. 2023. Assessment of smart mechatronics applications in agriculture: A review. *Applied Sciences*, 13(12): 7315.
- Amin, S., T. Jamasb, M. Llorca, L. Marsiliani, and T. I. Renström. 2022. Decarbonisation policies and energy price reforms in Bangladesh. *Energy Policy*, 170: 113224.
- Amjad, N., M. A. Hossen, S. Adhikari, V. Pronin, and N. D. Long. 2024. Mechanization of agriculture: market dynamics in Bangladesh, Nepal, Russian Federation and Viet Nam. New York, USA: the Centre for Sustainable Agricultural Mechanization (CSAM) of the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP).
- Amponsah, S. K., A. Addo, E. Bessah, and F. Kumi. 2020. Techno-economic assessment of mechanised reaping and sickle cutting options for smallholder rice farmers. *Cogent Food and Agriculture*, 6(1): 1847888.
- Aryal, J. P., S. Maharjan, and O. Erenstein. 2019. Understanding factors associated with agricultural mechanization: A Bangladesh case. *World Development Perspectives*, 13: 1-9.
- Asrafuzzaman, A. B. M. 2022. Gender equity in Bangladesh agriculture: Legal and policy vacuums to fulfill SDG obligations. *Dhaka University Law Journal*, 33(1): 23-42.
- Ayaz, M., M. Ammad-Uddin, Z. Sharif, A. Mansour, and E.-H.

- M. Aggoune. 2019. Internet-of-Things (IoT)-based smart agriculture: Toward making the fields talk. *IEEE Access*, 7: 129551-129583.
- Babu, K. E. K. 2021. Artificial intelligence in Bangladesh, its applications in different sectors and relevant challenges for the government: An analysis. *International Journal of Public Law and Policy*, 7(4): 319-333.
- Baishakhy, S. D., M. A. Islam, and M. Kamruzzaman. 2023. Overcoming barriers to adapt rice farming to recurring flash floods in haor wetlands of Bangladesh. *Heliyon*, 9(3): e14011.
- Bansal, S., and D. Kumar. 2020. IoT ecosystem: A survey on devices, gateways, operating systems, middleware and communication. *International Journal of Wireless Information Networks*, 27(3): 340-364.
- Biggs, S., and S. Justice. 2017. Rural and agricultural mechanization: A history of the spread of small engines in selected Asian countries. Dhaka, Bangladesh: Institute for Inclusive Finance and Development (InM).
- Billah, M. M., M. Rahman, and R. Naidu. 2023. Effect of excessive use of agrochemicals on farming practices: Bangladesh perspectives. *International Journal of Agricultural Extension*, 11(1): 79-90.
- Chel, A., and G. Kaushik. 2011. Renewable energy for sustainable agriculture. *Agronomy for Sustainable Development*, 31(1): 91-118.
- Chowdhury, T., H. Chowdhury, A. Ahmed, Y. K. Park, P. Chowdhury, N. Hossain, and S. M. Sait. 2020. Energy, exergy, and sustainability analyses of the agricultural sector in Bangladesh. *Sustainability*, 12(11): 4447.
- Chowhan, S., M. M. Rahman, R. Sultana, M. A. Rouf, M. Islam, and S. A. Jannat. 2024. Agriculture policy and major areas for research and development in Bangladesh. *Sarhad Journal of Agriculture*, 40(3): 819-832.
- Datta, P. M. 2022. *Global Technology Management 4.0*. New York, USA: Springer.
- De Brauw, A., J. Waid, C. A. Meisner, F. Akter, and B. F. Khan. 2020. Food systems for healthier diets in Bangladesh: Towards a research agenda. IFPRI Discussion Paper 1902. Washington, DC: International Food Policy Research Institute (IFPRI).
- Diao, X., J. Silver, and H. Takeshima. 2016. Agricultural Mechanization and Agricultural Transformation. Washington, DC, USA: International Food Policy Research Institute.
- Fabregas, R., M. Kremer, and F. Schilbach. 2019. Realizing the potential of digital development: The case of agricultural advice. *Science*, 366(6471): eaay3038.
- Faruque, O. 2012. Strategy to overcome barriers of agricultural machinery industry in Asian developing countries with special reference to Bangladesh. Dhaka, Bangladesh: Agricultural Manufacturers Association.
- Ferdous, Z., F. Zulfiqar, A. Datta, A. K. Hasan, and A. Sarker. 2021. Potential and challenges of organic agriculture in Bangladesh: a review. *Journal of Crop Improvement*, 35(3): 403-426.
- Fuad, M. A. F., and U. M. A. Flora. 2019. Farm mechanization in Bangladesh: a Review. *International Journal of Research in Business Studies and Management*, 6(9): 15-29.
- Giller, K. E., T. Delaune, J. V. Silva, K. Descheemaeker, G. van de Ven, A. G. Schut, M. van Wijk, J. Hammond, Z. Hochman, and G. Taulya. 2021. The future of farming: Who will produce our food? *Food Security*, 13(5): 1073-1099.
- Guan, N., L. Liu, K. Dong, M. Xie, and Y. Du. 2023. Agricultural mechanization, large-scale operation and agricultural carbon emissions. *Cogent Food and Agriculture*, 9(1): 2238430.
- Hasan, M. K., M. R. Ali, C. K. Saha, M. M. Alam, and M. E. Haque. 2019. Combine harvester: Impact on paddy production in Bangladesh. *Journal of the Bangladesh Agricultural University*, 17(4): 583-591.
- Hasan, M. A., and H. M. Irfanullah. 2022. Exploring the potential for rainwater use for the urban poor in Bangladesh. *Water Policy*, 24(4): 645-666.
- Hasan, M. K., and L. Kumar. 2022. Changes in coastal farming systems in a changing climate in Bangladesh. *Regional Environmental Change*, 22(4): 113.
- Hinnou, L. C., E. A. R. Obossou, and N. R. A. Adjovi. 2022. Understanding the mechanisms of access and management of agricultural machinery in Benin. *Scientific African*, 15: e01121.
- Hossain, I. 2023. Financial inclusion in Bangladesh through mobile financial services: A case study on marginal agricultural peoples of Bangladesh. M.S. thesis, Business Administration, The Degree Programme of Service Design, Turku.
- Hossain, M., M. Hossain, and B. Nath. 2013. Feasibility study of motor and engine driven open drum power thresher. *Eco-friendly Agriculture Journal*, 6(5): 83-92.
- Hossain, M. A. 2018. Shallow tubewell irrigation system in Bangladesh: Perspective structure, management and performance. Ph.D. diss., University of Rajshahi.
- Hossain, M. I., M. N. Bari, A. A. Kafy, Z. A. Rahaman, and M. T. Rahaman. 2022. Application of double lifting method for river water irrigation in the water stressed Barind Tract of northwest Bangladesh. *Groundwater for Sustainable Development*, 18: 100787.
- Hossain, M. S., M. M. Chowdhury, B. K. Das, M. R. Islam, M. G. Kibria, and S. Banik. 2024. A sustainable energy approach for pumping and irrigation in the Barind

- Region of Bangladesh. *Clean Technologies and Environmental Policy*, 26(7): 2151-2180.
- Hossen, M. A., B. C. Nath, A. Raihan, M. A. Haque, and M. S. Islam. 2010. Performance evaluation of the BRRI development wet and dry land weeder. *International Journal BioResearch*, 8(1): 27-34.
- Hossen, M. A., M. S. Islam, M. D. Huda, M. A. Zami, M. G. K. Bhuyan, and B. C. Nath. 2011. Design and development of a weeder for both lowland and upland conditions. *AMA-Agricultural Mechanization in Asia Africa and Latin America*, 42(2): 56-62.
- Hossen, M. A. 2019. Mechanization in Bangladesh: Way of modernization in agriculture. *International Journal of Engineering Trends and Technology*, 67(9): 69-77.
- Hossen, M. A., M. R. A. Talukder, M. R. Al Mamun, H. Rahaman, S. Paul, M. M. Rahman, M. Miaruddin, M. A. Ali, and M. N. Islam. 2020. Mechanization status, promotional activities and government strategies of Thailand and Vietnam in comparison to Bangladesh. *AgriEngineering*, 2(4): 489-510.
- Hossen, M. A., M. M. Shahriyar, S. Islam, H. Paul, and M. M. Rahman. 2022. Rice transplanting mechanization in Bangladesh: Way to make it sustainable. *Agricultural Sciences*, 13(2): 130-149.
- Huda, M. D., B. C. Nath, S. Paul, M. G. K. Bhuiyan, S. Islam, and M. M. Islam. 2019a. Design and development of a head feed mini combine harvester suitable in Bangladesh condition. *Journal of Agricultural Engineering*, 42(2): 73-92.
- Huda, M., M. Bhuiyan, B. Nath, M. Milion, S. Islam, H. Paul, M. Islam, and M. Rahman. 2019b. Performance evaluation and economics of the reaper binders for harvesting the baddy of Bangladesh. *Journal of Agricultural Engineering*, 42(4): 61-67.
- Huda, M. D., B. C. Nath, S. Paul, M. G. K. Bhuiyan, H. Rahaman, F. Rahman, and M. M. Islam. 2024. Commercializing mechanical rice transplanter in Bangladesh: A review. *CIGR Journal*, 26(3): 79-94.
- Hunt, F. 2022. Agricultural mechanization in Bangladesh–The future: Workshop report. Dhaka, Bangladesh: CSISA-MEA, USAID, CIMMYT, iDE, Georgia Institute of Technology.
- Husain, A. M. M., and M. Hossain. 2022. Bangladesh's agricultural growth and development over fifty years. In *Towards a Sustainable Economy: The Case of Bangladesh*, eds. M. Hossain, Q. K. Ahmad, and M. M. Islam, ch. 8, 171-190. London: Routledge.
- Islam, A. 2016. Mechanized rice transplanting in Bangladesh. Gazipur: Bangladesh Rice Research Institute.
- Islam, A., M. Rahman, A. Rahman, M. Islam, and M. Rahman. 2016. Techno-economic performance of 4-row self-propelled mechanical rice transplanter at farmers field in Bangladesh. *Progressive Agriculture*, 27(3): 369-382.
- Islam, A. S., M. T. Islam, M. S. Islam, A. L. Rahman, and M. A. Rahman. 2017. Performance evaluation of BRRI power weeder for low land rice (*Oryza sativ* L.) cultivation. *The Agriculturists*, 15(1): 40-48.
- Islam, A. 2018. Status of rice farming mechanization in Bangladesh. *Journal of Bioscience and Agriculture Research*, 17(1): 1386-1395.
- Islam, A., M. Rahman, J. Rana, Z. Hasan, J. A. Soeb, S. Kayshar, and F. Jubayer. 2022. Challenges towards raising agromachinery industries in Bangladesh: Conceptualizing a multitasking framework for action. *Multidisciplinary Reviews*, 5(3): e2022015.
- Islam, M. S., and D. Shirazul. 2009. Farm mechanization for sustainable agriculture in Bangladesh: Problems and prospects. Manila, Philippines: United Nations Asian and Pacific Centre for Agricultural Engineering and Machinery.
- Kabir, M. S., M. U. Salam, A. Chowdhury, N. M. F. Rahman, K. M. Iftakharuddaula, M. S. Rahman, M. H. Rashid, S. S. Dipti, A. Islam, M. A. Latif, A. K. M. S. Islam, M. M. Hossain, B. Nessa, T. H. Ansari, M. A. Ali, and J. K. Biswas. 2015. Rice vision for Bangladesh: 2050 and beyond. *Bangladesh Rice Journal*, 19(2): 1-18.
- Kabir, M. S., M. U. Salam, A. K. M. S. Islam, M. A. R. Sarkar, M. A. A. Mamun, M. C. Rahman, B. Nessa, M. J. Kabir, H. B. Shozib, M. B. Hossain, A. Chowdhury, M. Nasim, K. M. Iftakharuddaula, M. S. Hossain, M. K. A. Bhuiyan, B. Karmakar, M. S. Rahman, M. M. Haque, M. T. Khatun, M. P. Ali, S. M. H. A. Rabbi, P. L. Biswas, E. S. M. H. Rashid, and N. M. F. Rahman. 2020. Doubling rice productivity in Bangladesh: A way to achieving SDG 2 and moving forward. *Bangladesh Rice Journal*, 24(2): 1-47.
- Kamble, S. S., A. Gunasekaran, and R. Sharma. 2020. Modeling the blockchain enabled traceability in agriculture supply chain. *International Journal of Information Management*, 52: 101967.
- Kamruzzaman, M., M. Awal, M. Hossen, S. Paul, B. Nath, and M. Islam. 2014. Protection of seedling in tray for mechanical rice transplanting from effect of cold weather using polythene shed. *Bangladesh Journal of Progressive Science and Technology*, 12(1): 5-10.
- Karim, N., A. Islam, M. Alam, and M. Hossain. 2023. IoT-based precision agriculture for sustainable production. Training Manual 2023-2024. Dhaka, Bangladesh: Bangladesh Agricultural Research Council (BARC).
- Karim, M. A., R. Shamma, M. M. Bakhtiar, B. Belton, A. Kishore, and A. U. Ahmed. 2024. Mechanizing agriculture in Bangladesh: Trends, challenges, and policy

- priorities. Dhaka, Bangladesh: Bangladesh Agricultural Research Council (BARC).
- Kaur, B., Mansi, S. Dimri, J. Singh, S. Mishra, N. Chauhan, T. Kukreti, B. Sharma, S. P. Singh, S. Arora, D. Uniyal, Y. Agrawal, S. Akhtar, M. A. Rather, B. Naik, V. Kumar, A. K. Gupta, S. Rustagi, and M. S. Preet. 2023. Insights into the harvesting tools and equipment's for horticultural crops: From then to now. *Journal of Agriculture and Food Research*, 14: 100814.
- Khan, A. U., A. S. Islam, M. K. Pintu, S. Paul, M. D. Huda, M. A. Hossen, M. M. Islam, and M. M. Ahmmed. 2024. Assessment of BRRI whole feed combine harvester (Model BRRI WCH2021) for mechanized rice harvesting in Bangladesh. *Agricultural Sciences*, 15(2): 274-291.
- Khatun, P., A. Islam, S. Sachi, M. Z. Islam, and P. Islam. 2023. Pesticides in vegetable production in Bangladesh: A systemic review of contamination levels and associated health risks in the last decade. *Toxicology Reports*, 11: 199-211.
- Kittichotsawat, Y., N. Tippayawong, and K. Yaibuathet Tippayawong. 2023. Improvement of coffee production performance via integrated lean and automated mechanization techniques. *Cogent Food and Agriculture*, 9(2): 2278934.
- Krupnik, T. J., U. Schulthess, Z. U. Ahmed, and A. J. McDonald. 2017. Sustainable crop intensification through surface water irrigation in Bangladesh? A geospatial assessment of landscape-scale production potential. *Land Use Policy*, 60: 206-222.
- Mada, D. A., and S. Mahai. 2013. The role of agricultural mechanization in the economic development for small scale farms in Adamawa State. *Journal of Engineering and Science*, 2(11): 91-96.
- Mainuddin, M., M. M. Alam, M. Maniruzzaman, M. J. Kabir, M. A. Mojid, M. M. Hasan, E. J. Schmidt, and M. T. Islam. 2021. Yield, profitability, and prospects of irrigated Boro rice cultivation in the North-West region of Bangladesh. *PloS one*, 16(4): e0250897.
- Majeed, Y., M. U. Khan, M. Waseem, U. Zahid, F. Mahmood, F. Majeed, M. Sultan, and A. Raza. 2023. Renewable energy as an alternative source for energy management in agriculture. *Energy Reports*, 10: 344-359.
- Majumder, S., and S. Dey 2020. Light engineering industry sector in Bangladesh: challenges and prospects. *The Cost and Management*, 48(1): 46-57.
- Malhotra, H. 2022. The perception of technology and data, and its impact on data governance decisions-A study on low literate women farmers in agricultural co-operatives of India. M.S. thesis, School of Business, Aalto University, India.
- McLennon, E., B. Dari, G. Jha, D. Sihi, and V. Kankarla. 2021. Regenerative agriculture and integrative permaculture for sustainable and technology driven global food production and security. *Agronomy Journal*, 113(6): 4541-4559.
- Mottaleb, K. A., T. J. Krupnik, and O. Erenstein. 2016. Factors associated with small-scale agricultural machinery adoption in Bangladesh: Census findings. *Journal of Rural Studies*, 46: 155-168.
- Naivinit, W., C. Le Page, G. Trébuil, and N. Gajaseeni. 2010. Participatory agent-based modeling and simulation of rice production and labor migrations in Northeast Thailand. *Environmental Modelling and Software*, 25(11): 1345-1358.
- Nath, B., G. Chen, L. Bowtell, and R. A. Mahmood. 2023. Assessment of densified fuel quality parameters: A case study for wheat straw pellet. *Journal of Bioresources and Bioproducts*, 8(1): 45-58.
- Nath, B., and Y. Nam. 2013. Improvement of baddy harvesting mechanization system for Bangladesh. In *Development of Research Capacity of BRRI*, ed. Y. S. Nam, ch. 1, 1-48. Seoul, Korea: KOICA.
- Nath, B. C., M. A. Hossen, A. K. M. S. Islam, M. D. Huda, S. Paul, and M. A. Rahman. 2016. Postharvest loss assessment of rice at selected areas of Gazipur district. *Bangladesh Rice Journal*, 20(1): 23-32.
- Nath, B. C., Y. Nam, M. D. Huda, M. M. Rahman, P. Ali, and S. Paul. 2017. Status and constrain for mechanization of rice harvesting system in Bangladesh. *Agricultural Sciences*, 8(06): 492-506.
- Nath, B. C., M. D. Huda, M. M. Rahman, and S. Paul. 2021. Essential steps for developing rice harvest mechanization in Bangladesh. *Cutting-edge Research in Agricultural Sciences*, 7: 109-125.
- Nath, B. C., S. Paul, M. D. Huda, M. A. Hossen, M. Bhuiyan, and A. S. Islam. 2022. Combine harvester: small machine solves big Rice harvesting problem of Bangladesh. *Agricultural Sciences*, 13(2): 201-220.
- Nath, B., G. Chen, C. M. O'Sullivan, and D. Zare. 2024. Research and technologies to reduce grain postharvest losses: A review. *Foods*, 13(12): 1875.
- Nath, B., H. Bari, H. Paul, M. I. Omar, M. A. Haque, S. Paul, M. G. K. Bhuiyan, and M. M. Ahmmed. 2025. Rice bran and rice bran oil production perspective in Bangladesh: a review. *Journal of the Science of Food and Agriculture*, 105(11): 5624-5639.
- Negrete, J. C. 2018. Trends and perspectives of mechanization and agricultural machinery in Mexico for the 21st century. *Journal of Agricultural and Crop Sciences*, 1: 29-38.
- Neumeyer, X., S. C. Santos, and M. H. Morris. 2020.

- Overcoming barriers to technology adoption when fostering entrepreneurship among the poor: The role of technology and digital literacy. *IEEE Transactions on Engineering Management*, 68(6): 1605-1618.
- Paul, H., S. Paul, M. A. Hossen, M. D. Huda, S. Islam, M. G. K. Bhuiyan, B. Nath, and M. A. Rahman. 2019. Performance evaluation of power operated automated seed sower machine of mat type rice seedling raising. *Journal of Agricultural Engineering*, 42(3): 69-77.
- Paul, P., A. Khair, and B. Nath. 2010a. Construct and performance evaluation of foot operated diaphragm pump for low lift irrigation. *Bangladesh Journal of Progressive Science and Technology*, 8(1): 75-78.
- Paul, P., A. Khair, and B. Nath. 2010b. Design and construction of a single acting diaphragm pump for low lift irrigation. *Bangladesh Journal of Progressive Science and Technology*, 8(1): 75-78.
- Paul, S., M. A. Hossen, B. C. Nath, M. A. Rahman, and S. Hosen. 2016. Effect of soil settling period on performance of rice transplanter. *International Journal of Sustainable Agriculture and Technology*, 12(11): 14-20.
- Paul, S., M. D. Huda, B. C. Nath, M. G. K. Bhuiyan, H. Paul, and M. M. Rahman. 2024. Enhancing rice harvesting efficiency: A whole feed combine harvester design, development, and fabrication in Bangladesh. *Nongye Jixie Xuebao/Transactions of the Chinese Society of Agricultural Machinery*, 55(7): 20-40.
- Paul, S., M. A. Rahman, B. C. Nath, A. Hossen, A. S. Islam, M. K. Milton, and M. K. Pintu. 2021. Design and development of a prilled urea applicator. *Agricultural Sciences*, 12(5): 530-548.
- Paul, S., B. C. Nath, A. Hossen, K. Pintu, H. Paul, S. Islam, A. U. Khan, and M. Ahmmmed. 2023. Development and fabrication of manually push-pull type conical weeder for Bangladesh condition. *Agricultural Sciences*, 14(5): 685-709.
- Paul, S., B. C. Nath, M. D. Huda, M. G. K. Bhuiyan, and H. Paul. 2025. Assessment of mechanical weeders in paddy fields: A study on operational effectiveness in Bangladesh. *Heliyon*, 11(4): e42639.
- Pokharel, D., R. K. Jha, T. P. Tiwari, M. K. Gathala, H. K. Shrestha, and D. Panday. 2018. Is conservation agriculture a potential option for cereal-based sustainable farming system in the Eastern Indo-Gangetic Plains of Nepal? *Cogent Food and Agriculture*, 4(1): 1557582.
- Pradhan, S., A. Dhar, and K. N. Tiwari. 2022. Sustainability of Boro rice cultivation in the canal irrigated command area of India. *Journal of Water and Climate Change*, 13(8): 3083-3099.
- Quy, V. K., N. V. Hau, D. V. Anh, N. M. Quy, N. T. Ban, S. Lanza, G. Randazzo, and A. Muzirafuti. 2022. IoT-enabled smart agriculture: architecture, applications, and challenges. *Applied Sciences*, 12(7): 3396.
- Rahaman, H., M. M. Rahman, A. K. M. S. Islam, M. D. Huda, and M. Kamruzzaman. 2022. Mechanical rice transplanting in Bangladesh: Current situation, technical challenges, and future approach. *Journal of Biosystems Engineering*, 47(4): 417-427.
- Rahman, A., R. Ali, S. N. Kabir, M. Rahman, R. Al Mamun, and A. Hossen. 2020. Agricultural mechanization in Bangladesh: status and challenges towards achieving the sustainable development goals (SDGs). *AMA, Agricultural Mechanization in Asia, Africa and Latin America*, 51(4): 106-120.
- Rahman, A., and M. J. Abedin. 2021. The fourth industrial revolution and private commercial banks: The good, bad and ugly. *International Journal of Organizational Analysis*, 29(5): 1287-1301.
- Rahman, M. M., M. R. Ali, M. M. H. Oliver, M. A. Hanif, M. Z. Uddin, T. U. Hasan, K. K. Saha, M. H. Islam, and M. Moniruzzaman. 2021. Farm mechanization in Bangladesh: A review of the status, roles, policy, and potentials. *Journal of Agriculture and Food Research*, 6: 100225.
- Rahman, S. M., A. Mori, and S. M. Rahman. 2022. How does climate adaptation co-benefits help scale-up solar-powered irrigation? A case of the Barind Tract, Bangladesh. *Renewable Energy*, 182: 1039-1048.
- Raihan, S., and F. Bourguignon. 2020. Bangladesh's development: Achievements and challenges. *Bangladesh Institutional Diagnostic, Economic and Development Institutions, Oxford Policy Management, Oxford*, 1-43.
- Raj, M., S. Gupta, V. Chamola, A. Elhence, T. Garg, M. Atiquzzaman, and D. Niyato. 2021. A survey on the role of Internet of Things for adopting and promoting Agriculture 4.0. *Journal of Network and Computer Applications*, 187: 103107.
- Rakhra, M., S. Sanober, N. N. Quadri, N. Verma, S. Ray, and E. Asenso. 2022. Implementing machine learning for smart farming to forecast farmers' interest in hiring equipment. *Journal of Food Quality*, 2022(1): 4721547.
- Razzak, M. A., P. Sangana, M. B. Hossain, D. Roy, and B. C. Nath. 2017. Quality assessment of ashugonj power plant disposal water for irrigation application. *Journal of AgriSearch*, 4(4): 259-263.
- Sangeetha, C., and P. Baskar. 2015. Influence of different crop establishment methods on productivity of rice—A Review. *Agricultural Reviews*, 36(2): 113-124.
- Sarkar, S., C. K. Saha, S. Ahamed, I. N. Khan, M. A. E. R. Rabbani, M. M. Hossain, and M. M. Alam. 2024. Mechanical rice transplanting: A profitable business for Bangladeshi agropreneurs. *Journal of Agricultural*

- Machinery and Bioresources Engineering*, 8(1): 20-25.
- Sarker, M. N. I., M. A. Salam, and R. R. Firdaus. 2024. Do female labor-migrated households have lower productivity? Empirical evidence from rural rice farms in Bangladesh. *Growth and Change*, 55(1): e12691.
- Sayed, H. A. A., Q. Ding, A. J. Odero, and T. Korohou. 2022. Selection of appropriate mechanization to achieve sustainability for smallholder farms: A review. *Al-Azhar Journal of Agricultural Engineering*, 3(1): 52-60.
- Scolaro, E., M. Beligoj, M. P. Estevez, L. Alberti, M. Renzi, and M. Mattetti. 2021. Electrification of agricultural machinery: A review. *IEEE Access*, 9: 164520-164541.
- Sims, B., and J. Kienzle. 2017. Sustainable agricultural mechanization for smallholders: What is it and how can we implement it? *Agriculture*, 7(6): 50.
- Singh, N. K., M. K. Narang, S. S. Thakur, M. Singh, S. K. Singh, and A. Prakash. 2023. Influence of transplanting techniques and age of wash root type seedlings on planting attributes of paddy rice. *Cogent Food and Agriculture*, 9(1): 2176978.
- Statistics, B. 2018. Bangladesh Bureau of Statistics. Dhaka. Bangladesh: Bangladesh Bureau of Statistics.
- Talukder, M. A., and S. M. Jahan. 2017. Competitiveness and growth hindrances of light engineering industry of Bangladesh: A study on Micro, Small and Medium-Sized Enterprise (MSME) owners. *Developing Country Studies*, 7(2): 30-41.
- Tasnim, S. T., M. A. Islam, R. J. Taifa, S. Mahub, and M. R. A. Rashid. 2022. Agri-food traceability using blockchain technology to ensure value chain management and fair pricing in Bangladesh. In *2022 IEEE 8th World Forum on Internet of Things (WF-IoT)*, 1-6. Yokohama, Japan, 26 October - 11 November.
- Titumir, R. A. M. 2021. *Numbers and Narratives in Bangladesh's Economic Development*. Singapore: Springer.
- Vortia, P., M. Nasrin, S. K. Bipasha, and M. M. Islam. 2021. Extent of farm mechanization and technical efficiency of rice production in some selected areas of Bangladesh. *GeoJournal*, 86: 729-742.
- Wassmann, R., S. V. K. Jagadish, K. Sumfleth, H. Pathak, G. Howell, A. Ismail, R. Serraj, E. Redona, R. Singh, and S. Heuer. 2009. Regional vulnerability of climate change impacts on Asian rice production and scope for adaptation. *Advances in Agronomy*, 102: 91-133.
- WHO. 2017. Reaching the every newborn national 2020 milestones: country progress, plans and moving forward. Geneva: WHO.