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AGRICULTURAL MECHANIZATION AND ECONOMIC DEVELOPMENT IN BANGLADESH: EVIDENCE FROM TIME-SERIES ANALYSIS

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Abstract

Bangladesh's economy benefited greatly from agricultural mechanization; however, it also faces challenges. The objective of this study was to examine the effects of mechanization on crucial economic indicators between 1991 and 2022. Advanced statistical and econometric techniques were applied to carry out the study. Despite the fact that the quantities of power tillers and irrigation equipment have a negative impact on crop production and gross domestic product, respectively, the study's findings indicate that agricultural mechanization has generally positive and significant effects on both. However, agricultural mechanization has a negative and significant impact on income inequality and employment in the agricultural sector; in contrast, energy consumption has a favorable effect on income inequality. The number of electricity users, irrigation equipment, and arable land area also has positive effect on employment creation. The study suggests that advanced farming techniques, timely cultivation, reduced input waste, more irrigation capacity, shorter harvest periods, and lower production costs are the main determinants of increased crop production and gross domestic product. Nevertheless, financial barriers to small-scale farmers, high-cost machinery, unfair distribution of machinery resources, and fragmented land contribute to increasing income inequality. Moreover, lack of skills, limited access to training facilities, and fewer job opportunities are responsible for declining employment, although the adoption of advanced technologies enhances employment opportunities. To overcome challenges in establishing agro-service centers, encouraging eco-friendly mechanization, reforming land policies, providing low-interest loan facilities, and establishing machinery rental service centers are necessary in Bangladesh.

Keywords: Agricultural mechanization; Crop productivity; Economic growth; Income inequality; Employment; Bangladesh

Introduction

Agricultural mechanization refers to the application of engineering principles and technologies in agricultural production, storage, and processing to increase productivity and efficiency, while reducing costs for farmers. It primarily involves replacing human and animal labor with machine power (Magdoff, 1982), making

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it a key factor in modern agricultural transformation. In Bangladesh 80-95% of such practices as tillage, irrigation, weeding, and pesticide application have been mechanized (DFPM, 2024). Before the agricultural mechanization project began in 2019, only 4% of rice was harvested using combine harvesters; this increased to 22% by the 2022-2023 fiscal year. Regional adoption has also risen significantly, with combine harvesters used in 71% of rice fields in Netrokona, 70% in Manikganj, 60% in Brahmanbaria, 52% each in Dinajpur, Thakurgaon, and Habiganj, 50% in Moulvibazar and Noakhali, 47% in Bhola, and 41% in Sunamganj and Patuakhali (Rai, 2023).

Agriculture is a vital sector in Bangladesh, with about 70-80% of the population directly or indirectly dependent on it. In the 2021-2022 fiscal year, the sector contributed 11.66% to country's gross domestic product (GDP) (Bangladesh Economic Review, 2024). Given the strong link between agriculture, the national economy, and people's livelihoods, transitioning from traditional farming to technology-based agricultural management is essential to ensure sustainable livelihood security.

Agricultural mechanization has both direct effects on production and indirect effects on agricultural value chains across the economy. By enabling farmers to cultivate larger areas in less time, mechanization increases production while reducing labor requirements. Technologies such as tractors with GPS-based guidance systems, allow precise fertilization and planting, reducing input waste and improving crop quality (Rahman, 2023)[1]. Mechanization also contributes to higher crop productivity and national GDP by supporting key farming operations, including seedbed preparation, transplanting, sowing, harvesting, and the application of pesticides and fertilizers. Despite its benefits, agricultural mechanization faces several challenges in a developing country like Bangladesh. High initial costs of machinery, limited maintenance services, and inadequate technical skills make it difficult for small-scale farmers to adopt, potentially increasing income inequality. Rapid mechanization also raises concerns about rural employment, as it may displace seasonal agricultural workers. In addition, excessive use of modern machinery can contribute to soil fertility decline and soil erosion (Ovie, 2024; Magdoff, 1982). Other barriers include, poor infrastructure, low investment, unskilled workforce, knowledge gap, limited digital literacy, and policy constraints.

In Bangladesh, the use of modern agricultural technology began in the late 1960s and early 1970s. This occurred during the 'Green Revolution,' a time of agricultural change that used mechanization, better irrigation techniques, and high-yielding crop varieties to boost food production and lower poverty (Rahman,

[1]GPS stands for Global Positioning System, a satellite-based navigation system used for determining precise location.

2023). The introduction of deep tube wells (DTWs) for irrigation in the early 1960s marked the beginning of agricultural mechanization in Bangladesh (Pingali, 2007). Bangladesh's irrigation policy changed dramatically following its independence in 1971, encouraging the use of low-lift pumps (LLPs) and shallow tube wells (STWs) (Biggs and Justice, 2015). Since its founding in 1973, the Bangladesh Agricultural Development Corporation (BADC) has been significant in advancing agricultural mechanization in Bangladesh. Only when considerable import barriers were eliminated for agricultural equipment in 1989, particularly for two-wheeled tractors (2WTs), a broader mechanized process begins. A spike in the import of small engines and machinery, mainly from China (Mottaleb et al., 2016), was caused by this policy shift. Local agro-machinery manufacturing workshops were established in the 1990s as a result of a steady increase in the demand for agricultural machinery (Islam, 2018). Now-a-days, tractors, power tillers, combine harvesters, rice transplanters, seeders and planters, sprayers, contemporary irrigation systems, threshers, chaff cutters, grain dryers, storage facilities, etc., are some of the prevalent modern agricultural machineries used in the country. The degree of agricultural mechanization in Bangladesh differs depending on the area and kind of farm. The overall degree of mechanization in the agricultural sector is still low when compared to many other developed nations, despite some modest improvements in the adoption of agricultural machinery.

Numerous studies have been carried out on agricultural mechanization both within Bangladesh and internationally. Hossen (2019) studied the agricultural mechanization and modernization strategies of Bangladesh. He concluded that for Bangladesh to have sustainable crop production, it needs to move from manual labor to a structured, regionalized mechanization strategy that focuses on developing skilled workers, fixing infrastructure, and providing good after-sales service. Emami et al. (2018) examined the fact that mechanization in agriculture is essential for food security in developing nations and proposed a strategy for Iran. Islam and Shirazul (2009) explored the importance of mechanization in sustainable agriculture in Bangladesh, highlighting its challenges and opportunities. Alam et al. (2017) analyzed agricultural machinery manufacturing in Bangladesh, including its potential and challenges. Rahman et al. (2020) investigated agricultural mechanization in Bangladesh and the barriers to meeting the Sustainable Development Goals (SDGs). Prior studies to examine the impacts of agricultural mechanization on key economic indicators of Bangladesh through rigorous statistical and econometric analyses are scarce. This study will discuss the effects of agricultural mechanization on the main economic indicators of Bangladesh, applying statistical and econometric methods, which will help policymakers to make policy on how we can overcome the challenges of mechanization and maintain sustainable economic development in our economy. The specific objectives of the study are: (i) To examine the impact of agricultural mechanization on crop and GDP (ii) To assess the effects of mechanization on

agricultural employment (iii) To analyze the relationship between mechanization and income inequality.

Materials and Methods

Data Collection

The study collected annual time series data from various authentic secondary sources and journal articles covering the years from 1991 to 2022. Fertilizer consumption (Kg per ha arable land) in the agriculture sector and arable land area ('000 acres) are sourced from the Food and Agriculture Organization (FAO, 2023 and 2024). Data on the number of tractors are gathered from FAO (2023), Alam et al. (2017), Gurung et al. (2017), and Alam and Khan (2017). The quantities of power tillers are also compiled based on secondary and authentic journal papers (Jabbar, 1980; Ahmmed, 2014; Mottaleb et al., 2017; International Development Enterprises, 2012). Data on the number of irrigation equipment (DTWs, STWs, and LLPs) and irrigated area ('000 ha) by irrigation equipment and the number of electricity consumers in agriculture are gathered from Bangladesh Agricultural Development Corporation (2020) and Bangladesh Power Development Board (2022-2023), respectively. Furthermore, energy consumption (TWh), which includes all energy uses, including electricity, is sourced from Ritchie *et al.* (2022)[2]. Data on gross domestic product (current US$) and Gini index (Gini, 1921) are gathered from the World Bank (2025c; 2025b). Here, the Gini index is a proxy variable for measuring income inequality in Bangladesh. It is most commonly used to quantify the disparity in income, although it may be used to measure inequality in any distribution, including wealth distribution as well as life expectancy. It determines inequality on a scale of 0 to 1, with higher numbers indicating more significant disparity. This is sometimes expressed as a percentage ranging from 0 to 100%, known as the Gini index (Joe, 2023). The crop production index, a proxy variable for overall crop production data, is obtained from the Food and Agriculture Organization (FAO, 2023). The base period for the crop production index is 2004-2006, and it covers all types of crops except fodder crops. Finally, the employment rates (%) in the agriculture sector are collected from the International Labor Organization (2019). Notably, specific data on the number of tractors and imported power tillers were missing for a few years and are extrapolated using trend analysis in time series analysis (Gupta and Gupta, 2007).

Model Specification

The present study measures the effect of farm mechanization on crop production, country's GDP, income inequality, and employment in the agricultural sector. Hence, a total of four multiple regression models were selected based on

[2]TWh stands for Terawatt-hour, a unit used to measure electricity.

preliminary diagnostic tests, including tests for normality, stationarity, and multicollinearity among the independent variables. The common independent variables of these models were the number of electricity consumers in the agricultural sector, number of irrigation equipment (deep tube wells, shallow tube wells, and low-lift pumps), irrigated area by irrigation equipment ('000 ha), the number of power tillers, the number of tractors, fertilizer consumption (Kg per ha), and energy consumption (Terawatt). These models include arable land area as a supporting independent variable. Conversely, the agriculture sector's employment rate, income inequality, crop production, and gross domestic product are the dependent variables since they are the leading economic indicators of Bangladesh. The analysis uses a log-log model, which applies natural logarithm (ln) to both independent and dependent variables. This technique aids in the management of nonlinearity, stabilizes heteroskedasticity, improves data interpretation, simplifies complex relationships, manages multiplicative effects, decreases skewness, and improves the residual distribution for regression. It also allows us to analyze percentage change in variables across many domains. The empirical models are given below:

$$\textbf{Ln(Crop Production}_t\textbf{)} = \alpha_0 + \alpha_1 Ln(\text{No. of Electricity Consumers in Agriculture}_t) + \alpha_2 Ln(\text{Irrigation Equipment}_t) + \alpha_3 Ln(\text{Irrigated Area by Irrigation Equipment}_t) + \alpha_4 Ln(\text{No. of Tractors}_t) + \alpha_5 Ln(\text{No. of Power Tillers}_t) + \alpha_6 Ln(\text{Fertilizer Consumption}_t) + \alpha_7 Ln(\text{Energy Consumption}_t) + \alpha_8 Ln(\text{Arable Land Area}_t) + U_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots (i)$$

$$\textbf{Ln(Gross Domestic Product}_t\textbf{)} = \beta_0 + \beta_1 Ln(\text{No. of Electricity Consumers in Agriculture}_t) + \beta_2 Ln(\text{Irrigation Equipment}_t) + \beta_3 Ln(\text{Irrigated Area by Irrigation Equipment}_t) + \beta_4 Ln(\text{No. of Tractors}_t) + \beta_5 Ln(\text{No. of Power Tillers}_t) + \beta_6 Ln(\text{Fertilizer Consumption}_t) + \beta_7 Ln(\text{Energy Consumption}_t) + \beta_8 Ln(\text{Arable Land Area}_t) + V_t \ldots\ldots\ldots\ldots\ldots\ldots (ii)$$

$$\textbf{Ln(Income Inequality}_t\textbf{)} = \eta_0 + \eta_1 Ln(\text{No. of Electricity Consumers in Agriculture}_t) + \eta_2 Ln(\text{Irrigation Equipment}_t) + \eta_3 Ln(\text{Irrigated Area by Irrigation Equipment}_t) + \eta_4 Ln(\text{No. of Tractors}_t) + \eta_5 Ln(\text{No. of Power Tillers}_t) + \eta_6 Ln(\text{Fertilizer Consumption}_t) + \eta_7 Ln(\text{Energy Consumption}_t) + \eta_8 Ln(\text{Arable Land Area}_t) + Et \ldots\ldots\ldots\ldots\ldots\ldots (iii)$$

$$\textbf{Ln(Employment in Agriculture}_t\textbf{)} = \Upsilon_0 + \Upsilon_1 Ln(\text{No. of Electricity Consumers in Agriculture}_t) + \Upsilon_2 Ln(\text{Irrigation Equipment}_t) + \Upsilon_3 Ln(\text{Irrigated Area by Irrigation Equipment}_t) + \Upsilon_4 Ln(\text{No. of Tractors}_t) + \Upsilon_5 Ln(\text{No. of Power Tillers}_t) + \Upsilon_6 Ln(\text{Fertilizer Consumption}_t) + \Upsilon_7 Ln(\text{Energy Consumption}_t) + \Upsilon_8 Ln(\text{Arable Land Area}_t) + \varepsilon_t \ldots\ldots\ldots\ldots\ldots\ldots (iv)$$

Statistical and Econometric Methods

The descriptive statistics method is used to identify the distribution of the data. Checking the stationarity of the variables is essential when dealing with annual time series data. To assess the stationarity of the variables, we utilized the augmented Dickey and Fuller (1979) and Phillips and Perron (1988) tests using Eviews (version 10) software. The four models are then tested by applying the Johansen (1988) co-integration test to determine the long-run relationship among the variables. According to Engle and Granger (1987), when the variables are co-integrated (results are not provided here), the regression coefficients confirm the validity of the outcomes, and the regression results are not spurious. Further, the co-integrating regression technique-fully modified ordinary least squares (FMOLS) method-is used to demonstrate the positive and negative effects of agricultural mechanization on the Bangladeshi economy. Phillips and Hansen (1990) introduced the fully modified ordinary least squares (FMOLS) technique, which assumes a single co-integration vector. According to their findings, the FMOLS estimator has excellent consistency and asymptotic deviations. The FMOLS co-integrating regression technique offers numerous significant advantages. It is particularly effective at obtaining robust parameter estimations, even with small sample numbers. It also addresses complex concerns, including measurement errors, endogeneity, serial correlation, and omitted variable bias. This technique additionally handles variations in long-term parameters, as demonstrated by the research of Kalim and Shahbaz (2009) and Fereidouni et al. (2017).

Results and Discussion

Descriptive Statistics

Before analyzing data, verifying the variables' descriptive statistics (mean, median, maximum, minimum, skewness, and kurtosis) is an essential task. Descriptive statistics is a very valuable technique for checking data normality, selecting outliers, identifying trends and patterns, and determining data variability.

Table 1 shows the mean, median, maximum, and minimum values, skewness, and kurtosis for each variable from 1991 to 2022 with a natural logarithm (Ln) transformation. The average crop production index during this period is 4.30, while GDP has a mean of 25.27. Most of the variables illustrate distributions close to normal, as indicated by skewness values near zero and moderate kurtosis. However, income inequality stands out with a negative skew (-1.06) and high kurtosis (6.44), suggesting a distribution with a high left tail and sharper peak. Arable land area also shows a notable right skew (1.03). Variables like employment in agriculture, fertilizer use, and energy consumption are more symmetrically distributed. Each variable includes 32 observations. These descriptive statistics provide a reliable basis for further econometric analysis.

Table 1. Descriptive Statistics of Dependent and Independent Variables

Variables	Mean	Median	Maximum	Minimum	Skewness	Kurtosis	Obs.
Crop Production (Index:2004-06=100)	4.3048	4.3290	4.7799	3.8024	-0.1536	1.5813	32
Gross Domestic Product (Current US$)	25.2704	25.0489	26.8547	24.1558	0.4120	1.9702	32
Income inequality (Gini Index, %)	3.4915	3.4990	3.6136	3.3178	-1.0599	6.4370	32
Employment in Agriculture (%)	3.9425	3.8704	4.2414	3.6071	-0.0021	1.5707	32
Electricity Consumers in Agriculture (Nos.)	10.0958	9.9275	10.9142	9.3652	0.1928	1.7122	32
Irrigation Equipment (DTWs, STWs, LLPs) (Nos.)	13.9458	14.1558	14.3869	12.8612	-0.9557	2.7063	32
Irrigated Area by Irrigation Equipment (DTWs, STWs, LLPs) (‘000 ha)	8.3359	8.4781	8.6566	7.6815	-0.8485	2.4910	32
No. of Tractors (Nos.)	7.6637	7.7366	8.6170	6.1092	-0.4780	2.2423	32
No. of Power Tillers (Nos.)	13.0556	12.9968	13.5410	12.4343	-0.0059	2.2658	32
Fertilizer Consumption (Kg per ha)	5.2847	5.2409	5.9802	4.6730	0.0914	1.9632	32
Energy Consumption (Terawatt)	5.3302	5.3422	6.2499	4.2626	-0.0783	1.8676	32
Arable Land Area (‘000 acres)	15.9057	15.8968	16.0546	15.8527	1.0287	4.3874	32

Source: Eviews software based on annual time series data (1991-2022).

Unit Root Test

For annual time series data, it is essential first to examine the stationarity of the variables, as the choice of an appropriate model depends on the presence of unit roots. Moreover, determining stationarity is fundamental for avoiding spurious regression, co-integration analysis, forecasting accuracy, and distinguishing between short-run and long-run analyses. However, the results of unit root tests in Tables 2 and 3 show that augmented Dickey and Fuller (1979) and Phillips and Perron (1988) tests are performed twice: first on the variables in their original form and then on their first differences with the intercept, and intercept and trend. Both tests demonstrate that all variables are non-stationary at their initial levels, but stationary at first differences, indicating a solid rationale for running co-integrating regression for further analysis.

Effect of Agricultural Mechanization on Crop Production

According to the results of FMOLS (Table 4), agricultural mechanization has a positive impact on crop production in Bangladesh. Except for the number of power tillers (significant at the 1% level), the number of electricity consumers (not significant), the number of irrigation equipment (significant at the 1% level), irrigated area by irrigation equipment (significant at the 1% level), the number of tractors (significant at the 5% level), fertilizer consumption (significant at the 1% level), energy consumption (significant at the 1% level), and the arable land area (not significant) have a positive influence on crop yield. Advanced technologies that encourage accuracy and precision in farming techniques are frequently included in modern agricultural machines. According to estimates, mechanization can ensure reduced waste of seed and fertilizer while also saving about 30% of time and labor. It is possible to raise overall productivity by about 15% (Hasib, 2021). Mechanization can boost crop yield per hectare, for instance, by breaking compact subsoil layers that limit root growth and water flow. On specific soil types, modern tools may also improve seedbed quality, leading to better germination and healthier plants. Moreover, timely farm operations-often made possible through mechanization-are essential for maximizing yields (Magdoff, 1982). Manual planting in Bangladesh is labor-intensive, taking 123 to150 person-hours per hectare, whereas mechanical transplanting with a four-row transplanter cuts it to just 9 to 11 hours, enhancing efficiency and easing labor shortages (Robin, 2023). Farm mechanization, which replaces human labor with machines, enables the efficient cultivation of large areas and improves agricultural productivity. A farm machine can cover more land in a day than thirty laborers can in a month (Ovie, 2024).

Table 2. Augmented Dickey-Fuller (ADF) Unit Root Test of Dependent and Independent Variables

Variables	Level		First Difference	
	Intercept	Intercept and Trend	Intercept	Intercept and Trend
Crop Production	0.93	0.37	0.00**	0.00**
Gross Domestic Product	1.00	0.97	0.00**	0.00**
Income Inequality	0.10	0.07	0.00**	0.00**
Employment in Agriculture	0.88	0.10	0.00**	0.01*
Electricity Consumers in Agriculture	0.62	0.74	0.00**	0.00**
Irrigation Equipment (DTWs, STWs, LLPs)	0.06	0.85	0.01*	0.00**
Irrigated Area by Irrigation Equipment (DTWs, STWs, LLPs)	0.19	0.98	0.00**	0.00**
No. of Tractors	0.40	0.33	0.00**	0.00**
No. of Power Tillers	1.00	0.74	0.00**	0.00**
Fertilizer Consumption	0.92	0.02*	0.00**	0.00**
Energy Consumption	0.39	0.01*	0.00**	0.00**
Arable Land Area	0.10	0.09	0.00**	0.00**

Source: Eviews software based on annual time series data (19991-2022). Notes: ** P<0.01, *P<0.05.

Table 3. Phillips-Perron (PP) Unit Root Test of Dependent and Independent Variables

Variables	Level		First Difference	
	Intercept	Intercept and Trend	Intercept	Intercept and Trend
Crop Production	0.93	0.29	0.00**	0.00**
Gross Domestic Product	1.00	0.98	0.00**	0.00**
Income Inequality	0.11	0.06	0.00**	0.00**
Employment in Agriculture	0.95	0.47	0.00**	0.01*
Electricity Consumer in Agriculture	0.58	0.57	0.00**	0.00**
Irrigation Equipment (DTWs, STWs, LLPs)	0.07	0.87	0.00**	0.00**
Irrigated Area by Irrigation Equipment (DTWs, STWs, LLPs)	0.07	0.64	0.00**	0.00**
No. of Tractors	0.44	0.37	0.00**	0.00**
No. of Power Tillers	0.40	0.04*	0.00**	0.00**
Fertilizer Consumption	0.97	0.03*	0.00**	0.00**
Energy Consumption	0.38	0.01*	0.00**	0.00**
Arable Land Area	0.11	0.09	0.00**	0.00**

Source: Eviews software based on annual time series data (19991-2022). Notes: **P<0.01, *P<0.05.

The use of machines in farming has helped Bangladesh increase the production of rice, wheat, maize, and some vegetables. It all started with water pumps for irrigation, and later, as high-yield rice became popular, the need for irrigation grew. According to the World Bank (2025a) report, 78.9% of the arable land area is irrigated, which has boosted food production. Machinery such as tractors and irrigation equipment increase crop production by working continuously, as opposed to humans, who feel tired. This continuous activity produces larger production though the cultivation of additional land. Producing and operating agricultural machines requires significant energy, mostly from fossil fuels, along with some human labor. Although mechanization reduces the need for human and animal effort, it increases reliance on energy for both manufacturing and operation. This links agriculture closely to the cost and availability of petroleum. While inputs like fertilizers and pesticides also demand high energy, their proper use often leads to higher crop yields (Magdoff, 1982). On the other side, the amount of power tillers (significant at the 1% level) has an undesirable effect on crop yields, which was not expected. Though power tillers boost crop yields, farmers in developing countries like Bangladesh lack proper training. Consequently, improper use of agricultural mechanization (power tillers, tractors, etc.) can result in poor water retention, decreased soil aeration, and compaction of the soil (Kansanga et al.

2020). Moreover, heavy machinery can compact soil, diminishing fertility and increasing erosion risk (Rahman, 2023). Heavy farm machines may harm soil structure, and lubricant can leak into the soil during servicing, resulting in soil pollution (Robin, 2024; Magdoff, 1982). Farm mechanization loosens soil structure, making it more vulnerable to erosion by wind and water. During heavy rainfall, oversaturation causes nutrient-rich soil to wash away, degrading soil quality (Ovie, 2024; Magdoff, 1982). Soil erosion depletes fertility and reduces crop yields. The loss of topsoil makes it difficult to sustain agricultural productivity, and in extreme cases, the land may become unsuitable for cultivation.

Effect of Agricultural Mechanization on GDP

Similar effects of agricultural mechanization can be observed on gross domestic product (GDP) in the country. Other than for the number of irrigation equipment, all independent variables have positive and significant (at 1% and 5% significance levels) effects on GDP in Bangladesh. As a result, higher agricultural mechanization contributes to an increase in GDP, although the impact of fertilizer use is not statistically significant. The usage of modern agrarian machinery has had a substantial impact on Bangladesh's agricultural sector. According to Solow's (1956) 'Growth Theory' technological progress in agriculture shifts the production function upward, leading to an increase in GDP per capita, although the capital and labor force are unchanged. By reducing seasonal variations, mechanization helps to significantly raise crop output, hence supporting food security in Bangladesh. Enhanced food security strengthens the trade position of the nation by lowering dependence on food imports. Moreover, as food becomes cheaper and more accessible, the standard of living and purchasing power of the people rise. Increased agricultural efficiency allows government spending on this sector to be cut, hence generating more budgetary space for investment in other sectors of the economy and finally helping gross domestic product to grow. Tractors and irrigation systems are examples of agricultural equipment that has increased agricultural output as well as effectiveness, allowing farmers for faster agricultural operations using fewer workers. This advancement has strengthened food security and contributed to economic growth (Rahman, 2023). Farm mechanization further drives economic development by improving agricultural efficiency, which, in turn, raises farmers' profits and supports broader economic growth (Agri Studoc, 2023). An estimated BDT 2,000 is required to prepare one Bigha (33 decimals) of land using an animal drawn plow[3]. The cost decreases to BDT 600 only if a tractor is used in Bangladesh (Hasib, 2021). Mechanized farming has played a transformative role in Bangladesh's economic advancement by streamlining agricultural processes, reducing dependence on manual labor, and increasing productivity (LightCastle Partners, 2022). The adoption of mechanized tools helps

[3]BDT=Bangladeshi Taka, the official currency of Bangladesh.

minimize post-harvest losses and lower production expenses, allowing farmers to enhance profitability and reinvest in innovative agricultural solutions (Cereal Systems Initiative for South Asia, 2022). The rising demand for farming technology has also driven investments in equipment manufacturing, fostering industrial growth and promoting advancements in the sector (LightCastle Partners, 2022). Mechanization contributes to increased agricultural output, which then, in essence, supports the expansion of numerous agro-based companies (Pran Group, ACI Limited, Kazi Farms Group, etc.) and raises the gross domestic product of the nation. Moreover, increasing agricultural production through mechanization boosts trade surplus, and that in effect increases GDP because it is a component of GDP. The overall growing use of mechanization strengthens the agricultural landscape of Bangladesh, fostering rural economic growth, and supports long-term economic resilience. Conversely, according to the regression results, irrigation equipment (significant at the 5% level) has an adverse effect on Bangladesh's gross domestic product (GDP). Over-dependence on irrigation equipment like deep tube wells, shallow tube wells, and low lift pumps can negatively impact GDP by depleting groundwater reserves and escalating energy expenditures, leading to unsustainable farming methods (Barbier, 2024). Additionally, excessive water application can harm soil health by washing out soil nutrients, diminishing long-term agricultural productivity, and, as a result, hindering economic growth. In developing countries like Bangladesh, over-irrigation, inefficient use of irrigation equipment, and poor maintenance impede output and growth.

Effect of Agricultural Mechanization on Income Inequality

According to findings, agricultural mechanization has an adverse impact on income inequality. Apart from consumption of energy (significant at the 1% level), every independent variable has a positive effect on income inequality. It means that increasing the number of electricity consumers (significant at the 5% level), the number of irrigation equipment (significant at the 5% level), the irrigated area by irrigation equipment (not significant), the number of tractors (not significant), power tillers (significant at the 10% level), fertilizer consumption (not significant), and arable land area (not significant) raises the Gini index, hence growing income inequality in Bangladesh. Small-scale farmers, who constitute a significant portion of the farm labor force, often struggle to afford modern technology, leading to disparities in mechanization levels. For small-scale farmers to successfully adopt and use mechanized technology, access to credit, training, and technical assistance can be essential. Income gaps may increase in areas without these support networks since wealthy farmers have greater access to resources and automation options. The high cost of purchasing and maintaining agrarian machinery creates financial barriers, limiting small farmers' ability to adopt advanced farming techniques. Although the government of Bangladesh distributed a significant number of farm machinery through subsidy programs, the needy farmers didn't receive the full

benefits because of third parties. Even many farmers are unaware of the allocation made in their name (Shahid, 2024). This, in turn, contributes to differences in productivity and income between large and small farms, potentially exacerbating economic inequality (Rahman, 2023). According to the International Food Policy Research Institute (IFPRI), smallholder and marginal farmers have comparatively limited access to labor-saving technologies like power tillers, which are used more frequently as farm sizes increase (Ahmed et al. 2021). The increased efficiency of automated farms can drive down prices, putting pressure on small farmers who lack the means to compete at the same scale. In Bangladesh, because land is often small and broken into scattered plots, it's tough for many small farmers to make cost-effective use of modern machinery. Meanwhile, better off landowners with larger farms find it easier to adopt these technologies, which boost their yields and income. Moreover, using machinery usually results in higher returns on investment, benefiting those who can afford such equipment. This shift reduces the share of income that goes to labor, which is the main source of income for poorer households. Mechanization, when focused primarily on already developed regions (for Bangladesh: Dhaka, Chattogram, Gazipur, parts of Rajshahi, and Sylhet), can unintentionally widen the gap between advanced and underdeveloped areas (Hill Tracts region, River Island region). This unequal distribution of machinery resources often leads to increased regional economic inequality. Such disparities make it more difficult to achieve social and economic equity across the country (Magdoff, 1982). Moreover, agricultural mechanization widens the income gap between skilled and unskilled workers because skilled workers who benefit from mechanization have greater opportunities to earn more than unskilled workers. On the contrary, energy consumption can help reduce income inequality in agriculture by facilitating the use of mechanized farming tools, improving productivity, and lowering operational costs. Access to energy enables small-scale farmers to enhance their yields and minimize labor requirements, ultimately increasing their income. This, in turn, narrows the income gap by allowing farmers to reinvest in their operations, leading to more excellent economic stability in rural areas (Ahlborg and Sjöstedt, 2015).

Effect of Agricultural Mechanization on Employment in the Agriculture Sector

Agricultural mechanization has had a mixed adverse and favorable effect on employment rates in Bangladesh's agricultural sector. Irrigated areas by irrigation equipment (significant at the 5% level), number of tractors used (significant at the 1% level), number of power tillers (significant at the 5% level), fertilizer consumption (not significant), and energy consumption (significant at the 1% level) all have a negative impact on agricultural employment rates. This means that these types of mechanization reduce jobs in the farming industry. However, the number of electricity consumers in the agricultural sector (significant at the 1%

level), the quantity of irrigation equipment (significant at the 1% level), and arable land area (not significant) have a favorable effect on employment rates. Therefore, these types of mechanization boost employment rates. Low-skilled workers make up the majority of the workforce in rural parts of developing nations like Bangladesh, and the majority cannot use modern agricultural equipment. They lose their jobs due to a dearth of training facilities in rural areas, which leads to structural unemployment in those places. Mechanization in agriculture shortens the harvesting period, which creates a seasonal unemployment problem. Technological advancements in agriculture can only help those who possess the necessary skills. Low-skilled or unskilled workers must change professions, which is challenging for them but causes frictional unemployment in countries like Bangladesh. Farm workers who rely on manual labor may be forced to seek alternative employment, often migrating to cities for work. Over the past three decades, many rural workers in Bangladesh have migrated to metropolitan areas, seeking opportunities in the growing service and RMG sectors. This shift has contributed to labor shortages in agriculture, particularly during crucial periods like planting and harvesting (Robin, 2023). This shortage of labor during crucial periods increases wage rates, and researchers found that participation in the agricultural labor force declined between 2005 and 2022, while real wages in agriculture steadily increased from 2010 to 2022 in Bangladesh. Additionally, farmers lacking the expertise to operate and maintain machinery may depend on external service providers, increasing production costs and reducing self-sufficiency (Rahman, 2023). As mechanization reduces the demand for farm labor, rural populations may decline, disrupting local economies and communities. In Bangladesh, significant number of (approximately 18.43 million in 2022) women are engaged in agricultural work. Mechanization displaces their jobs (Haggblade et al. 2010), and they have no alternatives to shift to other professions, which increases rural women's unemployment. The output per labor is significantly increased as a result of mechanization, which necessitates less labor in the agricultural sector (Magdoff, 1982), and it has a very adverse effect on employment in labor-intensive countries like Bangladesh. On the flip side, increasing electricity consumers in agriculture helps farmers adopt better technologies and irrigation facilities, leading to higher productivity and more jobs for skilled workers. More irrigation equipment enables year-round farming, creating additional employment opportunities in planting and maintenance. It is true that as machines take the place of animals, less animal feed is required, potentially freeing up more arable area for the production of human food (Magdoff, 1982). As the amount of arable land increases, more workers are needed for tasks like land preparation and harvesting, boosting employment in the agricultural sector of Bangladesh. Furthermore, modern farming machinery has raised domestic demand for machinery and spare parts, which has led to the creation of new job opportunities in the industrial sector of Bangladesh (ACI Motors Ltd., Alim Industries Ltd., and The Metal (Pvt.) Ltd., etc.).

Table 4. Results of Fully Modified OLS (FMOLS)

Independent Variables	Crop Production		Gross Domestic Product		Income Inequality		Employment in Agriculture	
	Coefficients	Prob.	Coefficients	Prob.	Coefficients	Prob.	Coefficients	Prob.
Electricity Consumers in Agriculture	0.004	0.86	0.152	0.00***	0.075	0.01**	0.076	0.00***
Irrigation Equipment (DTWs, STWs, LLPs)	0.517	0.00***	-0.415	0.01**	0.079	0.03**	0.201	0.00***
Irrigated Area by Irrigation Equipment (DTWs, STWs, LLPs)	0.828	0.00***	0.549	0.02**	0.134	0.30	-0.200	0.04**
No. of Tractors	0.037	0.03**	0.064	0.03**	0.024	0.15	-0.037	0.00***
No. of Power Tillers	-0.888	0.00***	0.848	0.02**	0.418	0.05*	-0.384	0.01**
Fertilizer Consumption	0.220	0.00***	0.019	0.88	0.086	0.27	-0.003	0.95
Energy Consumption	0.841	0.00***	1.024	0.00***	-0.354	0.00***	-0.575	0.00***
Arable Land Area	0.519	0.27	3.290	0.00***	0.011	0.97	0.530	0.12
R^2	0.98		0.99		0.58		0.98	

Source: Eviews software on the basis of annual time series data (1991-2020). **Notes:** *** p<0.01, **p<0.05, *p<0.10.

However, we have to take some important actions in order to overcome the obstacles of agricultural mechanization in Bangladesh. Promoting sustainable, eco-friendly machinery practices can help reduce the adverse effects and maintain a balanced approach to agricultural mechanization in Bangladesh (Rahman, 2023). Establishing agro-service centers, strengthening land policies, providing low-interest loans and long-term credit support from financial institutions, and allocating funds for machinery research and development are crucial for the sustainable development of the agricultural sector of Bangladesh (Islam and Shirazul, 2009; Hossen, 2019). The government and private sector should establish machinery rental centers for hiring agricultural machinery to enable small farmers to access modern equipment to increase crop production (West Africa Examination Councils, 2019).

Conclusion

Agricultural mechanization has produced both positive and negative effects on Bangladesh's national economy during the period 1991-2022. The empirical results indicate that mechanization contributes positively and significantly to overall crop production and gross domestic product (GDP), highlighting its important role in improving agricultural productivity and economic growth. However, the analysis also reveals some unfavorable outcomes. Specifically, the number of power tillers and irrigation equipment shows negative effects on crop production and GDP, respectively. Moreover, agricultural mechanization has a significant adverse impact on income inequality and employment in the agricultural sector, suggesting that increased mechanization may reduce labor demand and widen income disparities in rural areas. On the other hand, energy consumption has a favorable effect on income inequality, while the number of electricity consumers, irrigation equipment, and the area of arable land positively influence employment. Based on these findings, several policy measures are recommended to address the challenges associated with agricultural mechanization in Bangladesh. These include expanding agro-service centers, promoting environmentally sustainable mechanization, reforming land policies, providing low-interest credit facilities, establishing machinery rental service centers to ensure more inclusive and balanced agricultural development.

Limitations of the Study

Because of the unavailability of annual time series data from 1991 to 2022, this study could not include some important independent variables such as the number of transplanters, seeders, weeders, threshers, etc. Future research may find new dimensions by including these variables.

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