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Present Scenario and Future Outlook of Precipitation in the Boro Season of Bangladesh

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ABSTRACT

Bangladesh's economy still relies heavily on agriculture, which is intrinsically tied to climate. Climate change threatens the country's food security. Accurately forecasting future climatic conditions is essential for strategic agricultural planning and adaptation. The Boro season (January through April) constitutes one of Bangladesh's primary cropping periods, and many crops, especially rice, depend on rainfall. The objective of this study is to generate precipitation maps for Bangladesh over three periods: 1970–2000 (past), 2000–2018 (present), and 2040–2060 (future, around 2050), focusing on January through April. We used projected outputs from CMIP5 and CMIP6 global climate models and applied GIS techniques—raster statistics, raster extraction, and zonal statistics—to compile, analyze, and visualize the data. The results indicate that by 2050, rainfall is expected to increase by approximately 5–10 mm during January to March, while April precipitation will decline by about 3–6 mm compared to the 2010–2018 baseline. Such an increase is relatively small and generally within crop tolerance, meaning it is unlikely to negatively affect yield under normal drainage conditions. However, the projected increases in precipitation are relatively modest, they may pose localized challenges in poorly drained areas or during critical crop growth stages. Consistent with historical patterns, eastern Bangladesh is projected to receive the highest precipitation by 2050, while the northwestern region remains comparatively drier. These spatially explicit findings provide a scientific basis for region-specific.

1. Introduction

Bangladesh's economy relies heavily on agriculture (BER, 2020; Rahman et al., 2020). At present, the agricultural sector contributes 13.02 percent to the country's GDP. The performance of agriculture in any country is shaped by its meteorological conditions (Aziz et al., 2021). Weather and climate consistently pose risks to economic stability (Parker et al., 2019; Rahman et al., 2015; Farhan et al., 2022). One of the most critical factors shaping the future of global food security is the effect of climate change on agriculture (Yu et al., 2010). Rice is particularly important in this regard, as it is Bangladesh's staple food and covers more than 90 percent of the total net cropped area (Islam et al., 2019). While breeding advanced rice

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germplasm build crop resilience (Hasan et al., 2025) tracking climate ships remain essential to ensure these new varieties actually thrive under future conditions (Hussain et al., 2015). Key climate variables that affect rice production include temperature, rainfall, atmospheric CO2 concentration, and solar radiation (Amin et al., 2015; Ali et al., 2017). Any shift in rainfall patterns increases the chances of short-term crop failure as well as long-term yield loss (IFPRI, 2010).

Since the pre-industrial era, global greenhouse gas emissions have risen dramatically. The increasing volume of these gases has been the main driver of global warming over the last century (Yang et al., 2012). Rising global temperatures directly affect rainfall and temperature patterns, resulting in higher evaporation rates and greater surface drying, which intensify the severity and duration of droughts (Trenberth, 2011). Like many other countries, Bangladesh is experiencing the destructive effects of climate change (Das et al., 2024). Current greenhouse gas emissions are more than 27 and 50 percent higher from agriculture and waste management sector respectively than they were in 1990 (Chowdhury et al., 2020). Greenhouse gas emissions affect rainfall by intensifying the hydrological cycle, altering atmospheric moisture transport and circulation, which in turn changes precipitation intensity, seasonality, and spatial distribution. The climate system is now undergoing long-term shifts due to global warming, and these could have irreversible consequences if left unaddressed. Using machine learning and deep learning algorithms to predict temperature fluctuations bridges the gap between climate datasets and accurate projections of global climate shift. (Rahman et al., 2025; Rahman et al., 2026)

To respond to this challenge, the United Nations introduced the Sustainable Development Goals, with Goal 13 specifically focused on climate action (Rahman, 2021). Achieving this requires aligning climate strategies with disaster risk reduction, sustainable management of natural resources, and social protection within national development policies. It is still possible to limit the global average temperature rise to two degrees Celsius above pre-industrial levels, and ideally to 1.5°C, but this depends on strong political commitment, larger investments, and the use of available technologies (Hoegh-Guldberg et al., 2019). Such outcomes, however, demand urgent and ambitious collective measures. Addressing these concerns also connects directly with the climate-related challenges of the Fourth Industrial Revolution (Cole, 2021).

Bangladesh's food security is, above all, dependent on rice security (Rahman et al., 2021; Shozib et al., 2020; Kulsum et al., 2015). A large amount of water is required for proper growth of rice, making rainfall a vital factor in providing irrigation for rice production and reducing pressure on groundwater. The cropping pattern of Bangladesh is divided into three distinct seasons: Boro rice season (December to May), Aus rice season (March to August) and Aman rice season (June to November) (Sarker et al., 2012; Islam et al., 2022). Among these, the Boro season is the most diversified, and crops grown during this period are commonly referred to as winter crops in Bangladesh. The sowing of Boro crops such as Boro rice, wheat, cauliflower, cabbage, potato, carrot, radish, broccoli, and tomato usually begins in November–December and transplanted during December–January, although timing differs depending on the region. In the northern areas, winter arrives earlier, so crop sowing starts sooner compared to other regions. Winter crops generally perform well under low to moderate precipitation, particularly during establishment. In Bangladesh, the winter season is characterized by minimal rainfall, which supports controlled water management and favorable growing conditions for winter crop cultivation.

However, climate change has made noticeable shifts in spatio-temporal climatic variables. January is the coldest month in Bangladesh, and severe cold during January and February is a major reason for spikelet sterility in rice and wheat as well as reduced yields of winter vegetables (Prodhan et al., 2018; Rashid and Yasmeen, 2018; Sharmin et al., 2018).

In addition, cold weather increases the risk of seedling blight in rice and negatively impacts seed germination (Ansari & Ahmed, 2017). From March to May, the months just before the monsoon season, excessively high temperatures and delayed rainfall often dry out pollen and stigma, leading to empty spikelets in rice and wheat and reducing fruit set in crops like tomato and brinjal (Firon et al., 2006; Rahman et al., 2017; Tomás et al., 2020).

To address these challenges, policymakers require updated knowledge of future climate impacts to harmonize human society with natural systems (Miao et al., 2014). Climate models play a crucial role in understanding how the climate responds to different influences, producing seasonal to decadal predictions, and generating long-term projections for the coming centuries (Flato et al., 2014). The Coupled Model Intercomparison Project (CMIP) is a global collaboration in climatology aimed at enhancing understanding of climate change. Its fifth phase (CMIP5) has produced an advanced multi-model dataset to improve knowledge of climate variability and change. More than 20 modeling teams have contributed over 50 models to CMIP5 simulations (Taylor et al., 2012).

Climate model–based precipitation projections indicate that climate change is likely to modify rainfall intensity, seasonality, and spatial distribution across South Asia, including Bangladesh. CMIP-based studies consistently suggest an intensification of the hydrological cycle, with increases in monsoon rainfall variability and a higher likelihood of extreme precipitation events, alongside changes in dry-season rainfall (Odunmorayo et al., 2025). However, large uncertainties remain in simulating precipitation due to complex interactions among atmospheric circulation, land–surface processes, and regional topography, particularly in deltaic and monsoon-dominated regions. As a result, downscaled and region-specific precipitation assessments are essential for translating global climate projections into actionable information for national and sub-national planning.

Only a limited number of studies have projected precipitation scenarios for Bangladesh. Rahman et al. (2019) developed a climate simulation model for Bangladesh covering 1979–2006. Dastagir, M. R. (2015) created a climate change model with fine spatial resolution of 20 km to 50 km but faced issues of low confidence. Bosu (2020) produced a projected precipitation map for 2050–74, and Mondal, M. S. (2020) created an average annual rainfall map for 2041–60, although both focused only on annual totals and did not provide monthly precipitation forecasts.

Given ongoing climate change, forecasting future conditions is essential for coping with its impacts and ensuring food security in Bangladesh. Both the Government of Bangladesh and the United Nations' Sustainable Development Goals (SDGs) emphasize the need to build climate-resilient agricultural systems to safeguard food security (Rahman et al., 2021). Because Bangladesh's agriculture is highly rainfall-dependent, uncertainties in future precipitation pose a major challenge for crop planning, irrigation management, and risk reduction. In particular, the Boro season (January–April) is critically sensitive to rainfall variability, as insufficient or poorly timed precipitation can increase irrigation demand, production costs, and vulnerability to drought or water stress.

Despite this importance, existing climate studies in Bangladesh have largely focused on annual or monsoon-season rainfall, providing limited guidance for dry-season, crop-specific decision-making. The lack of reliable, region-specific monthly precipitation projections for the Boro season restricts the ability of policymakers and farmers to anticipate future water availability and design effective adaptation strategies. This gap is especially problematic given the spatial heterogeneity of rainfall across Bangladesh, where regional differences strongly influence agricultural outcomes.

Therefore, this research aims to project future rainfall scenarios for the year 2050 during the Boro season (January–April), both at the national and divisional levels, using CMIP5 climate model outputs integrated with GIS techniques. By comparing projected precipitation with observed rainfall patterns, this study provides a robust assessment of potential future changes. The findings offer region-specific insights that can support climate-resilient crop planning, irrigation scheduling, and policy formulation. Moreover, the GIS-based precipitation maps developed in this study can assist policymakers and researchers in optimizing resource allocation, strengthening early warning systems, and enhancing long-term food security planning under changing climatic conditions in Bangladesh.

2. Materials and methods

2.1. Study Area

Bangladesh is located in South-East Asia, extending from 20˚34'N to 26˚38'N latitude and 88˚01'E to 92˚41'E longitude. The country consists mainly of low-lying plains covering 147,570 square kilometers, bordered by the Meghalaya Plateau and West Bengal to the north, the Bay of Bengal to the south, the Assam hills to the east, and the West Bengal and Gangetic Plains to the west (Chowdhury et al., 2021). Climatic parameters in Bangladesh are strongly influenced by the Himalayan Mountains in the north and the Bay of Bengal in the south. Rainfall patterns in Bangladesh are more distinct and cyclical compared to temperature. Spatial and temporal variations in rainfall are significant, with maximum rainfall (about 400 cm) occurring in the northeast and minimum rainfall (about 150 cm) in the west-central region. The southeastern districts of Cox's Bazar and Bandarban, along with the northern part of Sylhet, receive the highest annual rainfall in the country (Wheeler, 1999).

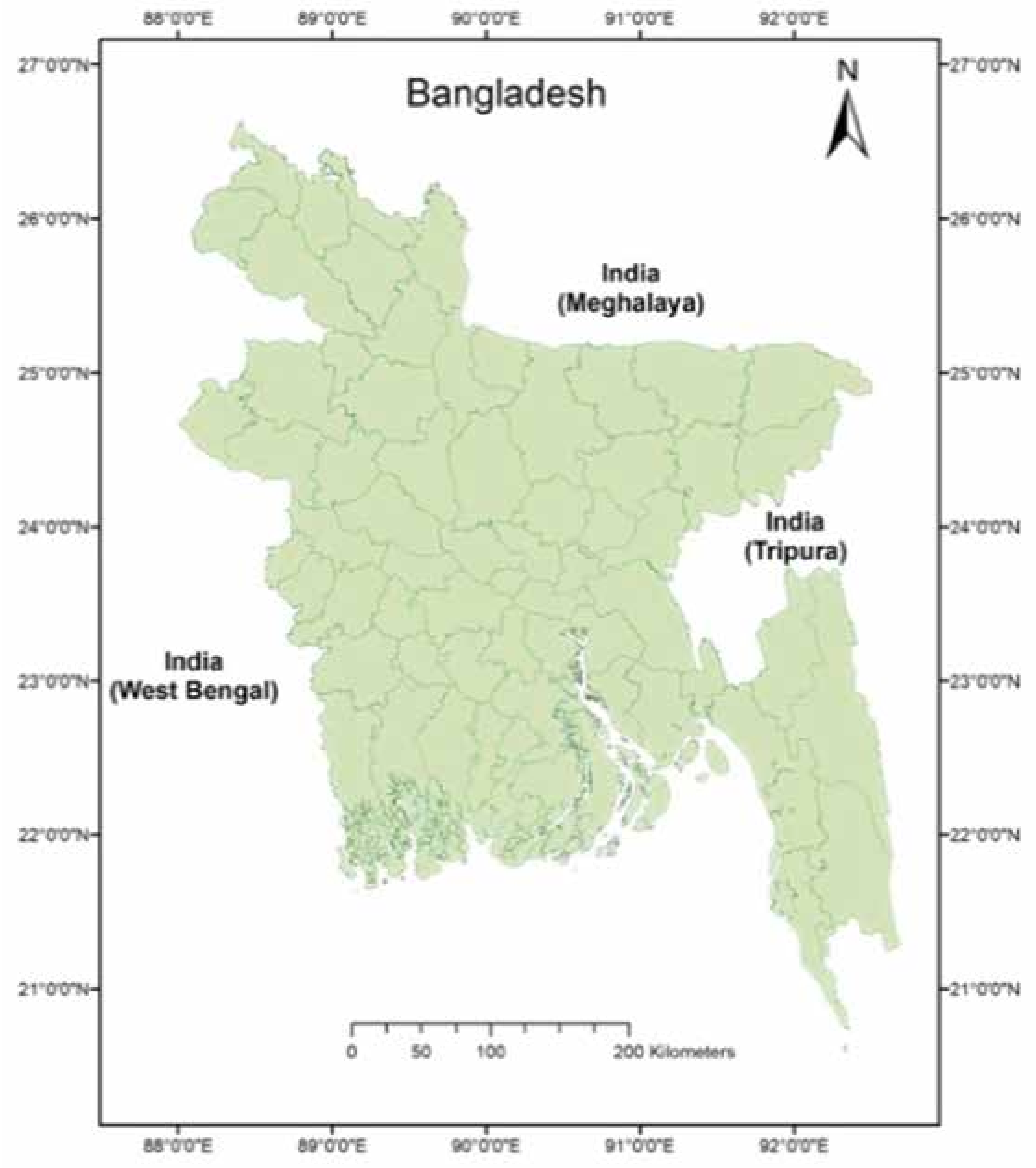

Fig. 1. Study Area Map.

2.2. Data source

In this study, the most widely used and freely accessible climate raster datasets of precipitation, WORLDCLIM 1.4 and its updated version WORLDCLIM 2.1 (Fick and Hijmans, 2017), were utilized. To analyze long-term precipitation patterns, the timeline was separated into three categories: past (1970 to 2000), present (2010 to 2018), and future (2040 to 2060). A summary of the dataset is presented in Table 1.

Table 1
List of datasets used in this study.

Climate Period	Climate Dataset	CMIP Phase	Author	Data Format	Obtained Spatial Resolution	Obtained Source
Past (1970-2000)	WORLDCLIM1.4	CMIP6	Hijmans et al., 2005	Raster	2.5 arc minutes resolution	https://www.worldclim.org/data/monthlywth.html
Present (2010-2018)	WORLDCLIM2.1	CMIP6	Fick and Hijmans 2017	Raster	2.5 arc minutes resolution	https://www.worldclim.org/data/worldclim21.html
Future (2040-2060)	WORLDCLIM1.4	CMIP5	Hijmans et al., 2005	Raster	2.5 arc minutes resolution	https://www.worldclim.org/data/monthlywth.html

Raster data consist of pixels, also referred to as grid cells. These cells are generally square and evenly spaced, although this is not mandatory. Since each pixel holds its own data value or class, raster datasets usually appear pixelated (GISGeography, 2021).

Global Climate Models (GCMs)

A total of 19 CMIP5 Global Climate Models (GCMs) were accessed from WORLDCLIM 1.4 (Fick and Hijmans, 2017) to project future precipitation (Table 2).

Table 2
List of CMIP5 global climate models used for forecasting projected precipitation in this study.

Model	Resolution	Modeling group	Obtained Source	Obtained Resolution
ACCESS1-0 (#)	1.9° × 1.3°	CSIRO-BOM, Australia	WORLDCLIM 1.4 (https://www.worldclim.org/data/monthlywth.html)	2.5 arc minutes resolution
BCC-CSM1-1	2.8° × 2.8°	Beijing Climate Center, China Meteorological Administration, China		
CCSM4	1.3° × 0.9°	National Center for Atmospheric Research (NCAR), USA		
CESM1-CAM5-1-FV2	1.3° × 0.9°	National Science Foundation, Department of Energy, NCAR, USA		
CNRM-CM5 (#)	1.4° × 1.4°	Centre National de Recherches Meteorologiques, France		
GFDL-CM3	2° × 2°	NOAA/Geophysical Fluid Dynamic Laboratory, United States		
GFDL-ESM2G	2° × 2°	NOAA/Geophysical Fluid Dynamic Laboratory, United States		
GISS-E2-R	2° × 2°	NASA Goddard Institute of Space Studies, United States		
HadGEM2-AO	1.9° ×.3°	National Institute of Meteorological Research/Korea Meteorological Administration, Korea		
HadGEM2-CC	1.9° × 1.3°	Met Office Hadley Centre (additional HadGEM2-ES realisations contributed by Instituto Nacional de Pesquisas Espaciais), UK		
HadGEM2-ES	1.9° × 1.3°	Met Office Hadley Centre (additional HadGEM2-ES realisations contributed by Instituto Nacional de Pesquisas Espaciais), UK		
INMCM4	2° × 1.5°	Institute for Numerical Mathematics, Russia		
IPSL-CM5A-LR	3.8° × 1.9°	Institut Pierre-Simon Laplace, France		
MIROC-ESM-CHEM (#)	2.8° × 2.8°	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan		
MIROC-ESM (#)	2.8° × 2.8°	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan		
MIROC5 (#)	1.4° × 1.4°	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan		
MPI-ESM-LR	1.8° × 1.8°	Max Planck Institute for Meteorology (MPI-M), Germany		
MRI-CGCM3	1° × 1°	Meteorological Research Institute, Japan		
NorESM1-M	2° × 2°	Norwegian Climate Centre, Norway		

The main focus of this research was projecting future precipitation under four Representative Concentration Pathways (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5). These RCPs represent low (2.6), medium (4.5), high (6.0), and very high (8.5) scenarios, with radiative forcing values of 2.6, 4.5, 6.0, and 8.5 W/m^2, respectively, by the year 2100 (Miao et al., 2014).

An RCP is defined by the Intergovernmental Panel on Climate Change (IPCC) as a greenhouse gas concentration pathway rather than an emissions trajectory. The IPCC Fifth Assessment Report (AR5, 2014) highlights four pathways that can be applied for climate research and modeling. These represent different but plausible climatic futures, depending on the amount of greenhouse gases (GHG) released in the future (Moss et al., 2008).

RCP 2.6

RCP 2.6 is the lowest-emission scenario among the four Representative Concentration Pathways (RCPs) defined by the IPCC for climate modeling. The Pathway explains that carbon dioxide (CO2) emissions must peak around 2020 and reach net zero by 2100. It also aims to cut methane (CH4) emissions by half and sulfur dioxide (SO2) emissions by about 10 percent compared to their 2020 and 1980–1990 levels, respectively. By 2100, RCP 2.6 seeks to limit global temperature rise to below 2˚C (IPCC, 2014: Climate Change 2014: Synthesis Report).

RCP 4.5

RCP 4.5 is regarded as a mid-level scenario by the IPCC. In this pathway, emissions peak around 2040 and then begin to decline. Its objective is to keep the global temperature rise within 2–3˚C by 2100, with sea level rise limited to less than 35 percent higher than that of RCP 2.6 (Team et al., 2015).

RCP 6.0

This scenario assumes a stabilized condition, where radiative forcing levels off after 2100. It involves the use of different technologies and strategies to mitigate greenhouse gas emissions (Fujino et al., 2006).

RCP 8.5

RCP 8.5 represents a pathway where greenhouse gas emissions continue to rise throughout the 21st century. It was originally based on an overestimation of coal use and is often treated as the worst-case climate change projection. However, researchers argue that the RCP 8.5 pathway is becoming increasingly realistic with time (Hausfather & Peters, 2020).

2.3. Analytycal methods

The methodology of this research is organized into two main steps, employing GIS techniques such as raster statistics, raster extraction, and zonal statistics.

Step-1: Compilation and Processing of Climate Data

GCM data were collected from open-access sources, and raster statistics processing was carried out using ArcGIS 10.8. The cell statistics tool was applied to compute the mean of multiple monthly raster files from different years, producing one raster file per month. This tool works by analyzing cell values across several rasters pixel by pixel and assigning a calculated value for each location on the output raster. The mean function was selected to derive the average precipitation values.

Step-2: Preparation of Precipitation Projection Map

To extract location-specific information, the raster extraction technique was used. The extract by mask process was applied, which isolates raster cells corresponding to the designated study area from the averaged raster data. Afterward, the zonal statistics tool was employed to generate division-wise precipitation estimates based on administrative boundaries. The mean statistics function was chosen to calculate division-level precipitation values. Using ArcGIS 10.8, division-wise maps as well as country-level precipitation maps were prepared for the past (1970 to 2000) and the future (2040 to 2060, or 2050).

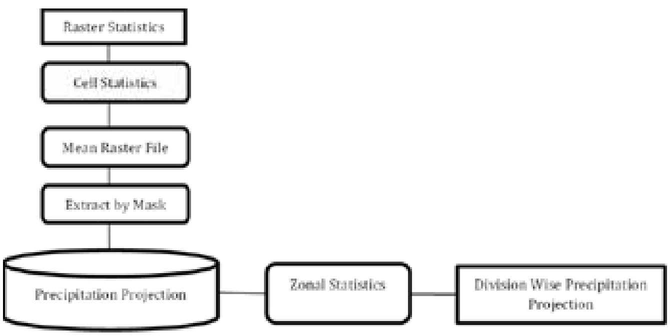

Fig. 2. Methodological Framework.

3. Results

3.1. Precipitation of January

Table 3 indicates the average precipitation in January between 1970 and 2000 in Bangladesh. The results indicate higher precipitation in the northeast and lower northwest regions, moderate precipitation in the central part, and the lowest levels in the southeast. Division-wise analysis reveals that Rajshahi recorded the highest average precipitation (12.29 mm), followed by Sylhet (11.78 mm), while Chattogram had the lowest (7.23 mm). It also shows the average January precipitation during 2010–2018, when the highest rainfall was again in the northeast, followed by the lower northwest, with moderate levels in central Bangladesh and the lowest in the southeast. Division-wise analysis for 2010–2018 shows that Sylhet had the highest average precipitation (8.76 mm), followed by Rajshahi (8.01 mm). Notably, during the earlier period (1970 to 2000), Rajshahi was the highest, and the lowest shifted from Chattogram to Dhaka division (5.18 mm).

The projected average precipitation for January 2050 under the RCP 2.6 scenario. The pattern is similar to earlier observations: the northeast and lower northwest will experience the highest rainfall, the central part moderate rainfall, and the southeast the lowest. Division-level analysis suggests that Sylhet and Rajshahi will both reach the highest average precipitation (12.27 mm), while Chattogram will have the lowest (6.82 mm).

The projected January precipitation for 2050 using the RCP 4.5 scenario. The results are broadly consistent with RCP 2.6, with Sylhet (11.56 mm) and Rajshahi (11.08 mm) recording the highest rainfall and Chattogram the lowest (6.23 mm).

It also illustrates the projected January average precipitation in Bangladesh under the RCP 6.0 model. The rainfall distribution pattern is nearly identical to what was found in the RCP 2.6 and RCP 4.5 models. The results show that in 2050, Sylhet will receive the highest precipitation (14.03 mm), followed by Rajshahi (13.79 mm), while Chattogram will experience the lowest (7.98 mm).

The table also contain the projected January average precipitation for 2050 under the RCP 8.5 model. The overall precipitation distribution is very similar to that of the RCP 2.6, 4.5, and 6.0 models, with the only difference being a decline in rainfall in the central southern part of the country. Under this scenario, Sylhet is expected to have the highest precipitation (13.53 mm), followed by Rajshahi (12.67 mm), while Chattogram will again record the lowest (7.38 mm) in 2050.

Table 3
Comparison of average total precipitation in January across 1970–2000, 2010–2018, and the 2050 forecast (Based on RCP models 2.6, 4.5, 6.0, and 8.5).

Division	Average Precipitation (mm) 1970 to 2000	Average Precipitation (mm) 2010 to 2018	Precipitation (mm) 2050 (RCP 2.6)	Precipitation (mm) 2050 (RCP 4.5)	Precipitation (mm) 2050(RCP 6.0)	Precipitation (mm) 2050 (RCP 8.5)	Average of Precipitation (mm) 2050 (RCP 2.6, 4.5, 6.0 and 8.5)	Average of Precipitation (mm) 2050 to 2010-2018
Rangpur	9.8	6.8	9.6	8.13	10.26	9.5	9.3725	2.5725
Rajshahi	12.29	8.01	12.27	11.08	13.79	12.67	12.4525	4.4425
Khulna	11.65	6.43	10.71	10.33	12.96	11.49	11.3725	4.9425
Mymensingh	9.15	6.83	10.81	9.89	12.26	11.28	11.06	4.23
Sylhet	11.78	8.76	12.27	11.56	14.3	13.53	12.915	4.155
Dhaka	7.54	5.18	8.71	8.34	10.26	9.25	9.14	3.96
Barishal	8.55	5.19	8.47	8.01	10.29	9.18	8.9875	3.7975
Chattogram	7.23	5.42	6.82	6.23	7.98	7.38	7.1025	1.6825

3.2. Precipitation of February

Table 4 presents the average precipitation scenario for February between 1970 and 2000 in Bangladesh. The northeastern region received the highest rainfall, followed by the southwestern part. Both the northern and southern central regions experienced moderate rainfall, while the southeastern region had the lowest precipitation. Division-wise analysis indicates that in February between 1970 and 2000, Barishal received the highest precipitation (28.07 mm), followed by Sylhet (27.44 mm). Rangpur had the lowest with an average of 11.85 mm.

It also shows the February precipitation scenario for 2010–2018. During this period, the highest rainfall was observed in the northeastern part, followed by the southwestern side, with central Bangladesh experiencing moderate rainfall and the southeastern side having the lowest. Division-wise data reveal that Sylhet recorded the highest precipitation (18.01 mm), followed by Khulna (15.74 mm), while the lowest shifted from Rangpur (in 1970–2000) to Chattogram

(10.02 mm).

The projected average precipitation for February in 2050 under the RCP 2.6 scenario. The northeastern region is expected to receive the highest rainfall, while central areas will see moderate amounts. The lowest precipitation is forecasted for the northwestern and parts of the southeastern regions. At the division level, Sylhet is projected to receive the highest rainfall (22.35 mm), while Rangpur will experience the lowest (9.51 mm).

It also noticeable from the table that the rainfall pattern is almost identical to that of RCP 2.6. Here, Sylhet is expected to record the highest precipitation (29.22 mm), followed by Barishal (25.86 mm), while Chattogram will receive the lowest (11.07 mm) in 2050. Precipitation projection for February under the RCP 6.0 scenario. The overall rainfall pattern is again similar to the RCP 2.6 and 4.5 models. Under this scenario, Sylhet is forecasted to receive the highest rainfall (26.92 mm), followed by Barishal (23.8 mm), while Rangpur will have the lowest (10.33 mm) in 2050, and the February precipitation forecast for 2050 under the RCP 8.5 scenario shows that the distribution is nearly the same as under the RCP 2.6, 4.5, and 6.0 models. According to this projection, Sylhet will again have the highest rainfall (27.78 mm), followed by Barishal (23.34 mm), while Rangpur will record the lowest (10.42 mm).

Table 4
Summary of February month average total precipitation of 1970 to 2000, 2010 to 2018 and forecasted 2050 (By RCP model 2.6, 4.5, 6.0 and 8.5)

Division	Average Precipitation (mm) 1970 to 2000	Average Precipitation (mm) 2010 to 2018	Precipitation (mm) 2050 (RCP 2.6)	Precipitation (mm) 2050 (RCP 4.5)	Precipitation (mm) 2050 (RCP 6.0)	Precipitation (mm) 2050 (RCP 8.5)	Average of Precipitation (mm) 2050 (RCP 2.6, 4.5, 6.0 and 8.5)	Average of Precipitation (mm) 2050 to 2010-2018
Barishal	28.07	15.36	19.62	25.86	23.8	23.34	23.15	7.79
Chattogram	18.27	10.02	14.85	19.75	17.62	18.19	17.60	7.58
Dhaka	22.07	14.14	17.88	21.75	19.76	20.5	19.97	5.83
Khulna	26.58	15.74	16.13	19.82	18.33	18.25	18.13	2.39
Mymensingh	15.07	10.97	14.47	17.89	16.47	16.84	16.42	5.45
Rajshahi	16.13	12.25	14.40	16.75	15.39	15.84	15.59	3.34
Rangpur	11.85	11.94	9.51	11.07	10.33	10.42	10.33	-1.61
Sylhet	27.44	18.01	22.35	29.22	26.92	27.78	26.57	8.56

3.3. Precipitation of March

Table 5 shows the average precipitation for March between 1970 and 2000 in Bangladesh. The northeastern region experienced the highest rainfall. Central Bangladesh (north and south) received less rainfall, while the lowest was recorded in the northwest, followed by the southeast. Division-wise analysis indicates that Sylhet had the highest rainfall (106.28 mm), followed by Dhaka (49.99 mm), while Rajshahi had the lowest (24.16 mm) and the highest rainfall from 2010-2018 was in the northeastern region, while central Bangladesh had low rainfall. The lowest values were recorded in the northwest, followed by the southeast. Division-wise analysis for this period shows that Sylhet had the highest precipitation (84.58 mm), while Rajshahi had the lowest (20.77 mm).

The March precipitation forecast for 2050 under the RCP 2.6 scenario shows that the northeastern region is projected to have the highest rainfall, while central areas will experience moderate precipitation. The lowest levels will occur in the northwest, followed by the southeast. Division-wise analysis indicates Sylhet will receive the highest rainfall (101.82 mm), while Rajshahi will have the lowest (25.67 mm).

It also describes the March precipitation projection under the RCP 4.5 scenario. The overall distribution is very similar to the RCP 2.6 projection. The results indicate Sylhet will again be the wettest division (97.88 mm), and Rajshahi the driest (25.29 mm) by 2050.

Table 5 also shows the March precipitation forecast under the RCP 6.0 scenario. The rainfall pattern is again comparable to the RCP 2.6 and RCP 4.5 models. According to this projection, Sylhet will record the highest rainfall (116.66 mm), while Rangpur (27.27 mm) and Rajshahi (27.73 mm) will have the lowest.

Under the RCP 8.5 scenario, the pattern is nearly the same as those of RCP 2.6, 4.5, and 6.0. By 2050, Sylhet will again have the highest rainfall (103.43 mm), while Rangpur will remain the driest division (24.39 mm).

Table 5
Summary of the March month average total precipitation of 1970 to 2000, 2010 to 2018 and forecasted 2050 (By RCP model 2.6, 4.5, 6.0 and 8.5)

Division	Average Precipitation (mm) 1970 to 2000	Average Precipitation (mm) 2010 to 2018	Precipitation (mm) 2050 (RCP 2.6)	Precipitation (mm) 2050 (RCP 4.5)	Precipitation (mm) 2050 (RCP 6.0)	Precipitation (mm) 2050 (RCP 8.5)	Average of Precipitation (mm) 2050 (RCP 2.6, 4.5, 6.0 and 8.5)	Average of Precipitation (mm) 2050 to 2010-2018
Barishal	48.21	34.91	40.68	43.96	46.95	41.45	43.26	8.35
Chattogram	48.57	37.8	44.79	48.18	51.13	45.47	47.39	9.59
Dhaka	49.99	36.79	48.84	48.50	55.84	50.75	50.98	14.19
Khulna	38.76	26.76	31.75	32.73	36.17	32.6	33.31	6.55
Mymensingh	45.12	37.68	51.33	49.48	57.07	51.12	52.25	14.57
Rajshahi	24.16	20.77	25.67	25.29	27.73	25.41	26.03	5.26
Rangpur	25.41	25.65	26.56	25.53	27.27	24.39	25.94	0.29
Sylhet	106.28	84.58	101.82	97.88	116.66	103.43	104.95	20.37

3.4. Precipitation of April

Table 6 presents the average precipitation for April in Bangladesh during the period 1970 to 2000. The northeastern part of the country recorded the highest rainfall, while central Bangladesh experienced moderate to low precipitation. The western part showed the lowest rainfall during this period. Division-level analysis for April between 1970 and 2000 indicates that Sylhet received the highest average precipitation (264.85 mm), whereas Rajshahi had the lowest (56.28 mm).

For April precipitation averages for 2010 to 2018 in Bangladesh, the northeastern part recorded the highest rainfall, while the central and southeastern areas had moderate to low precipitation, and the western side experienced the lowest. A division-wise breakdown shows that Sylhet had the highest precipitation (307.28 mm), while Rajshahi was the lowest with 62.6 mm on average. It is also noteworthy that Mymensingh experienced slightly more rainfall compared to earlier years, while Dhaka and Chattogram showed a slight decline.

Table 6 also indicates the projected average precipitation for April in Bangladesh under the RCP 2.6 scenario for 2050. The northeastern region is expected to receive the most rainfall, while central and southeastern parts will have lower to moderate levels. The northwestern and southwestern regions will experience the least precipitation. Division-wise forecasts under RCP 2.6 show Sylhet with the highest rainfall (287.95 mm) and Rajshahi with the lowest (65.41 mm).

For April precipitation projection under RCP 4.5 for 2050, the northeastern part will again have the highest rainfall, while the central and southeastern regions will receive relatively low amounts, and the northwestern and southwestern regions will remain the driest. According to this model, Sylhet is expected to have the highest rainfall (259.61 mm), and Rajshahi the lowest (51.3 mm).

The overall rainfall distribution under the RCP 6.0 scenario appears almost identical to that of the RCP 2.6 model. Division-level data reveal Sylhet as the highest with 264.2 mm, while Rajshahi remains the lowest with 54.55 mm in 2050. And under the RCP 8.5 scenario, the rainfall pattern is very similar to the RCP 4.5 model. Value from the table confirms that Sylhet will again receive the highest rainfall (276.59 mm), while Rajshahi will continue to record the lowest (51.81 mm), consistent with the other RCP scenarios.

Table 6
Summary of April month average total precipitation of 1970 to 2000, 2010 to 2018 and forecasted 2050 (By RCP model 2.6, 4.5, 6.0 and 8.5)

Division	Average Precipitation (mm) 1970-2000	Average Precipitation (mm) 2010-2018	Precipitation (mm) 2050 (RCP 2.6)	Precipitation (mm) 2050 (RCP 4.5)	Precipitation (mm) 2050 (RCP 6.0)	Precipitation (mm) 2050 (RCP 8.5)	Average of Precipitation (mm) 2050 (RCP 2.6, 4.5, 6.0 and 8.5)	Average of Precipitation (mm) 2050 to 2010-2018
Barishal	105.46	116.82	104.16	90.95	97.44	92.13	96.17	-20.65
Chattogram	128.83	143.08	131.12	112.53	115.7	119.87	119.80	-23.28
Dhaka	129.52	147.92	137.22	112.66	119.44	120.55	122.47	-25.45
Khulna	74.18	81.18	74.38	62.37	67.94	64.49	67.29	-13.89
Mymensingh	117.09	133.57	145.07	123.91	127.34	127.95	131.07	-2.50
Rajshahi	56.28	62.6	65.41	51.3	54.55	51.81	55.77	-6.83
Rangpur	77	82.27	88.23	73.97	76.59	71.52	77.58	-4.69
Sylhet	264.85	307.28	287.95	259.61	264.2	276.59	272.09	-35.19

3.5. Trend of average precipitation across divisions

The analysis of average precipitation trends across Bangladesh's divisions in figure 3 shows the seasonal and spatial variations from the past period (1970–2000) through the recent decade (2010–2018) and into the projected climate of 2050. During the month of January, it shows the stable dry-season conditions with minor differences between periods. Slight increases are observed in the 2050 projections, particularly in Sylhet, Khulna, and Mymensingh. In February, precipitation rises moderately, and future values remain higher than the recent decade but comparable to the historical baseline. Divisions such as Khulna, Sylhet, and Barishal exhibit the most noticeable increases, suggesting early pre-monsoon intensification. In March, rainfall increases significantly across the country, and Sylhet shows the peak for all periods, reflecting its strong convective activity during the pre-monsoon season. April records the highest rainfall among the four months, with a sharp peak in Sylhet in recent study period exceeding 300 mm historically. However, unlike the earlier months, most divisions show slight reductions in April rainfall in 2050 compared to 2010–2018, indicating a possible shift or delay in the peak pre-monsoon rainfall pattern.

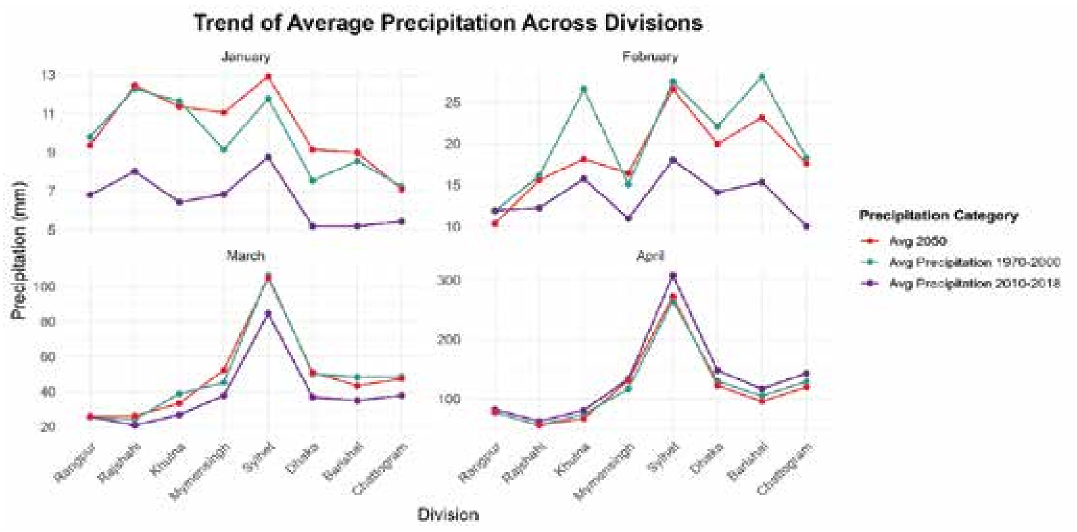

Fig. 3. Trend of average precipitation across divisions.

3.6. Precipitation trend for several RCP models projection

The projected precipitation patterns under all four RCP scenarios in figure 4 show a consistent trend across Bangladesh. April receives the highest rainfall in every scenario, with a sharp peak in Sylhet, followed by Mymensingh and Chattogram. In contrast, January, February, and March show relatively low rainfall across all divisions, with only moderate increases in February and March. The overall spatial pattern remains stable regardless of the emission scenario: Sylhet is consistently the wettest region, while Rajshahi and Rangpur remain the driest. Differences between RCP 2.6, 4.5, 6.0, and 8.5 are small for the early months but slightly more pronounced in April, where higher-emission scenarios show marginally higher rainfall. Overall, April rainfall is the most dominant and sensitive to climate change across all divisions.

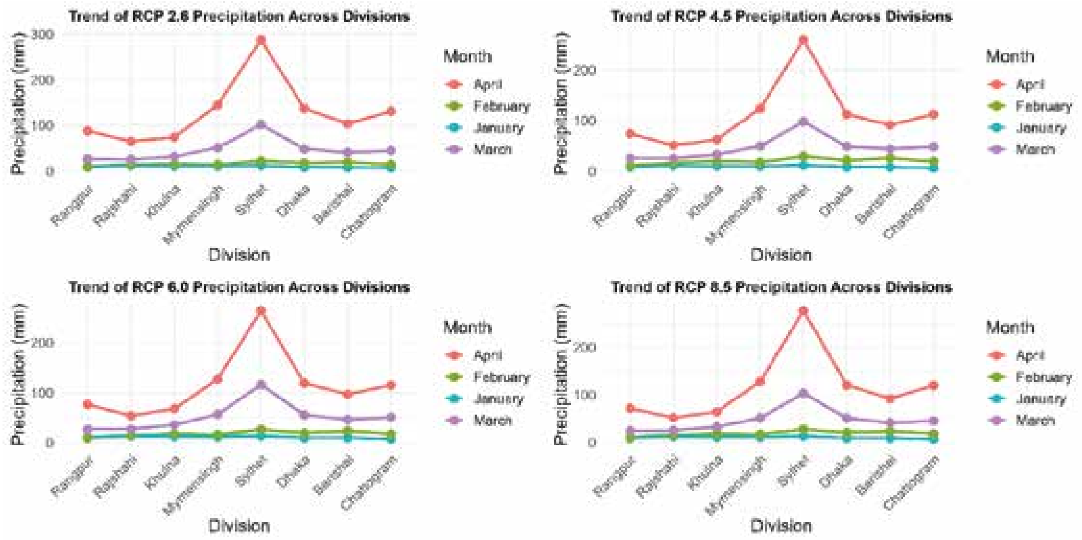

Fig. 4. Precipitation trend for several RCP models projection.

4. Discussion

As the climate continues to change, forecasting future climatic conditions becomes critical in mitigating its impacts and ensuring food security in Bangladesh. Projecting future precipitation patterns is essential for designing effective adaptation strategies, particularly in agriculture. This study aimed to forecast precipitation scenarios for the months of January to April in 2050, at divisional levels, to enhance the understanding of regional climatic variations. The precipitation projections derived from CMIP5 GCMs were compared with observed historical and current precipitation trends to assess potential future changes.

The findings of the study reveal significant regional and temporal variations in precipitation patterns across Bangladesh from January to April. In January, historical data from 1970 to 2000 and 2010 to 2018, along with projections for 2050, indicate that Sylhet historically received the highest precipitation, while Dhaka had the lowest. Bari et al. (2016) found that Sylhet station recorded maximum decrement in monsoon rainfall and minimum in Mymensingh. By 2050, all divisions are expected to see an increase in precipitation, with Sylhet and Rajshahi continuing to receive the most, while Chattogram remains the driest. In February, the highest precipitation during 1970-2000 was recorded in Barishal followed by Sylhet and Khulna, while Chattogram had the lowest. From 2010 to 2018, Sylhet maintained its position as the wettest division, and by 2050, precipitation is projected to increase across most divisions, with Sylhet receiving the highest, and Rangpur the lowest. In March, Sylhet continued to experience the highest rainfall across all periods, with projections for 2050 showing increased precipitation, particularly in Sylhet, Dhaka, and Mymensingh. The April data revealed that Sylhet had the highest precipitation from 1970 to 2000 and 2010 to 2018, with Rajshahi recording the lowest. By 2050, however, a decrease in precipitation is forecasted for most divisions, including a reduction in Sylhet's precipitation, though it will still remain the wettest region. These trends highlight distinct regional shifts and increasing variability in precipitation patterns across the months. In a study conducted by Aziz et al. (2023) reveals that the Mymensingh division will experience a dramatic increase in precipitation along with Sylhet, and Rajshahi will also see some rise in precipitation in mid-century (2040–2060).

A comparative assessment across the RCP scenarios (2.6, 4.5, 6.0, and 8.5) reveals that while the overall spatial pattern of precipitation remains similar, the magnitude of change varies slightly. Under RCP 8.5, precipitation tends to increase marginally more in January–March and shows a sharper decline in April compared to RCP 4.5. These findings suggest that while the direction of change is consistent across emission pathways, the intensity of projected precipitation shifts is influenced by the severity of greenhouse gas concentration scenarios. Similar result is shown from the study of Rahman et al. (2019), Hossain et al. (2020) and Saim et al. (2021).

The Boro season in Bangladesh is traditionally characterized by relatively dry conditions, with precipitation playing a pivotal role in determining agricultural productivity. Recent observations have revealed notable spatial variations in rainfall, with the eastern regions receiving higher precipitation and the northwestern areas experiencing significantly lower rainfall during this period (Aziz et al., 2021). These regional disparities are primarily influenced by the country's topography and prevailing climate patterns. As such, the amount and distribution of precipitation during the Boro season are critical factors for agricultural planning and water resource management.

Looking ahead, future projections indicate an overall increase in precipitation during the Boro season, except for the month of April, which is expected to experience a decrease (Islam et al., 2022; Ta et al., 2022). This trend is supported by multiple climate models, including those from CMIP5 and CMIP6, which forecast higher precipitation levels in the coming decades. Despite the overall increase in precipitation, the spatial distribution of rainfall is expected to remain largely unchanged, with the eastern regions continuing to receive the highest levels of precipitation, while the northwestern region remains the driest (Kamruzzaman et al., 2019). This enduring spatial pattern is significant for agricultural and water management strategies, as it highlights the necessity for region-specific measures to address water availability and crop management challenges.

From a seasonal perspective, while the Boro season spans the dry winter months and the transitional period leading into the monsoon, projections suggest that the monsoon season will experience the most substantial increase in precipitation. The result is similar to the findings of Aadrita & Jahan (2021) and Fahad et al. (2018). This could lead to more frequent and intense rainfall events, raising concerns regarding the potential for flooding and waterlogging, particularly in the eastern and northeastern regions, which are already prone to heavy rainfall (Ahmed et al., 2017; Kamruzzaman et al., 2019). In contrast, the dry winter months are projected to experience reduced rainfall, which may exacerbate drought conditions in the northwestern regions, which are already susceptible to such extremes. In a study, Rajib et al. (2011) found that Percentage of precipitation increment is expected to be quite lower for dry and pre-monsoon months compared to the monsoon season. These projections underscore the importance of developing targeted water management strategies to mitigate the risks associated with both flooding and drought.

Additionally, rising temperatures, particularly in the northwest and south-central regions, are likely to further complicate agricultural practices by altering evapotranspiration rates and soil moisture conditions (Ahmed et al., 2017). Moreover, large-scale climate phenomena such as the Indian Ocean Dipole (IOD) and the El Niño-Southern Oscillation (ENSO) are recognized for their influence on Bangladesh's precipitation patterns. Research indicates that the IOD has a more substantial teleconnection with Bangladesh's monsoon precipitation compared to ENSO, suggesting that future shifts in IOD patterns could have significant implications for the Boro season (Ahmed et al., 2017).

Projected rainfall changes during the Boro season have clear management implications. Slight increases in January–March may reduce irrigation needs in wetter divisions like Sylhet, while drier regions such as Rajshahi and Rangpur will still require intensive irrigation. However, early-season rainfall could raise waterlogging risks in poorly drained fields, demanding better drainage and disease control. The expected April decline is critical for Boro rice flowering, making precise irrigation scheduling essential to prevent yield loss. These trends call for region-specific strategies, including efficient irrigation systems, rainwater harvesting, and climate-resilient crop varieties.

5. Conclusion

This research analyzed the historical and present precipitation conditions during the Boro season in Bangladesh and projected average rainfall for 2050 using multiple Global Climate Models (GCMs) and Representative Concentration Pathways (RCPs).

January shows low rainfall across all divisions with only small changes over time, and Sylhet records the highest values. In February, rainfall increases slightly, with Sylhet consistently highest and Rangpur lowest. March shows a significant rise in precipitation, especially in Sylhet. April has the highest rainfall overall, dominated by a peak in Sylhet, though most divisions show a slight projected decline compared to recent years. Overall, Sylhet remains the wettest division across all months, largely due to its proximity to the Meghalaya Plateau and enhanced orographic rainfall from moist southwesterly monsoon flows, while Rajshahi and Rangpur remain the driest divisions because of their inland location, distance from major moisture sources, and comparatively weaker monsoon influence. Although the various RCP models produce slightly different trends, the differences are not significant enough to alter the overall conclusions. These results are important for developing agricultural strategies under climate change. The projections can support climate-smart farming practices, guide technological innovations, and help secure future food production. This study also emphasizes the importance of extending research to other climatic factors such as maximum and minimum temperatures, humidity, and sunshine hours, as further investigation is needed to predict future climatic conditions in Bangladesh.

Policy Recommendation

Based on the projected precipitation patterns during the Boro season (January–April) for 2050, several targeted policy interventions are recommended to enhance climate-resilient agricultural planning in Bangladesh

First, region-specific water management policies are essential. The persistent low rainfall projected for the northwestern divisions, particularly Rajshahi and Rangpur, indicates continued dependence on groundwater irrigation. Policymakers should prioritize investment in efficient irrigation technologies (such as drip and sprinkler systems), surface water storage, and rainwater harvesting to reduce groundwater depletion and drought vulnerability in these regions.

Second, in high-precipitation regions such as Sylhet, where rainfall remains consistently higher even during the Boro season, policies should focus on improving drainage infrastructure and field-level water management. Although increased rainfall may reduce irrigation demand, even modest increases during sensitive crop stages can raise the risk of waterlogging and disease. Strengthening canal maintenance, promoting raised-bed cultivation, and supporting drainage-sensitive crop varieties can mitigate these risks.

Third, the GIS-based precipitation maps developed in this study should be institutionalized within national planning frameworks. These spatial tools can support evidence-based crop zoning, optimize regional cropping calendars, and guide the allocation of water and agricultural inputs. Integrating these maps into existing platforms such as early warning systems and weather-based advisory services will improve preparedness for climate variability.

Finally, long-term agricultural policy should emphasize climate-resilient crop development and farmer capacity building. Investment in drought-tolerant and waterlogging-tolerant crop varieties, combined with farmer training on climate-smart practices, will strengthen adaptive capacity across diverse agro-climatic zones. Coordinated action among government agencies, research institutions, and local stakeholders is crucial to ensure sustainable food production under changing precipitation regimes.

Author's Contributions

N M F Rahman conceived and designed the study, developed the methodological framework, conducted the analysis, and prepared the initial draft of the manuscript. M A Aziz contributed to study design, performed statistical analyses, and assisted in interpreting the results. Rokib Ahmed contributed to data curation, literature review, and preparation of supporting materials. ABM Z Hossain, M A Siddique, M C Rahman, S A I Nihad, M A Qayum, M A A Mamun, and M I Hossain assisted in manuscript editing, visualization, and provided critical revisions. M R Islam provided senior guidance, critical feedback, overall supervision, and final approval of the manuscript.

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