

## **Impact of Environmental Conditions on Rice Farming Productivity and Efficiency in Bangladesh**

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[Received July 14, 2025; Accepted October 10, 2025]

### **Abstract**

Rice farming plays a critical role in ensuring food security and economic stability in Bangladesh, with environmental conditions significantly affecting its productivity and efficiency. This study assesses the impact of climatic, soil and ecological factors on the performance of three major rice varieties Aus, Aman and Boro using secondary data from 1980 to 2021. Data Envelopment Analysis (DEA) was employed to estimate technical efficiency and Total Factor Productivity (TFP) growth while Tobit regression models were used to quantify the influence of environmental variables including average temperature, rainfall, humidity, sunshine and wind speed, under both Constant Returns to Scale (CRS) and Variable Returns to Scale (VRS) assumptions. The results revealed that average temperature showed a significant positive effect on all rice types under both CRS ( $\beta = 0.3356$ ,  $p < 0.001$ ) and VRS ( $\beta = 0.0813-0.1949$ ,  $p < 0.05$ ) models. Rainfall slightly improved Aman efficiency under CRS ( $\beta = 0.0001$ ,  $p < 0.05$ ) and had mixed effects under VRS positive for Aus ( $\beta = 0.0013$ ,  $p < 0.10$ ) but negative for Aman ( $\beta = -0.0027$ ,  $p < 0.05$ ). Humidity decreased Aus and Aman efficiency under CRS ( $\beta = -0.1001$  and  $-0.0531$ ,  $p < 0.01$ ) but enhanced Boro under VRS ( $\beta = 0.0224$ ,  $p < 0.05$ ). Sunshine reduced efficiency for Boro ( $\beta = -0.1699$ ,  $p < 0.001$ ) and Aman ( $\beta = -0.1953$ ,  $p < 0.001$ ), while wind speed had negative effects on Aus and Aman under CRS ( $\beta = -0.1563$  and  $-0.1971$ ,  $p < 0.05$ ) and a positive impact on Aus under VRS ( $\beta = 0.3719$ ,  $p < 0.05$ ). These findings underscore the differential sensitivity of rice varieties to environmental fluctuations and provide valuable insights for climate-resilient rice production and sustainable agricultural policymaking in Bangladesh.

**Keywords:** Rice farming, environmental conditions, technical efficiency, DEA, Total Factor Productivity (TFP), CRS, VRS.

**AMS Classification:** Primary 90C05; Secondary 91B38, 91B76, 62P20.

### **1. Introduction**

Rice is the staple food of Bangladesh and a cornerstone of its agricultural economy, contributing approximately 50% of the agricultural GDP and employing nearly half of the rural labor force (Sayeed and Yunus 2018). With over 15 million farms cultivating rice, the sector plays a crucial role in ensuring food security and rural livelihoods. Bangladesh cultivates three major rice

varieties Aus, Aman, and Boro across different agro-climatic seasons, each with unique environmental requirements and vulnerabilities. While Aus and Aman are predominantly rainfed, Boro relies heavily on irrigation and favorable dry-season conditions.

Environmental conditions such as temperature, rainfall, humidity, sunshine, and wind speed significantly influence rice productivity and technical efficiency. Bangladesh's geographical location and tropical monsoon climate expose its rice farming system to frequent floods, irregular rainfall, and temperature fluctuations (Nahar 2016). For instance, about 21% of the country experiences annual flooding, with severe floods occasionally affecting over two-thirds of the land area, posing major challenges to stable rice production (Dewan, Nishigaki, and Komatsu 2003; Sherlund, Barrett, and Adesina 2005). Given the country's dependence on rice, understanding how environmental variability affects productivity and efficiency is vital for sustainable agricultural development. Although numerous studies have explored rice production efficiency in Bangladesh, many have focused primarily on socio-economic factors or employed general efficiency models without adequately incorporating environmental influences (Ahmed, Zander, and Garnett 2011; Anik et al. 2022; Kubitza et al. 2024; Salam, Sarker, and Sharmin 2021). Some research has examined climate impacts on rice yield using time series models or simulation tools, while others have assessed technical efficiency using methods like Stochastic Frontier Analysis (SFA) or Data Envelopment Analysis (DEA) (Ho et al. 2024; Md Kamrul Hossain et al. 2012; Mohammad Kamrul Hossain et al. 2012; Piya, Kiminami, and Yagi 2012; Xue, Mizuki, and Kawashima 2025). However, there remains a significant gap in systematically analyzing the distinct impacts of environmental conditions on the efficiency of different rice varieties across a multi-decade timeline.

This study aims to fill that gap by evaluating the influence of environmental factors on the productivity and efficiency of Aus, Aman, and Boro rice production in Bangladesh over the period 1980–2021. Using DEA, we measure technical efficiency under two scenarios with and without environmental variables to assess their impact. In addition, Tobit regression is employed to analyze how specific environmental factors contribute to variations in production efficiency. By combining efficiency analysis with environmental assessment, this study provides deeper insights into how climatic and ecological variables affect rice farming performance. The findings are intended to inform agricultural policy, improve resource allocation, and support the development of climate-resilient rice farming strategies in Bangladesh.

## **2. Materials and Methods**

### **2.1 Study design and data collection**

This study utilizes secondary data covering the period from 1981 to 2022 to examine the relationship between environmental conditions and the productivity and efficiency of rice farming in Bangladesh. Data on three major rice varieties Aus, Aman, and Boro were collected from the Yearbook of Agricultural Statistics, published annually by the Bangladesh Bureau of Statistics (BBS). Key agricultural variables extracted include total rice production (in metric tons) and cultivated area (in hectares) for each rice type. Environmental data were obtained from the Bangladesh Meteorological Department (BMD). The climatic variables incorporated into the analysis include average temperature (°C), total rainfall (mm), relative humidity (%), sunshine duration (hours), and wind speed (m/s) factors known to influence crop growth and productivity.

## 2.2 Data Preprocessing

Environmental data were collected from 35 meteorological stations distributed across Bangladesh to ensure comprehensive geographic coverage. To create a consistent and nationally representative dataset, the climatic variables from these stations were averaged annually. The processed environmental data were then merged with corresponding rice production and cultivated area data for each rice variety (Aus, Aman, and Boro), resulting in a structured panel dataset suitable for efficiency and regression analysis. This preprocessing ensured alignment across variables and time periods, enabling accurate assessment of the relationship between environmental factors and rice farming performance.

## 2.3 Variable Measures

This study employed a combination of agricultural and environmental variables to evaluate the efficiency of rice production in Bangladesh. The output variable was the annual production of the three major rice types Aus, Aman, and Boro measured in thousand metric tons. The primary input variable was the cultivated area for each rice variety, expressed in thousand hectares, representing the land allocated for rice production by farmers. To account for non-controllable influences on productivity, five key environmental variables were included: average temperature, rainfall, humidity, sunshine, and wind speed. Average temperature, measured in degrees Celsius, was calculated by averaging the daily maximum and minimum temperatures over the respective rice-growing periods. Rainfall was measured in millimeters per square meter, with the majority occurring during the monsoon season (June to September), which coincides with the growing periods of Aus and Aman, while Boro is cultivated primarily during the drier winter months (November to February) when rainfall is minimal. Humidity, recorded as a percentage, plays a critical role in rice cultivation and varies seasonally, typically peaking during the monsoon and dropping significantly during winter. Sunshine was measured as the average number of sunlight hours received per day during the production period, which is vital for photosynthesis and grain filling. Lastly, wind speed, measured in meters per second, was considered for its potential effects on plant physiology and pollination during critical stages of crop development.

## 2.4 Statistical Analysis

To assess the technical efficiency of rice production over time, Data Envelopment Analysis (DEA) was employed to calculate annual efficiency scores. Subsequently, Tobit regression was used to examine the impact of environmental factors on production efficiency, considering that efficiency scores are bounded between 0 and 1.

Analytical framework of CRS-DEA: Let's consider that,  $p^{\text{th}}$  farm used 's' number of inputs to produce 't' number of outputs. To measure efficiency of production in Constant Return to Scale (CRS), the CCR model could be used which is defined as,

Objective function:

$$\text{Max } \theta_p$$

Subject to constraints,

$$x_{pi} \geq \sum_{p=1}^n \lambda_p x_{pi}; \quad i = 1, 2, \dots, s$$

and

$$\theta_p y_{pj} \geq \sum_{p=1}^n \lambda_p y_{pj} \quad j = 1, 2, \dots, t$$

where,  $x_{pi} \geq 0$  is the  $i^{\text{th}}$  input and  $y_{pj} \geq 0$  is the  $j^{\text{th}}$  output for  $p^{\text{th}}$  firm.  $\lambda_p \geq 0$  represent the weight of the variables. This problem has to be solved  $n$  times because the total number of farms is  $n$ .

Analytical framework of VRS-DEA: For production efficiency according to variable return to scale (VRS), the BCC model could be used. This model is same as CCR model except it has an extra constraint:

$$\sum_{p=1}^n \lambda_p = 1$$

So, the BCC model can be defined as,

Objective function:

$$\text{Max } \theta_p$$

Subject to constraints,

$$x_{pi} \geq \sum_{p=1}^n \lambda_p x_{pi}; \quad i = 1, 2, \dots, s$$

and

$$\theta_p y_{pj} \geq \sum_{p=1}^n \lambda_p y_{pj}; \quad j = 1, 2, \dots, t$$

Tobit regression: After measuring the relative efficiencies, the determinants of the DEA efficiency scores can be investigated. The dependent variable 'efficiency' is a limited dependent variable because the DEA score lies in the interval of 0 and 1. Therefore, it is appropriate to use censored regression such as the Tobit regression model. It may be defined as:

$$\theta_p = \begin{cases} \theta_p^*; & 0 \leq \theta_p^* \leq 1 \\ 0; & \theta_p^* \leq 0 \\ 1; & \theta_p^* \geq 1 \end{cases}$$

$$\theta_p^* = \alpha + \sum_{m=1}^s \beta_m w_{pm} + \varepsilon_p; \quad \varepsilon_p \sim N(0, \sigma^2)$$

where,

- $\theta_p$  = DEA efficiency score of  $p^{\text{th}}$  farm
- $\theta_p^*$  = Unobserved efficiency score of  $p^{\text{th}}$  farm
- $\beta_m$  = Parameter to determine the relationship between independent variables and the dependent variable
- $w_{pm}$  =  $m^{\text{th}}$  environmental factor of  $p^{\text{th}}$  farm

### 3. Results and Discussion

Tables 1 to 3 present the year-wise technical efficiency scores for Aus, Aman, and Boro rice production, respectively. A consistent trend is observed across all rice varieties: the inclusion of environmental factors in the DEA model results in higher efficiency scores compared to models that exclude these variables. Under the Constant Returns to Scale (CRS) assumption, the mean efficiency scores without environmental factors were 0.589 for Aus, 0.712 for Aman, and 0.749

for Boro. When environmental variables such as temperature, rainfall, humidity, sunshine, and wind speed were included, the mean efficiency scores increased to 0.766, 0.761, and 0.768, respectively. This improvement suggests that environmental conditions play a significant role in influencing production efficiency and omitting them may lead to biased or underestimated efficiency measurements. These findings are consistent with Sherlund et al. (2002), who emphasized the importance of including environmental and farm-specific conditions in efficiency analyses to obtain more accurate results (Sherlund et al. 2005).

**Table 1:** Year wise technical efficiency of Aus rice

Year	Without environmental factor			With environmental factors		
	TE			TE		
	CRS	VRS	SE	CRS	VRS	SE
1980-81	0.398	1.000	0.398	1.000	1.000	1.000
1981-82	0.391	0.994	0.394	1.000	1.000	1.000
1982-83	0.365	0.932	0.392	0.955	1.000	0.955
1983-84	0.386	0.980	0.395	0.982	0.988	0.995
1984-85	0.357	0.846	0.421	0.854	1.000	0.854
1985-86	0.374	0.860	0.435	0.898	1.000	0.898
1986-87	0.406	0.952	0.426	0.962	1.000	0.962
1987-88	0.404	0.910	0.444	0.905	0.910	0.994
1988-89	0.401	0.869	0.461	0.881	0.909	0.969
1989-90	0.413	0.753	0.549	0.794	1.000	0.794
1990-91	0.404	0.688	0.587	0.733	1.000	0.733
1991-92	0.428	0.663	0.646	0.705	1.000	0.705
1992-93	0.450	0.632	0.713	0.790	1.000	0.790
1993-94	0.422	0.563	0.750	0.578	1.000	0.578
1994-95	0.405	0.545	0.743	0.574	1.000	0.574
1995-96	0.409	0.510	0.802	0.541	1.000	0.541
1996-97	0.442	0.569	0.777	0.611	0.743	0.822
1997-98	0.451	0.571	0.790	0.598	1.000	0.598
1998-99	0.427	0.492	0.868	0.501	0.633	0.793
1999-00	0.483	0.528	0.915	0.545	0.545	1.000
2000-01	0.544	0.583	0.933	0.592	0.640	0.926
2001-02	0.548	0.568	0.965	0.568	0.568	1.000
2002-03	0.560	0.581	0.965	0.587	1.000	0.587
2003-04	0.573	0.587	0.977	0.589	0.681	0.864
2004-05	0.551	0.597	0.923	0.551	1.000	0.551
2005-06	0.635	0.683	0.931	0.635	0.698	0.910
2006-07	0.629	1.000	0.629	0.629	1.000	0.629
2007-08	0.618	0.868	0.711	0.618	1.000	0.618
2008-09	0.670	0.702	0.954	0.670	1.000	0.670
2009-10	0.654	0.734	0.890	0.654	1.000	0.654
2010-11	0.722	0.732	0.986	0.723	0.739	0.979
2011-12	0.772	0.773	0.999	0.777	0.848	0.916
2012-13	0.772	0.817	0.945	0.772	0.817	0.944
2013-14	0.833	0.883	0.943	0.833	0.885	0.941
2014-15	0.839	0.894	0.939	0.839	1.000	0.839
2015-16	0.907	0.982	0.923	0.916	1.000	0.916
2016-17	0.853	1.000	0.853	0.853	1.000	0.853
2017-18	0.949	0.988	0.961	0.978	1.000	0.978

Year	Without environmental factor			With environmental factors		
	TE			TE		
	CRS	VRS	SE	CRS	VRS	SE
2018-19	0.960	0.964	0.996	0.993	1.000	0.993
2019-20	1.000	1.000	1.000	1.000	1.000	1.000
2020-21	0.948	1.000	0.948	1.000	1.000	1.000
2021-22	0.972	0.980	0.991	1.000	1.000	1.000
Average	0.589	0.780	0.768	0.766	0.919	0.841

Among the three rice varieties, Boro exhibited the smallest difference in efficiency between the models with and without environmental factors. This may be attributed to Boro's cultivation during the dry season under controlled irrigation systems, which potentially minimizes the variability introduced by environmental conditions. This observation is supported by previous findings, who noted that irrigated rice systems, such as Boro, tend to demonstrate higher and more stable efficiency levels due to better management of inputs and growing conditions (Bell et al. 2015; Hossain et al. 2019; Islam et al. 2024).

**Table 2: Year wise technical efficiency of Aman rice**

Year	Without environmental factor			With environmental factors		
	TE			TE		
	CRS	VRS	SE	CRS	VRS	SE
1980-81	0.398	1.000	0.398	1.000	1.000	1.000
1981-82	0.391	0.994	0.394	1.000	1.000	1.000
1982-83	0.365	0.932	0.392	0.955	1.000	0.955
1983-84	0.386	0.980	0.395	0.982	0.988	0.995
1984-85	0.357	0.846	0.421	0.854	1.000	0.854
1985-86	0.374	0.860	0.435	0.898	1.000	0.898
1986-87	0.406	0.952	0.426	0.962	1.000	0.962
1987-88	0.404	0.910	0.444	0.905	0.910	0.994
1988-89	0.401	0.869	0.461	0.881	0.909	0.969
1989-90	0.413	0.753	0.549	0.794	1.000	0.794
1990-91	0.404	0.688	0.587	0.733	1.000	0.733
1991-92	0.428	0.663	0.646	0.705	1.000	0.705
1992-93	0.450	0.632	0.713	0.790	1.000	0.790
1993-94	0.422	0.563	0.750	0.578	1.000	0.578
1994-95	0.405	0.545	0.743	0.574	1.000	0.574
1995-96	0.409	0.510	0.802	0.541	1.000	0.541
1996-97	0.442	0.569	0.777	0.611	0.743	0.822
1997-98	0.451	0.571	0.790	0.598	1.000	0.598
1998-99	0.427	0.492	0.868	0.501	0.633	0.793
1999-00	0.483	0.528	0.915	0.545	0.545	1.000
2000-01	0.544	0.583	0.933	0.592	0.640	0.926
2001-02	0.548	0.568	0.965	0.568	0.568	1.000
2002-03	0.560	0.581	0.965	0.587	1.000	0.587
2003-04	0.573	0.587	0.977	0.589	0.681	0.864
2004-05	0.551	0.597	0.923	0.551	1.000	0.551
2005-06	0.635	0.683	0.931	0.635	0.698	0.910
2006-07	0.629	1.000	0.629	0.629	1.000	0.629
2007-08	0.618	0.868	0.711	0.618	1.000	0.618
2008-09	0.670	0.702	0.954	0.670	1.000	0.670
2009-10	0.654	0.734	0.890	0.654	1.000	0.654

Year	Without environmental factor			With environmental factors		
	TE			TE		
	CRS	VRS	SE	CRS	VRS	SE
2010-11	0.722	0.732	0.986	0.723	0.739	0.979
2011-12	0.772	0.773	0.999	0.777	0.848	0.916
2012-13	0.772	0.817	0.945	0.772	0.817	0.944
2013-14	0.833	0.883	0.943	0.833	0.885	0.941
2014-15	0.839	0.894	0.939	0.839	1.000	0.839
2015-16	0.907	0.982	0.923	0.916	1.000	0.916
2016-17	0.853	1.000	0.853	0.853	1.000	0.853
2017-18	0.949	0.988	0.961	0.978	1.000	0.978
2018-19	0.960	0.964	0.996	0.993	1.000	0.993
2019-20	1.000	1.000	1.000	1.000	1.000	1.000
2020-21	0.948	1.000	0.948	1.000	1.000	1.000
2021-22	0.972	0.980	0.991	1.000	1.000	1.000
Average	0.589	0.780	0.768	0.766	0.919	0.841

Under the Variable Returns to Scale (VRS) assumption, the average efficiency ranking across all scenarios both with and without environmental variables remains consistent: Boro rice shows the highest average efficiency, followed by Aman, with Aus showing lower efficiency when environmental factors are excluded. Interestingly, when environmental factors are included, Aus emerges as the most efficient variety under both CRS and VRS models. This indicates that Aus production may be more sensitive to environmental conditions, and accounting for these factors enhances the accuracy of efficiency estimation. Similar efficiency patterns and rankings were also observed in the studies, which highlighted differences in rice variety performance based on seasonal and climatic conditions (Assefa et al. 2021; Phoeurn et al. 2024).

**Table 3:** Year wise technical efficiency of BORO rice

Year	Without environmental factor			With environmental factors		
	TE			TE		
	CRS	VRS	SE	CRS	VRS	SE
1980-81	0.534	1.000	0.534	0.534	1.000	0.534
1981-82	0.570	0.949	0.601	0.570	1.000	0.570
1982-83	0.583	0.895	0.651	0.583	1.000	0.583
1983-84	0.563	0.880	0.640	0.563	1.000	0.563
1984-85	0.585	0.840	0.696	0.585	0.924	0.633
1985-86	0.564	0.825	0.684	0.564	0.984	0.573
1986-87	0.572	0.797	0.718	0.572	0.877	0.653
1987-88	0.574	0.733	0.782	0.574	0.930	0.617
1988-89	0.563	0.657	0.857	0.563	1.000	0.563
1989-90	0.579	0.674	0.859	0.579	1.000	0.579
1990-91	0.588	0.676	0.870	0.588	0.955	0.616
1991-92	0.609	0.692	0.879	0.609	1.000	0.609
1992-93	0.597	0.682	0.875	0.597	1.000	0.597
1993-94	0.618	0.708	0.873	0.618	0.870	0.710
1994-95	0.578	0.656	0.882	0.578	1.000	0.578
1995-96	0.618	0.694	0.891	0.618	0.891	0.693
1996-97	0.632	0.707	0.893	0.632	1.000	0.632
1997-98	0.664	0.735	0.903	0.664	1.000	0.664

Year	Without environmental factor			With environmental factors		
	TE			TE		
	CRS	VRS	SE	CRS	VRS	SE
1998-99	0.705	0.744	0.948	0.721	0.890	0.810
1999-00	0.711	0.745	0.955	0.735	0.913	0.805
2000-01	0.747	0.777	0.960	0.768	0.929	0.826
2001-02	0.735	0.765	0.961	0.759	0.904	0.840
2002-03	0.749	0.777	0.964	0.774	0.917	0.844
2003-04	0.767	0.791	0.969	0.793	0.927	0.855
2004-05	0.802	0.823	0.974	0.824	0.915	0.901
2005-06	0.810	0.831	0.975	0.833	0.932	0.893
2006-07	0.830	0.845	0.982	0.857	0.981	0.873
2007-08	0.908	0.912	0.995	0.934	0.972	0.961
2008-09	0.890	0.891	0.999	0.944	0.977	0.966
2009-10	0.904	0.905	0.998	0.944	0.978	0.966
2010-11	0.919	0.921	0.998	0.957	0.992	0.965
2011-12	0.920	0.927	0.992	0.960	0.985	0.974
2012-13	0.929	0.930	0.999	0.968	1.000	0.968
2013-14	0.935	0.940	0.995	1.000	1.000	1.000
2014-15	0.940	0.953	0.987	0.977	1.000	0.977
2015-16	0.955	0.958	0.998	1.000	1.000	1.000
2016-17	0.954	0.960	0.993	0.954	0.977	0.977
2017-18	0.949	0.963	0.985	0.982	0.997	0.985
2018-19	0.978	1.000	0.978	1.000	1.000	1.000
2019-20	1.000	1.000	1.000	1.000	1.000	1.000
2020-21	0.838	1.000	0.838	1.000	1.000	1.000
2021-22	0.988	0.996	0.991	0.999	1.000	0.999
Average	0.749	0.837	0.893	0.768	0.967	0.794

Table 4 reports the minimum technical efficiency scores for Aus, Aman, and Boro rice under both Constant Returns to Scale (CRS) and Variable Returns to Scale (VRS) assumptions, with and without the inclusion of environmental variables. In the CRS model, the lowest efficiency scores without environmental factors were 0.357 for Aus, 0.455 for Aman, and 0.534 for Boro. When environmental variables were incorporated, the minimum efficiency increased for Aus and Aman to 0.501 and 0.486, respectively, while remaining unchanged for Boro at 0.534. Under the VRS model, which captures pure technical efficiency, the minimum efficiency of Aus increased from 0.492 to 0.545, Aman from 0.465 to 0.796, and Boro from 0.656 to 0.870 upon incorporating environmental variables. The most significant relative gain was observed for Aman, suggesting that its production efficiency is highly sensitive to climatic factors. These findings align with Sherlund et al. (2002), who highlighted the critical role of environmental heterogeneity in shaping agricultural efficiency outcomes (Sherlund et al. 2005). The stability in Boro's minimum efficiency across CRS models, and its modest improvement under VRS, is likely due to its reliance on controlled irrigation during the dry season, which minimizes exposure to rainfall variability (Bhattacharyya et al. 2022; Mishra et al. 2015). In contrast, Aman and Aus being rainfed are more vulnerable to fluctuations in temperature, rainfall, and humidity, and thus show greater efficiency improvements when these variables are considered. The results further support the findings of Khan et al. (2010), who emphasized the differential response of rice varieties to environmental constraints.

**Table 4:** Minimum efficiency of rice

Rice	Without environmental factors		With environmental factors	
	CRS	VRS	CRS	VRS
AUS	0.357	0.492	0.501	0.545
AMAN	0.455	0.465	0.486	0.796
BORO	0.534	0.656	0.534	0.870

CRS = Constant return to scale, VRS: Variable return to scale

Table 5 presents Tobit regression results assessing the impact of environmental factors on the technical efficiency of Aus, Aman, and Boro rice under the CRS model. Average temperature had a significantly positive effect across all varieties, with the strongest impact on Aus ( $\beta = 0.3356, p < 0.001$ ), consistent with other studies, who found temperature to enhance productivity, especially for rainfed crops (Anwar et al. 2007; Rahman et al. 2017). Rainfall showed a positive but small effect only for Aman ( $\beta = 0.0001, p < 0.05$ ), while being insignificant for Aus and Boro. A study showed that irrigation reduces Boro’s sensitivity to rainfall variability (Hossain et al. 2019). Humidity negatively influenced Aus ( $\beta = -0.1001, p < 0.01$ ) and Aman ( $\beta = -0.0531, p < 0.01$ ), aligning with other studies (Guarnieri et al. 2023; Rayamajhee, Guo, and Bohara 2021), who linked high humidity to reduced efficiency due to increased disease pressure. Boro showed a marginally positive effect ( $\beta = 0.0157, p < 0.10$ ). Sunshine had a significant negative impact on Boro efficiency ( $\beta = -0.1699, p < 0.001$ ), supporting Bhuyan et al. (2023) & Ferdous (2022), who reported adverse effects of excessive sunlight in dry-season cultivation (Basak et al. 2014; Bhuyan et al. 2023). Wind speed negatively affected Aus ( $\beta = -0.1563, p < 0.05$ ) and Aman ( $\beta = -0.1971, p < 0.05$ ), but not Boro, consistent with Backman et al. (2011), who observed that high winds can damage rainfed crops and reduce efficiency through increased evapotranspiration.

**Table 5:** Impact of environmental factors on efficiency in CRS using Tobit regression

	AUS		AMAN		BORO	
	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error
Average Temperature	0.3356***	0.0541	0.2603***	0.0446	0.0817*	0.0341
Rainfall	0.00058	0.0005	0.0001*	0.0004	-0.0024	0.0010
Humidity	-0.1001**	0.0238	-0.0531**	0.0195	0.0157.	0.0094
Sunshine	-0.1178	0.0886	-0.1079	0.0727	-0.1699***	0.0333
Wind speed	-0.1563*	0.1089	-0.1971*	0.0895	-0.0363	0.0947

‘\*\*\*’, ‘\*\*’, ‘\*’ and ‘.’ are the indicator of significance at 0.1%, 1%, 5% and 10% of significance level, respectively

Table 6 presents the Tobit regression estimates examining the influence of environmental variables on the technical efficiency of Aus, Aman, and Boro rice under the Variable Returns to Scale (VRS) assumption. Average temperature positively and significantly influenced the efficiency of all three rice types Aus ( $\beta = 0.1949, p < 0.05$ ), Aman ( $\beta = 0.1301, p < 0.001$ ), and Boro ( $\beta = 0.0813, p < 0.05$ ). These findings are consistent with other studies, who reported that moderate increases in temperature enhance photosynthetic activity and crop growth, particularly for rainfed varieties like Aus and Aman (Al Mamun et al. 2025; Miah et al. 2025). Rainfall showed a mixed effect. For Aus, it had a marginally significant positive influence ( $\beta = 0.0013, p < 0.10$ ), whereas for Aman, the effect was negative and significant ( $\beta = -0.0027, p < 0.05$ ). For Boro, rainfall had no significant effect. The negative impact on Aman may be attributed to excess monsoon rainfall

leading to waterlogging or flooding, which adversely affects rainfed rice yields a pattern also noted by Sarker et al. (2017) and Chowdhury et al. (2015) (Iftekhar Uddin and Mohammad Abul 2015; Sarker, Alam, and Gow 2019). Humidity negatively influenced Aus efficiency ( $\beta = -0.0995$ ,  $p < 0.01$ ), likely due to increased vulnerability to pest and fungal attacks in high-humidity conditions (Rushsa et al. 2025). In contrast, humidity positively affected Boro ( $\beta = 0.0224$ ,  $p < 0.05$ ), possibly due to improved microclimatic moisture during the dry season. The effect on Aman was not statistically significant.

**Table 6:** Impact of environmental factors on efficiency in VRS using Tobit regression

	AUS		AMAN		BORO	
	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error
Average						
Temperature	0.1949*	0.0832	0.1301***	0.0383	0.08129*	0.0368
Rainfall	0.0013.	0.0007	-0.0027*	0.0011	-0.00003	0.0011
Humidity	-0.0995**	0.0357	0.0151	0.0103	0.0224*	0.0101
Sunshine	0.1254	0.1338	-0.1953***	0.0368	-0.0142***	0.0857
Wind speed	0.3719*	0.1654	-0.1362	0.1032	-0.0349	0.1013

Sunshine had a significantly negative impact on Aman ( $\beta = -0.1953$ ,  $p < 0.001$ ), while having no significant effect on Aus. Although generally beneficial for crop development, excessive solar exposure especially during sensitive stages like flowering may lead to photoinhibition or thermal stress (Xu, Chu, and Yao 2021). For Boro, the effect of sunshine was negative but statistically insignificant. Wind speed had a positive and significant effect on Aus ( $\beta = 0.3719$ ,  $p < 0.05$ ), which is an unexpected finding. It may indicate a beneficial role in reducing excess humidity or aiding pollination in certain upland areas. However, wind speed had no significant influence on Aman or Boro efficiency. While prior studies (Lapworth and McGregor 2008; Shah, Hellegers, and Siderius 2021) typically report negative effects of high wind due to physical crop damage, localized or seasonal variation may explain this exception.

#### 4. Conclusion

This study evaluates the production efficiency of Aus, Aman, and Boro rice in Bangladesh using Data Envelopment Analysis under constant and variable returns to scale, incorporating environmental factors. The findings reveal that accounting for environmental conditions improves the measured efficiency of all rice types, with Boro consistently demonstrating the highest efficiency likely due to controlled irrigation and more favorable climatic conditions. While temperature positively and significantly enhances the efficiency of all rice types, the effects of rainfall, humidity, sunshine, and wind vary by crop and season. Notably, Aus and Aman show greater sensitivity to environmental fluctuations, indicating the need for targeted interventions. To enhance national rice productivity, policymakers should prioritize strategies that improve the efficiency of Aus and Aman production by mitigating environmental constraints and promoting adaptive farming practices.

#### Abbreviations list

CNN: Convolutional Neural Network, ROC: Receiver Operating Characteristic, AUC: Area Under the Curve, Xception: Extreme Inception, VGG16: Visual Geometry Group 16-layer network,

ResNet152V2: Residual Network 152-layer Version 2, InceptionResNetV2: Inception-ResNet Version 2, DenseNet201: Densely Connected Convolutional Network with 201 layers, MobileNetV2: Mobile Network Version 2.

### **Authors contribution**

Rasna Begum was responsible for data collection and preprocessing. Nayanaviram Nayan and Yasir Arafat conducted the model implementation and analysis. Md. Saifur Rahman performed the statistical evaluation and interpretation of results. Md. Kaderi Kibria conceived and designed the study, supervised the research process, and prepared the manuscript. All authors reviewed and approved the final manuscript.

### **Acknowledgement**

We would like to acknowledge the Department of Statistics, Hajee Mohammad Danesh Science and Technology University, Dinajpur, for their unconditional support. The authors appreciate the reviewer's careful reading and thoughtful remarks that helped refine this work.

### **Data Availability Statement**

The data used in this study are available on reasonable interest to corresponding author.

### **Conflict of Interest**

The authors declare no conflict of interest related to this study.

### **Funding**

This study did not receive any specific funding.

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