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RESEARCH

Impacts of climate variability on rice yield and diseases in coastal Bangladesh

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Abstract
Climate change has added a new dimension to the unpredictability of rice yields. Climate variability and change directly impact rice yields through fluctuations in climatic variables. Changes in temperature, rainfall, and humidity may facilitate the spread of pests and diseases, further compromising yields. Despite various studies focusing on the impact of climate variability on rice yields and diseases, region-specific mixed-methods research is scarce in coastal Bangladesh. The current study fills this gap using a mixed-methods approach over the 38 years (1981–2018). Data obtained from systematic reviews were analyzed using thematic content analysis. To assess trends in climate variables, we employed Mann-Kendall tests, and a quadratic polynomial regression was used to evaluate the influence of climatic variables on rice yields. Logit models were used to determine which climate variables were most influential on disease occurrence in rice. In the analyzed literature, 61% of studies reported a negative effect of climate variability on rice yields, while 18% reported a positive effect. The historical climate data showed significant increases in temperature (0.04 °C per year) and humidity (0.14% per year). Despite a short-term positive effect of rising temperature and humidity on rice yields, the long-term cumulative effect over the 38 years was negative. Regarding rice diseases, sheath blight increased more rapidly than blast and bacterial blight due to rising temperature and humidity. Our study concludes that sustainable rice production requires the adoption of climate-smart agriculture strategies. The government should continue and enhance policy support for developing climate-resilient crop varieties and climate-based crop disease forecasting and management services for coastal farmers. Furthermore, collaboration among government authorities, local agricultural services, researchers, and farming communities is crucial for the effective implementation of these policy strategies.

Keywords Climate change impacts · Rice yield · Rice disease · Trend analysis · Systematic literature review · Coastal Bangladesh

Introduction

The changing climate has a negative impact on crop yields worldwide (Ceglar and Kajfež-Bogataj 2012; Chun et al. 2016; Rao et al. 2016). Among crops, rice is of primary importance. It is a major supplier of human calorie intake, a key commodity in international trade, and an important staple for addressing global hunger (Adenle et al. 2019; Khanom 2016; Samal et al. 2022). Yet, rice is also greatly influenced by climate change (Ali et al. 2022; Rahman et al. 2017; Tolba et al. 2019). Shifts in climate variables, such as temperature and rainfall, affect rice crop yields as well as quality (Boonwichai et al. 2018). For example, temperatures in excess of 32 °C are deleterious to seed setting, pollen disposition, and pollen availability (Krishnan et al. 2011). When higher temperatures are combined with low

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and erratic rainfall, further declines in production and yields may result (Chandio et al. 2021). Beyond such direct effects, shifts in temperatures and precipitation patterns can affect rice crop pathogens, altering the incidence, prevalence, and severity of rice diseases and thus also affecting rice yields and quality (Garrett et al. 2022; Krengel-Horney et al. 2021; Richard et al. 2022).

Around the world, the severity and impact of climate change and variability on rice production vary by region, due to factors such as geographical location, prevailing climatic conditions, types of crop production, and adaptation capabilities (Chandio et al. 2021). In Asia, which is a major rice-producing region, higher temperatures reduce rice production by causing sterility and curtailing the growing period (Li et al. 2015; Van Oort and Zwart 2018). Throughout Asia, rice productivity is expected to decline by 37% by 2100 due to rising temperatures (Lal 2011). In India, rice yields are expected to decline by 10% by the end of the century, compared to the 1971–2009 period, due to the effects of climate change (Saravanakumar 2015). Similarly, Shrestha et al. (2017) found a negative effect of climate change and variability on rice yields in northeast Thailand. In Pakistan's semi-arid zones, climate change is expected to reduce rice yields by 36% between 2070 and 2099 (Ahmad et al. 2015). In China, Wang and Hijmans (2019) found that the overall effect of rising temperatures on rice yields has been quite small since the mid-twentieth century, but extreme weather and climate events have had a significant negative impact (Vogel et al. 2019). In the Philippines, rice yields were found to have increased due to rising temperatures (Ahmad et al. 2015).

Like rice growth and yields, the impact of climate change and variability on rice diseases also varies by region, affecting both disease occurrence and severity. Rice crops are susceptible to various fungal, bacterial, and viral pathogens. Globally, rice blast reduces rice production up to 80–100% (Nalley et al. 2016; Sakulkoo et al. 2018; Simkhada and Thapa 2022). In tropical Asia, sheath blight is a common fungal disease and reduces rice yields by up to 50% (Khoshkdaman et al. 2021; Singh et al. 2019; Yellareddygari et al. 2014). Yield reductions of up to 69% have been found in India due to this disease (Margani and Widadi 2018; Sivalingam et al. 2006).

In South Asia, Bangladesh, one of the world's leading rice producers, serves as a notable example of the challenges faced by developing countries due to climate change and variability. Chowdhury and Khan (2015) demonstrated that variation in climate, such as changes in temperature, rainfall, and humidity, significantly impacts the three major rice varieties grown in Bangladesh (*aus*, *aman*, and *boro*). Within Bangladesh, rice growth and yields are further influenced by regional variations in temperatures and precipitation patterns (Khatun et al. 2016). The impacts of climate change have been particularly severe in the coastal region, due to its proximity to the Bay of Bengal. Here, the agricultural landscape is dominated by rice monoculture (Sarker et al. 2012), accounting for over 90% of all grain produced and grown on nearly 80% of the cropped area (Asaduzzaman et al. 2012; BBS 2011).

In Bangladesh, coastal rice farmers have experienced a rising incidence of rice diseases, due largely to irregular weather and changing climate patterns (Mousumi et al. 2023). Among these diseases, blast, sheath blight, and bacterial leaf blight are the most significant and affect all of the major high-yielding rice varieties grown in the country (Fahad et al. 2019; Haq et al. 2011; Khatun et al. 2021; Velásquez et al. 2018). Such diseases affect rice plant physiology and can ultimately lead to immense losses in terms of crop quality and quantity. In nearly all rice-growing seasons in Bangladesh, these diseases are prevalent and responsible for significant yield loss depending on the crop variety, environmental circumstances, cultivation practices, and crop stage at disease emergence (Ansari et al. 2018; Khatun et al. 2021). According to Haq et al. (2011), blast and sheath blight have become more destructive to rice production over time due to the higher temperatures and humidity brought about by climate change. Some pathogens benefit from climate change, as new environmental conditions may facilitate their spread to new crops, while increasing the infectivity and aggressiveness of existing pathogen strains (Lee et al. 2022). Deviations from conventional plant-disease ecosystems are also becoming more frequent, compounding crop losses around the globe (Lee et al. 2022). In view of these effects and considering the importance of rice for future food security, greater insight is needed into the impacts of climate change and climate variability on rice yields and diseases (Basak et al. 2010).

While most early studies on the effects of climate change focused on developed countries (Zhang et al. 2014), recent research has shifted to examine crop yields in the developing world, particularly in Asia and Africa (Mendelsohn 2014; Wang et al. 2009). Despite Bangladesh's reliance on rice as a major commodity and food staple, and its status as a country extremely vulnerable to climate change (Minar et al. 2013), few studies have analyzed the impact of climate variability on the rice crop in this region (Rashid and Islam 2007). Research is similarly scant on how climate change has impacted rice diseases in Bangladesh. Although several global and regional studies have been conducted on the impact of climate change on rice yield and diseases, there is a lack of localized and integrative research that combines both systematic review and climate data to see the impact of climate variability on rice yield and disease in coastal Bangladesh (Jamal et al. 2023; Lu 2024; Luck et al. 2011; Rashid and Islam 2007; Shahrier et al. 2025; Tang et al. 2023).

Therefore, the objectives of this research are to analyze the nexus between climatic variables (temperature, precipitation, and humidity) and rice yield, as well as the effects of these climatic variables on rice diseases in coastal Bangladesh. To clarify the relationship between the changes in climate variables and rice yields and rice diseases, we integrated a mixed-methods approach (a systematic literature review with analysis of historical climate and crop data). A quadratic polynomial regression analysis and the logit model were employed to assess the impact of climate variability on rice yield and diseases, respectively. A systematic literature review with climate-crop data analysis is crucially needed to synthesize existing knowledge, identify trends and divergences, and assess the cumulative impact of climatic factors on both rice yield and diseases in coastal Bangladesh. The findings of this study will provide critical insights into how climate variability affects rice yield and the occurrence of diseases in the climate-vulnerable coastal region of Bangladesh. This review aims to provide a clearer picture of the adaptation needs of coastal rice systems, recommend future climate-smart rice production and disease management options, support evidence-based policymaking, and highlight future research priorities in coastal Bangladesh. Lastly, the study will serve as a reference point for the academic community in conducting future multidisciplinary research that connects climate science, plant pathology, and sustainable crop production.

Materials and methods

Study area

Bangladesh was selected as the study country, as it is among the world's top rice producers, while also providing a snapshot of the challenges faced by developing countries in adapting to climate change. Within Bangladesh, Patuakhali District, situated at approximately 22°21′15″N latitude and 90°20′5″E longitude, is one of the most vulnerable areas, due to its close proximity to the sea, as illustrated in Fig. 1. It encompasses a geographical area of 3221.31 square kilometers. About 83% of the total arable land is used for rice cultivation. Though rice cultivation is the backbone of Patuakhali's rural economy and a source of livelihoods for

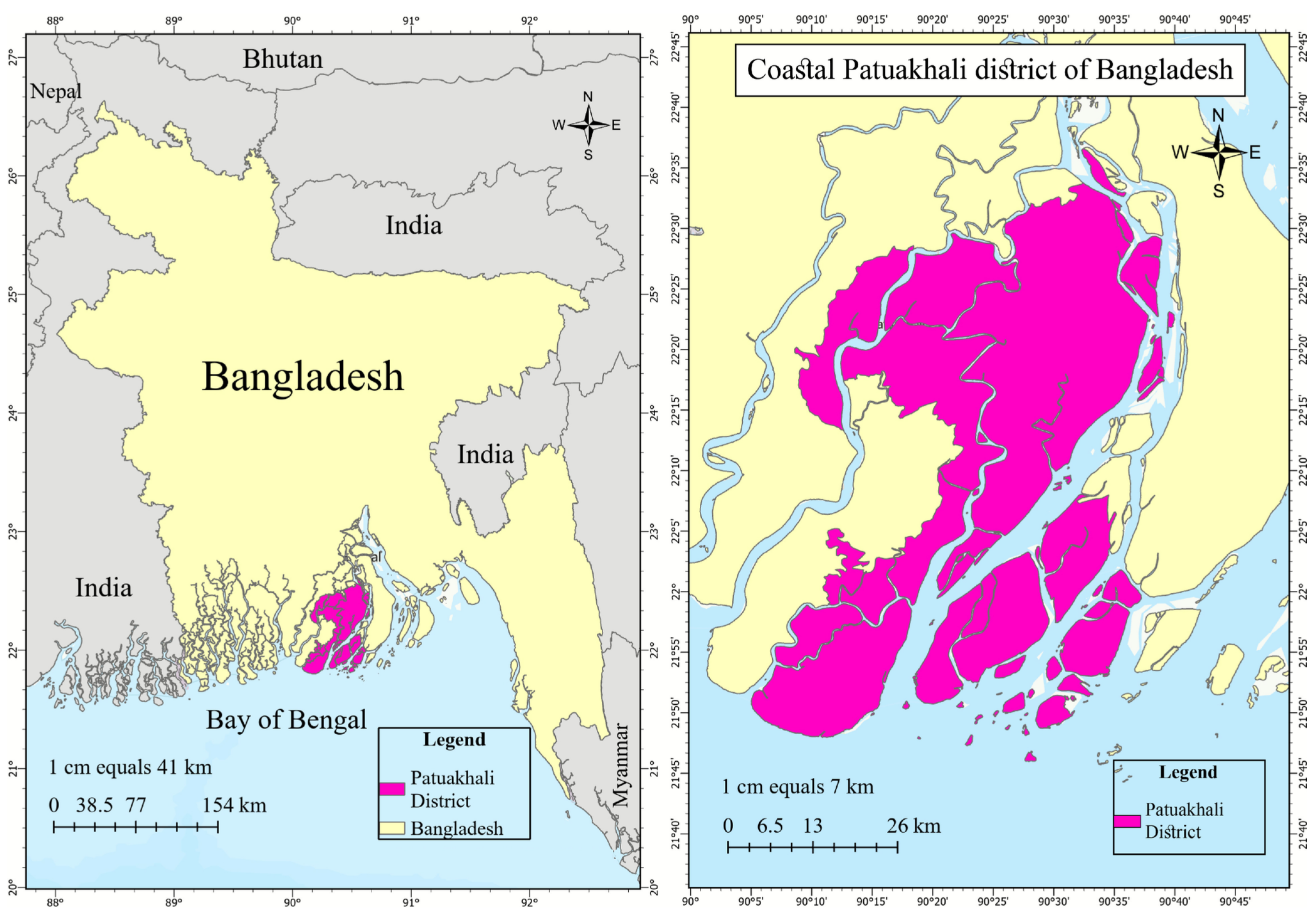

Fig. 1 Study area map showing the location of the coastal Patuakhali District in Bangladesh

farming communities, its production is under threat due to climate change influence (Mousumi et al. 2023). Owing to its frequent exposure to extreme weather and climatic events, along with proximity to the coast, Patuakhali represents a critical case for investigating how climatic factors affect rice crop production and disease prevalence, and what farmers can adapt to sustain rice production in a changing climate.

Moreover, with a tropical monsoon climate, Patuakhali experiences intense rainfall from April to September and minimal rainfall the rest of the year (Hoque et al. 2019). The annual average temperature is 25.9 °C, and the mean annual rainfall is 2654 mm (Hoque et al. 2019). Some 80–90% of the rainfall occurs during the monsoon months of May to October, which provides a prime opportunity for rainfed rice cultivation (Kumar et al. 2020). Patuakhali lies within the Ganges tidal floodplain, which is prone to extreme climate phenomena, such as cyclones, storm surges, warm days, extreme rainfall, waterlogging, and drought (Ferdous et al. 2017). These factors lead to both abiotic and biotic stress, including the prevalence of rice diseases such as sheath blight, blast, and bacterial blight, ultimately reducing rice yield (Mousumi et al. 2023). Climatic variables, such as temperature, humidity, and rainfall, in this coastal region are key factors that directly cause rice crop stress and the incidence of diseases, which in turn hinder crop yield (Jakariya et al. 2021).

In this study, the methodological context was subdivided into mainly two parts: (a) SLR and (b) climate and crop data analysis (Fig. 2). The systematic review covers literature from across the globe, while the climate and crop data are specific to the coastal Patuakhali district in Bangladesh. Then, reviews and data-based results were synthesized to assess the impact of climate variability on rice yield and diseases in the coastal Patuakhali region of Bangladesh.

Systematic literature review

The qualitative component of our study consisted of a systematic literature review. The objectives of this review were to uncover how climate variability affects rice yields and diseases. To guide the systematic review, we employed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method, a widely adopted framework for transparent and standardized reporting (Fargnoli and Lombardi 2019; Moher et al. 2009). This method (1) enhances the value, quality, visuality, and transparency of research (Bhuiyan et al. 2021; Liberati et al. 2009); (2) facilitates the systematic and reproducible synthesis of research on a particular question using a structured procedure (Linnenluecke et al. 2015); and (3) offers a more rigorous approach compared to traditional narrative reviews (Snyder 2019).

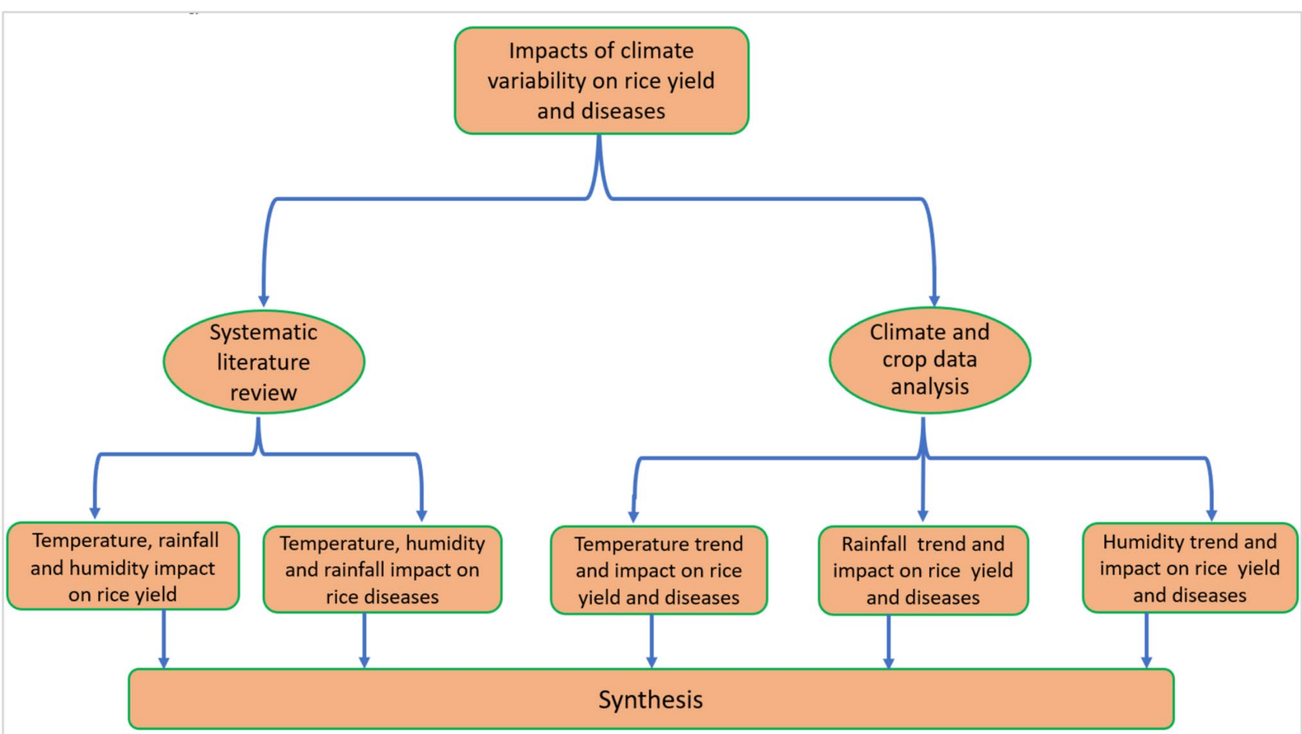

Fig. 2 Methodological flowchart of the study combining systematic literature review and climate-crop data analysis and their synthesis to assess the impact of climate variability on rice yield and diseases

Figure S1 presents the literature review procedure (Malhi et al. 2021; Nor Diana et al. 2022), which consists of four steps: study identification, article screening, evaluation of eligibility, and inclusion of the study for analysis. The first step was the identification of relevant studies. For this, we formulated keywords related to climate variability's impact on rice yields and diseases. Using those keywords (see Appendix 1), we searched Scopus, employing Boolean operators to ensure inclusion of all pertinent articles. Scopus is the largest database among other sources. Additionally, this database was used due to its high-quality content, broader coverage, and multidisciplinary focus. As the articles found in Scopus fully cover Web of Science, we only use Scopus databases for literature searches (Pophiwa et al. 2025). The preliminary search yielded 375 documents, including articles, book chapters, review papers, conference papers, books, editorials, errata, and notes in English, Chinese, German, Russian, Italian, and Japanese. For the second step, article screening, we developed a set of inclusion and exclusion criteria to identify the targeted articles more precisely (Table S1). During the screening process, 189 documents were excluded, resulting in 186 papers being retained for eligibility evaluation, the third step in the process. The eligibility evaluation was conducted manually by reviewing the titles and abstracts of the identified documents. Studies focused on the impacts of climate variability on other aspects of rice and other crops were excluded from further consideration. Of the 186 papers, 81 met the requirements and were retained for information retrieval and analysis. Our focus was primarily on regional studies. However, when we found a small number of regional studies specifically on rice diseases, we also included the global studies in the review.

The final step in the systematic review was data analysis. Here, the 81 remaining documents were analyzed to derive the main research lines and data for the study. Descriptive statistics were performed based on the metadata compiled from the 81 documents. Furthermore, thematic content analysis was employed to categorize information from the included articles, uncovering common themes and insights into how climate variables affect rice yields and diseases.

To standardize effect sizes across the different literature, we used Cohen's *d*. Thus, we converted the various statistical outputs, such as correlation coefficients, regression coefficients, and R^2 values, into a standard effect size (Cohen's *d*) (Appendix 2). Cohen's *d* is widely used and easily interpretable (Halbeisen et al. 2024; Ratsiatosika et al. 2021). The interpretation of Cohen's *d* was done following Cohen's conventions, with "large," "moderate," and "small" effects indicated by $d > 0.8$, $d = 0.2$–0.8, and $d = 0$–0.2, respectively (Cohen 1988; Gurevitch et al. 1992).

Climate and crop data analysis

We examined trends over 38 years, from 1981 to 2018, using data from the Patuakhali weather station of the Bangladesh Meteorological Department (BMD). Data on *aman* rice yields for Patuakhali District over the past 38 years were collected from the Bangladesh Bureau of Statistics (BBS) and national statistical yearbooks. Here, "*aman rice*" refers to rice grown during the monsoon season (June to December) in Bangladesh (Hasan and Kumar 2021). Our analysis sought to identify any monotonic trends in the observed climate and crop data series. To achieve this, we employed nonparametric Mann-Kendall tests (Kendall 1975; Mann 1945) (Appendix 3).

Rice yield impact analysis using quadratic polynomial regression

To determine the potential impacts of climatic variables on rice yield, this study aims to investigate the relationship between *aman* rice yields in Patuakhali District and three climate variables: temperature, rainfall, and humidity. In this analysis, rice yield was the dependent variable, while the average temperature, total rainfall, and average humidity during the *aman* growing season (June–December) were independent variables (Lobell and Field 2007; Sarker et al. 2012). This approach acknowledges that climate conditions during the growing season influence the complete development cycle of rice, thus affecting yields (Lobell and Field 2007). We estimated trends in *aman* rice yields for the period from 1981 to 2018. We then used a quadratic polynomial regression (Appendix 4), adapted from Lobell et al. (2011) and Hasan and Kumar (2021), to regress *aman* rice yields against a series of climate variables to quantify the impacts of temperature, rainfall, and humidity trends on rice yields.

In addition to the quadratic polynomial regression model, we conducted correlation and regression analyses to estimate the impact of individual climate variables on rice yields (Tables S2 and S3).

Regarding the impact of the climate variables on rice disease occurrence in this coastal region, we first determined threshold levels using favorable weather conditions for disease occurrence in rice (Table S4). As we were dealing with *aman* rice, we calculated the number of favorable days only during the *aman season* for the occurrence of three major diseases: blast, sheath blight, and bacterial leaf blight. Here, we assumed that the number of favorable days for disease development corresponded with the actual occurrence of that disease in the crop field. We employed a logit model to identify meteorological variables that contribute to the dependent variables (i.e., the occurrence of diseases). This method, which uses disease occurrence as the dependent variable and weather parameters as independent variables, has been employed by other authors to identify the most critical weather parameters influencing disease development (Kodaty and Halavath 2021; Ossifo et al. 2022; Saha 2022). However, a virulent pathogen, a susceptible host, and a favorable environment are necessary for diseases to develop in crop plants (Agrios 2005). In our research, we assumed the pathogen was virulent and the crop plant was susceptible. Hence, our investigation focused solely on environmental factors (temperature, humidity, and rainfall) that influence disease development.

For data analysis, we used RStudio (Version 2023.06.1) (R Core Team 2023), along with several additional packages, specifically, "ggplot2," "ggpubr," and "patchwork." The "imputeTS" R package (Moritz and Bartz-Beielstein 2015) was used to impute the missing data in the time series.

Results

Outcomes from the systematic literature review

This section presents insights from our analysis of the 81 targeted documents. In the content analysis, the documents were classified mainly into two categories. Then, these two categories were subcategorized into four (each has two subcategories). The total six thematic categories: (a) overall impact of climate variability on rice yield, (i) impact of temperature on rice yield, (ii) impact of rainfall and humidity on rice yield, (b) overall impact of climate variability on rice disease, (i) impact of temperature on rice disease, and (ii) impact of humidity and rainfall on rice disease, were used to organize findings from the systematic literature review (with definition and example presented in Table S5).

Table S6 and Table S7 present summaries of the literature review on the impact of climate variability on rice yields and diseases, respectively. Of the 81 documents, 65% ($n=53$) focused on climate variability's impact on rice yields, while 35% ($n=28$) concerned climate variability's impact on rice diseases.

Impact of climate variability on rice yields

Among the targeted studies, 61% ($n=51$) found a negative impact of climate variability on rice yields, and a smaller number (18%, $n=15$) reported a positive effect. Most studies have pointed to temperature and rainfall as the primary climate variables that hamper rice yields (Table S6). Based on Cohen's d values, 57% of the studies found the temperature's effect on rice yields to be significant. A large effect was observed in 18 studies, a medium effect in 5 studies, and a small effect in 3 studies. On the other hand, in terms of Cohen's d value, rainfall had significant large ($n=8$), medium ($n=1$), and minor effects ($n=4$) on rice yields (Table S6). Many parts of the world are experiencing extremely high temperatures, which exceed the optimum values for rice cultivation. Over half of the studies were conducted in India ($n=27$) and Bangladesh ($n=13$), reflecting the importance of these countries as the world's second- and third-largest rice producers.

Impact of temperature on rice yields Among all factors, temperature appears to be particularly key in affecting rice crop growth, development, and ultimately yield. Most of the studies (Bhatt et al. 2019; Debnath et al. 2021; Kashyap and Agarwal 2021; Khairulbahri 2022; Prabnakorn et al. 2018; Wu et al. 2021) considered the effect of increased minimum temperatures in reducing rice yields, though some studies (Bhardwaj et al. 2022; Debnath et al. 2021; Kashyap and Agarwal 2021; Pranuthi and Tripathi 2018) also identified an increase in maximum temperature as causing decreased rice yields (Fig. 3). Maximum and minimum temperatures exceeding threshold levels for rice production (20–36 °C), particularly during critical development phases, were shown to affect rice production negatively (Fahad et al. 2019). According to some authors (Dkhar et al. 2017; Maniruzzaman et al. 2017; Sarker et al. 2012; Wu et al. 2021), an increased maximum temperature can improve rice productivity, though relatively few studies (Bhardwaj et al. 2022; Sarker et al. 2012) indicated that an increased minimum temperature enhanced rice yields. According to Welch et al. (2010), the cumulative negative marginal effect of increased minimum temperature during the vegetative and ripening phases is expected to outweigh the combined positive marginal effect of increased maximum temperature. The precise effect of rising temperatures on rice yields depends on geographical location, agro-climatic conditions, crop variety, crop growth stage, and agronomic practices.

Impact of rainfall and humidity on rice yields Rice is mainly grown under rainfed conditions. Its yield is thus influenced by rainfall variability and availability. Analysis of the reviewed literature suggests that increased rainfall diminishes rice yields (Aziz et al. 2023; Baig et al. 2022; Bhardwaj et al. 2022; Debnath et al. 2021; Gupta and Mishra 2019; Hasan and Rahman 2020; Zhao et al. 2022), but rainfall shortfalls also reduce yields (Fig. 3) (Jha et al. 2020; Prabnakorn et al. 2018; Wu et al. 2021; Zhao et al. 2022). Some findings deviate slightly from this perspective. For example, Baig et al. (2022) found that a decrease in rainfall increased rice yields in the short term—although not in the long term—in regions where heavy rain creates flood-like conditions. Among all the countries considered in the analyzed literature, India and Bangladesh were the two nations where variations in precipitation had the most significant impact on rice crop productivity. In India, increasing precipitation is expected to

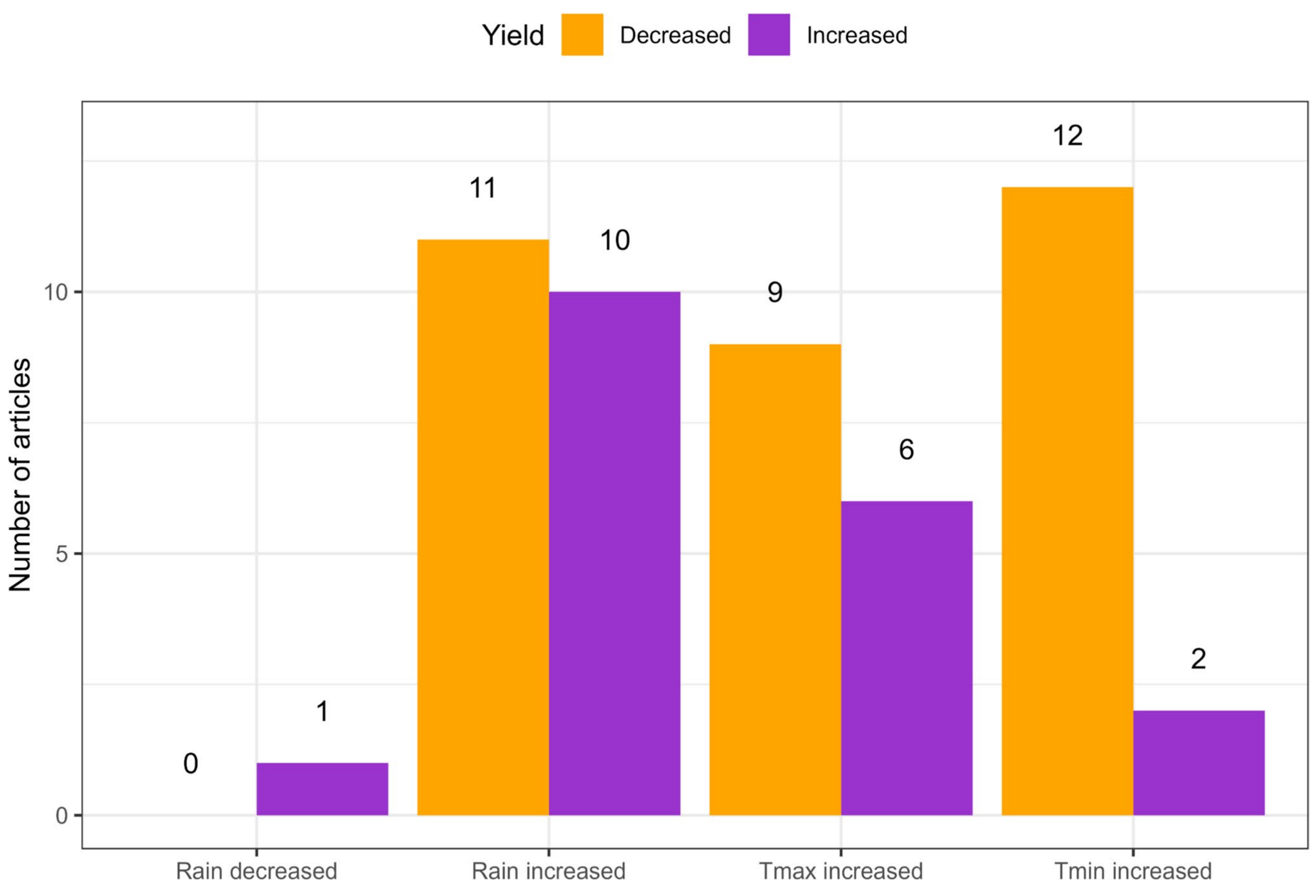

Fig. 3 Summary of findings from systematic literature review on the impact of temperature and rainfall on rice yields

reduce rice yields up to 2100 (Gupta and Mishra 2019). In contrast, Sarker (2021) reported that a 1% increase in rainfall would enhance rice yields in Bangladesh. Overall, variations in rainfall either increase or decrease rice yields, depending on regional distribution, intensity, rainfall type, rice variety, cultural practices, and technological advancements. Interestingly, little work has been done on the effect of humidity on rice yields, despite the influence of this factor on leaf growth, photosynthetic rate, and pollination.

Impact of climate variability on rice diseases

Changes in temperature, humidity, and rainfall have diverse effects on disease development. Over one-third of the targeted articles (35%, $n = 28$) dealt with the impacts of climate change on rice diseases. Most studies were conducted on a global scope (Table S7) and found either a positive or negative effect of climate variables on blast, sheath blight, and bacterial leaf blight of rice. Overall, the incidence and severity of these diseases were expected to rise due to temperature variability and changes in humidity and rainfall (Gautam et al. 2013; Haq et al. 2011; Kim and Cho 2016; Luck et al. 2011; Velásquez et al. 2018; Wang et al. 2022). This finding aligns with Miah et al. (1985), who reported that in Bangladesh the severity of sheath blight had shifted from minor to major due to increased temperature and humidity.

According to projections, crop disease risk will increase up to 2100, primarily due to rising temperatures, which in many cases will facilitate the development of crop pathogens and diseases. This will be the case especially in cooler regions and seasons (Juroszek et al. 2022). For example, in Europe, blast occurrence is projected to rise from 2030 to 2050, compared to the reference period of 1993–2007 (Bregaglio et al. 2013). However, in Asia, the risk of blast will likely diminish in the future, due to increasing temperatures (Juroszek et al. 2022). This is because *Pyricularia oryzae*, the blast disease pathogen, requires comparatively low temperatures (minimum 16–20 °C, maximum 25–30 °C) for growth and development. Climate change is set to result in much higher temperatures in Asia, surpassing optimum blast infection values.

In addition, higher temperatures are expected to increase blast severity in cool subtropical zones, like Japan and northern China, whereas blast disease severity will decrease in the humid tropics and warm humid subtropics, like southern China, the Philippines, and Thailand, since current temperatures in these regions are over the threshold for blast incidence (Ghini et al. 2008; Luck et al. 2011; Wang et al. 2022). In India, a 1.5 °C temperature rise is expected to increase blast occurrence in the winter season (December–March), under 2020 and 2050 climate scenarios (Viswanath et al. 2017). In Bangladesh, blast disease severity started to rise in the last two decades of the twentieth century, due to smaller variation between maximum and minimum temperatures and because of increasing minimum temperatures from January to March (Haq et al. 2011).

The other diseases considered, sheath blight and bacterial leaf blight, were found to become more pervasive with rising temperatures. After the blast, sheath blight of rice was the second most studied disease in the targeted literature (Gautam et al. 2013; Haq et al. 2011; Kim and Cho 2016; Pal, 2017; Singh et al. 2019; Velásquez et al. 2018; Wang et al. 2022). With the rise of temperatures, sheath blight will become the most common rice crop disease in Asia (Das 2017; Velásquez et al. 2018). In Bangladesh, too, the rapid development of sheath blight and spread of this pathogen will be facilitated by the higher temperatures and humidity brought by climate change (Haq et al. 2011). In the case of bacterial leaf blight of rice, its severity in Asia will also increase due to rising temperatures (Velásquez et al. 2018; Webb et al. 2010).

Impact of temperature, humidity, and rainfall on rice diseases Different environmental factors influence the onset and development of rice diseases. This is reflected in the "disease triangle" concept in plant pathology, which emphasizes the interaction between three factors—the pathogen, the host plant, and the environment—in creating conditions for a disease to develop (Agrios 2005). More favorable weather conditions for rice diseases are a concern among farmers in much of the world. Moreover, temperature, rainfall, and humidity are projected to fluctuate more, which will likely aggravate the occurrence of rice diseases in this century. Although water availability in terms of rain, high air humidity, high soil moisture, and fog has a substantial impact on rice disease development (Velásquez et al. 2018), temperature was the focal variable in most of the reviewed literature (Das 2017; Duku et al. 2016; Juroszek et al. 2022; Luck et al. 2011; Shew et al. 2019; Velásquez et al. 2018; Wang et al. 2022), though some studies examined both temperature and humidity (Table S7).

In general, the development of rice blast is favored by prolonged leaf wetness, high relative humidity, and temperatures between 17 and 28 °C (Greer and Webster 2001). Temperatures between 25 and 28 °C with a relative humidity of 89% are ideal for the sporulation of blast pathogens (Bevitori and Ghini 2014). Nonetheless, Bevitori and Ghini (2014) found infection to be absent when the nighttime temperature was above 20 °C. Thus, the expected rise in temperatures due to climate change may lead to a decrease in blast incidence.

Meteorological conditions, including air temperature and humidity, also directly influence the development of the sheath blight pathogen (*Rhizoctonia solani*) (Bhukal et al. 2015; Senapati et al. 2022) and bacterial leaf blight in the field. Biswas et al. (2011) and Wang et al. (2022) recorded maximum spread and development of sheath blight at temperatures of 28–32 °C and a relative humidity greater than 80%. Rising temperatures may thus facilitate the rapid spread of hypha and the development of sheath blight disease (Wang et al. 2022). Regarding bacterial leaf blight of rice, a temperature of 25–34 °C, relative humidity of 70–90%, and rainfall above 30 mm are required for disease development (Haque et al. 2022). In the future, the severity of this disease is expected to increase due to rising temperatures (Velásquez et al. 2018). Moreover, the effect of increasing temperatures can stimulate the occurrence of new disease strains. Overall, our literature review made it abundantly evident that there has been minimal advancement in the study of the effects of climate change on rice diseases in Bangladesh.

Outcome from climate and crop data analysis

Trend of climatic variables

The trend in climate variables (maximum and minimum temperature, rainfall, and humidity) of the coastal Patuakhali region over the period 1981–2018 was analyzed using non-parametric Mann-Kendall tests (Table 1). Results from the Mann-Kendall test showed a significantly increasing trend ($|Z| > 1.96$) in the annual average maximum temperature over the 38-year period. Sen's slope estimator determined that the maximum temperature during the *aman* season (June–December) rose at a rate of 0.04 °C per year, which is statistically significant (Fig. S2a) (Table 1). In the case of minimum temperature, the Mann-Kendall test indicated a slight increase (not significant) from 1981 to 2018; according to Sen's slope estimation, the rate of increase was 0.004 °C per year (Fig. S2b) (Table 1).

Regarding the annual average rainfall in Patuakhali District from 1981 to 2018, the Mann-Kendall test revealed a statistically insignificant decreasing trend (Table 1). Sen's slope estimation found that annual average rainfall declined at a rate of −4.29 mm per year (Fig. S2c) (Table 1), which is not statistically significant. For annual average humidity, the Mann-Kendall test indicates a gradually increasing trend ($|Z| > 1.96$) over the 38 years in the study area, with this result being statistically significant. Sen's slope estimation showed an increase in humidity of 0.16% per year (Fig. S2d) (Table 1).

Table 1 Summary of the Mann-Kendall (MK) test and Sen's slope test (SS) of the climatic variables in the coastal Patuakhali District of Bangladesh over the period 1981–2018

Climatic variables	Mann-Kendall (MK) test (Z)	Significant level	*p*-value	Sen's slop estimation (Q)	Number of observations	Year of observation
Maximum temperature	5.7328	***	9.879e−09	0.03854624	38	1981–2018
Minimum temperature	1.3075	NS	0.1911	0.004498574	38	
Rainfall	−0.55316	NS	0.5802	−4.288	38	
Humidity	4.6265	***	3.72e−06	0.1592451	38	

*, **, and *** indicate significance at the 0.05, 0.01, and 0.001 levels, respectively; NS indicates nonsignificant

Impact of climatic trends on rice yields

Aman rice yields exhibited an increasing trend, rising by an average of 26 kg/ha per year over the 38-year study period (Fig. S3). Moreover, climate trends had different effects on the *aman* rice yield trend. Results of the quadratic polynomial regression indicate that the temperature, rainfall, and humidity trends adversely affected the *aman* yield trend by −2.1%, −0.3%, and −1.5%, respectively. The combined effect was −10.9% (Table 2), equivalent to a yield reduction of 0.14 Mt/ha per year, or 5.4% of the total yield, between 1981 and 2018. The mean maximum temperature was 30.44 °C over the 38 years and increased at the rate of 0.04 °C per year. The optimum temperature required for rice production is 20–36 °C. If the current trend continues, the maximum temperature will be closer to or cross the optimum maximum temperature limit (36 °C) in this century or the upcoming century. This will affect the growth and development of the rice plant, ultimately reducing yield.

The *aman* rice yield was regressed against the climate variables (Fig. S4). Table S2 summarizes the results, which indicate that 63% of the variance in rice yields is explained by climate variables (temperature, rainfall, and humidity) and 37% is explained by non-climatic factors (such as soil and crop factors and agronomic practices). The results of Pearson's product-moment correlation (Table S3) indicate that temperature had a strong positive correlation with rice yield ($r = 0.75$), rainfall was negatively correlated with rice yield ($r = -0.32$), and humidity had a moderate positive correlation ($r = 0.57$). These findings suggest that while temperature currently has a positive effect on rice yield, the overall trend of rising temperatures will likely have a negative impact. If this trend continues, increasing temperatures could drastically reduce rice yields in coastal Bangladesh in the future.

Table 2 Percentages of impacts of climatic trends on rice yields over the period 1981–2018

Climatic variables	% effect on yield	95% confidence interval	
		Lower bound	Upper bound
Temperature (T)	−2.081	−5.538	1.376
Rainfall (R)	−0.3099	−1.019	0.3995
Humidity (H)	−1.4941	−4.963	1.975
Combined (T, R, H)	−10.9209	−29.11	7.269

Effect of climate variables on rice diseases

Climate variables were found to have considerable influence on the development of blast, sheath blight, and bacterial leaf blight in rice in coastal Bangladesh.

Trend of the number of favorable days for disease development Temperature and humidity, the key climate variables in initiating disease development in crop plants, showed an increasing trend over the study period (see Fig. S2, Table 1). Favorable days for sheath blight of rice during the *aman* season increased in this coastal region over the 38 years analyzed, implying that with rising numbers of hot and humid days, disease occurrence will also increase in this region (Fig. 4). These results support findings from the literature review suggesting that in Asian countries (including Bangladesh), sheath blight, blast, and bacterial leaf blight have increased as temperatures and humidity have increased. However, blast requires both a minimum temperature (16–20 °C) and a maximum temperature (25–30 °C), and humidity above 90%. Only when these three conditions are fulfilled will blast infect a rice crop. These three conditions do not always coincide, which is why the occurrence of blast was lower than that of sheath blight. Our data analysis showed that the mean minimum and maximum temperatures were 23.3 °C and 30.4 °C, respectively, which are above the threshold for blast occurrence. Additionally, the trends were 0.04 °C/year (for maximum temperatures) and 0.004 °C/year (for minimum temperatures) (Table 1), which indicates that blast occurrence is likely to recede in the future.

Besides, bacterial leaf blight occurrence is still comparatively low in coastal Bangladesh (see Fig. 4). This can be attributed to the irregularity of rainfall in this region.

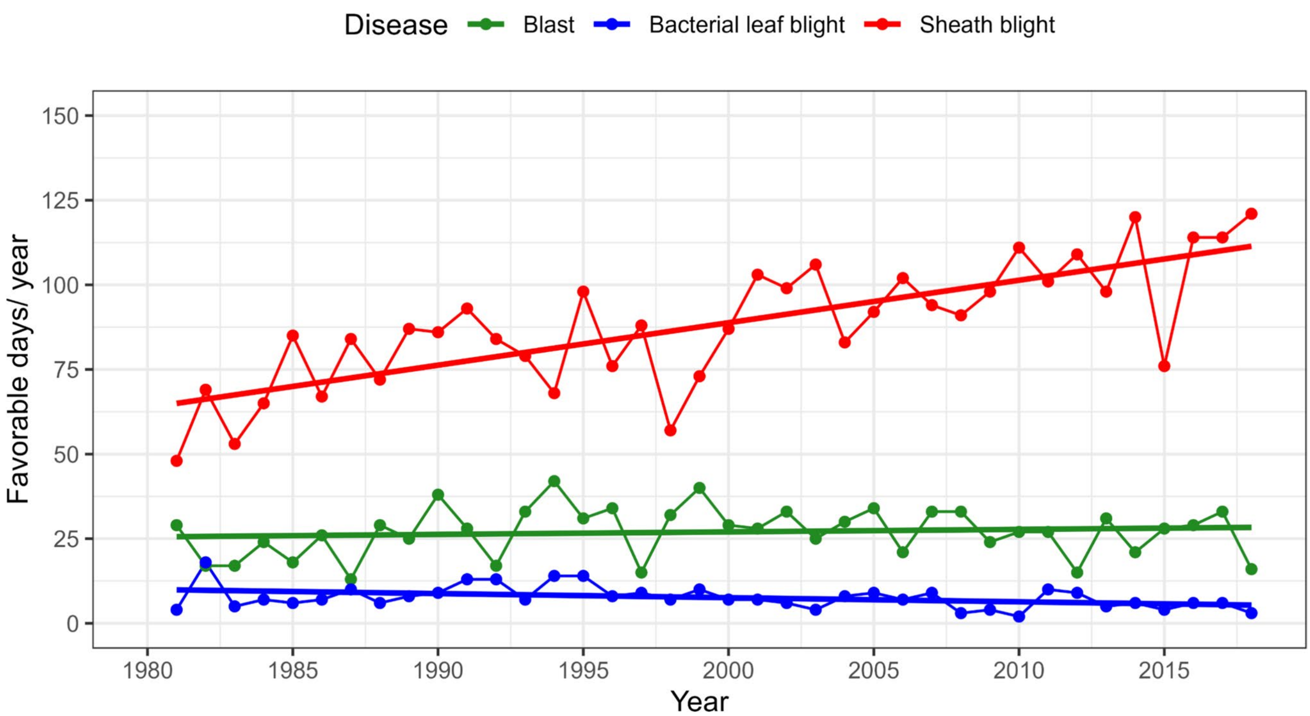

Fig. 4 Trend in the number of favorable days per year for sheath blight, blast, and bacterial leaf blight in rice during the *aman* season in Patuakhali District in the period 1981–2018

Bacterial leaf blight development in rice requires temperatures of 25–34 °C, a relative humidity of 70–90%, and rainfall above 30 mm/day. Though temperature and humidity were favorable, bacterial leaf blight could not develop in rice fields in coastal Bangladesh due to the lack of rainfall.

Relationship between rice diseases and climate variables Logit models were used to estimate the coefficient of determination (R^2) to establish a quantifiable association between the climate variables and the occurrence of blast, sheath blight, and bacterial leaf blight. For all three diseases, multiple correlation coefficients revealed a strong relationship between disease occurrence and meteorological variables. The coefficient values of the climate variables showed that each variable significantly influenced the occurrence of all three diseases (Table 3).

First, sheath blight was positively correlated with average temperature and average humidity, meaning that with the rise in average temperature and humidity, the occurrence of sheath blight increased (Table 3). Moreover, the combined influence of the climate variables significantly contributed to the increased occurrence of sheath blight. The significant R^2 value (0.72) for the occurrence of sheath blight indicates that the climate variables were responsible for up to 72% of the variation in the occurrence of sheath blight in rice.

For blast and bacterial leaf blight, R^2 values were 0.81 for both diseases, indicating a highly significant relationship between disease occurrence and the climate variables (Table 3). Moreover, for blast, maximum temperature and minimum temperature were identified as critical factors, with maximum temperature having a negative impact and minimum temperature and humidity making positive

Table 3 Logit model for the relationship between climate variables and occurrence of rice diseases

Climatic variables and occurrence of diseases	Logit model equation	R^2 Value
Y1 and X1, X4	−66.680979 + 1.627357 X1 + 0.238786 X4	0.72***
Y2 and X2, X3, X4	−31.84874 − 1.16830 X2 + 0.55936 X3 + 0.56299 X4	0.81***
Y3 and X1, X4, X5	−35.001704 + 0.578534 X1 + 0.143043 X4 + 0.172331 X5	0.81***

*Significant at 5% level, **significant at 1% level, ***significant at 0.1%; X1 = average temperature, X2 = average maximum temperature, X3 = average minimum temperature, X4 = average humidity, X5 = total rainfall, Y1 = occurrence of sheath blight disease, Y2 = occurrence of blast disease, and Y3 = occurrence of BLB disease contributions to disease occurrence. For bacterial leaf blight, all weather variables were positively correlated with disease occurrence, meaning that increases in these variables will increase the occurrence of the disease in coastal Bangladesh.

Integration of findings from literature review and climate and crop data analysis

Both the literature review and the climate and crop data analysis pointed to temperature's influence, either positive or negative on rice yields (Fig. 3). According to the literature review, higher minimum and maximum temperatures reduce rice yields in most cases. This is consistent with the results of our climate and crop data analysis, which indicated that the trend of rising temperatures reduced rice yields in coastal Bangladesh. Furthermore, the trend of rising temperatures is set to impede rice production to an even greater extent in the future. If temperatures rise above or fall below optimum values for rice cultivation (20–36 °C), rice yields will be compromised.

While most of the literature emphasizes the detrimental effects of increased temperatures on rice yields, our analysis showed a positive correlation between temperature and rice yield in certain contexts. This contradiction may be due to different factors. The relationship between temperature and yield is possibly nonlinear. Region-specific analyses revealed that increased temperature in cooler environments enhances photosynthetic activity; on the other hand, increased temperature in warmer regions reduces fertility and grain quality (Peng et al. 2004; Welch et al. 2010). Other factors, such as baseline climate conditions, agronomic practices, and varietal adaptation, significantly affect whether increased temperatures are beneficial or harmful for crop production (Al Mamun et al. 2025; Sarker et al., 2022).

However, according to our data analysis, the mean average temperature in the *aman* growing season (June–December) in coastal Bangladesh was 26.9 °C over the 38 years under study. This is within the optimum temperature range (20–36 °C) for rice production. For this reason, our results suggest that temperature was positively correlated with rice yields. Temperature has a positive effect on rice yield in the short run but has a negative effect in the long run. In correlation analysis, it is found that yearly temperature is positively correlated with yearly rice yield. In the quadratic polynomial regression model, it is found that the overall increasing trend of temperature over 38 years has a negative impact on rice yield. Up to a certain point, changes in temperature and rainfall can be advantageous for crop production. However, if temperatures exceed the optimum range, yields begin to decline.

In regard to rice diseases, our literature review pointed to blast, sheath blight, and bacterial leaf blight as the most destructive rice diseases under changing climatic conditions. Our crop and climate data confirmed that blast and sheath blight were the most prevalent diseases in the study area. Furthermore, findings from the literature review suggest that sheath blight will increase with rising temperatures, which is consistent with the results of our crop and climate data analysis. In contrast, the literature suggests that blast will decrease with rising temperatures, and this is also in line with our data analysis findings.

Discussion

Historic climatic trends

Our climate data analysis revealed an upward trend in maximum temperature (0.04/year, $p < 0.05$) and humidity (0.16%/year, $p < 0.05$) and a downward trend (−4.29 mm/year, non-significant) in rainfall in Patuakhali District over the 38 years from 1981 to 2018. The change in maximum temperature was larger than that for minimum temperature. These findings tally with existing literature highlighting an increasing trend in temperature (Amin et al. 2014; Hossain et al. 2017; IPCC 2021; Rahman et al. 2017; Zannat et al. 2019). Looking specifically at coastal Bangladesh, Sarker (2021) found that annual average maximum and minimum temperatures were increasing at rates of 0.026 °C per year and 0.013 °C per year, respectively. Similar to Sarker (2021), who reported a 6.7 mm per year decrease in rainfall, we found a declining trend in rainfall. Nonetheless, some studies have found rising precipitation in other parts of the country (Ahmed et al. 2016a; Hasan and Kumar 2021).

Influence of climatic variables on rice yields

Our climate and crop data analysis found that the rising temperature trend caused an increase in *aman* rice yields in the study area. This result aligns with that of Hasan et al. (2016) and Sarker et al. (2012), who also observed that *aman* rice yields were positively correlated with rising temperature in southern Bangladesh. Several other researchers (Dkhar et al. 2017; Maniruzzaman et al. 2017; Sarker et al. 2012) have also reported positive correlations between crop yields and rising annual average temperatures. However, in the longer term, the effect of the rising average temperature trend on *aman* rice yields is negative, according to the results of quadratic polynomial regression. This aligns with Hasan and Kumar (2021), who also found a negative effect of the rising temperature trend on *aman* rice yields in coastal Bangladesh (see also Baig et al. 2022). Our study found the impact of the historical temperature trend (1981–2018) on rice yields in Patuakhali District to be as yet relatively minor (−2.1%) (Table 2).

However, the yield decline is projected to become more severe in the future, if the increasing temperature trend persists (Bhardwaj et al. 2022; Debnath et al. 2021).

The current study extracted numerous arguments from the literature in support of the finding that a higher mean temperature is initially beneficial for rice yields, but above a certain optimum, further temperature rises are detrimental to rice yields (Prajapati 2015). One reason for this is the effect of higher temperatures in reducing the length of the growing season, which could potentially reduce rice yields (Kumar et al. 2021). Moreover, increased maximum temperatures, particularly those above 35 °C and lasting for more than 1 h during the anthesis or flowering phase, can induce spikelet sterility, resulting in yield decrease (Yoshida et al. 1981). A minimum temperature is required to achieve high grain number in rice; nevertheless, any increase in minimum temperature causes a reduction in the number of fertilized spikelets (Cheng et al. 2009; Prasad et al. 2006).

According to our literature review, the effect of changes in rainfall on rice yields depends on the amount, frequency, intensity, distribution, and timing of precipitation; the crop growing stage and region; and the agro-climate; in addition to factors such as soil characteristics, crop variety, and agronomic practices. Our climate and crop data analysis found that *aman* rice yields were negatively correlated with rainfall. Mamun et al. (2015) reported similar findings, revealing that *aman* rice yields depended on monsoon rainfall but were negatively correlated with high rainfall amounts. This is because *aman* rice does not require a substantial amount of rainfall to grow, but it thrives on consistent and well-distributed precipitation throughout the season. Various studies align with our results concerning the effects of rainfall (Auffhammer et al. 2012; Aziz et al. 2023; Jakariya et al. 2021; Mondol et al. 2021; Singh et al. 2017). In the Satkhira region of coastal Bangladesh, Rimi et al. (2009) found that rainfall had an insignificant negative correlation with *aman* rice yields. In nearby Punjab, India, Bhardwaj (2022) found a significant negative effect of rainfall on rice productivity. Nonetheless, a number of studies have found a positive effect of increased rainfall on rice yields (Abeysingha et al. 2016; Dkhar et al. 2017; Hasan et al. 2016; Hossain et al. 2019).

Excessive rainfall during the flowering and ripening stages can cause spikelet sterility and reduce rice yields (Abbas and Mayo 2021). Pattanayak and Kumar (2014) found that, in India, a 1% increase in rainfall during ripening resulted in a 0.02% reduction in rice yield. In addition, continuous rainy weather during the growing season is detrimental to rice yields because of the associated insufficiency of solar radiation and greater occurrence of pests and diseases (Tao and Yokozawa 2005). Our climate and crop data analysis found that the impact of changes in rainfall on rice yields in this coastal region was as yet insignificant. However, if precipitation trends continue at the observed levels, the yield reduction effect is likely to become more acute due to insufficient rainfall in the future.

This study also found that the combined impact of climate trends (temperature, rainfall, and humidity) on rice yields was equivalent to a yield reduction of 140 kg/ha per year. This aligns with the findings of Hasan and Kumar (2021) regarding the combined impact of climate trends on *aman* rice yield reduction in coastal Bangladesh. However, despite the negative effect of climate change, our rice yield analysis showed an annual increase of 0.026 Mton/ha, which can be attributed to technological advancements, farmer adaptations, and increased gross cultivated area (Bagchi et al. 2019). In this regard, He et al. (2020) found that highly dynamic climate variables stimulated use of advanced agricultural practices, such as resistant and improved varieties, more fertilizer and pesticide, and irrigation, as well as increased land under cultivation. These factors have cushioned the direct negative effect of the identified climate trends.

Influence of climatic variability on rice diseases

Most of the analyzed literature on rice diseases concerned the effect of temperature changes on rice disease development (Das 2017; Duku et al. 2016; Juroszek et al. 2022; Luck et al. 2011; Shew et al. 2019; Velásquez et al. 2018; Wang et al. 2022). Juroszek et al. (2022), too, observed that temperature is the most frequently studied parameter in climate change biological research concerning plant pathogens and crop disease risk. Due to temperature changes, sheath blight and bacterial leaf blight of rice will increase, though blast will diminish in some parts of the world, including Bangladesh (Gautam et al. 2013; Haq et al. 2011; Kim and Cho 2016; Luck et al. 2011; Luo et al. 1998; Velásquez et al. 2018; Wang et al. 2022). These findings from the literature align with our own climate and crop data analysis, which demonstrated that the number of favorable days for sheath blight occurrence had greatly increased in Patuakhali District. In addition, our logit model showed a positive correlation between temperature and humidity and sheath blight occurrence (see Table 3). Sheath blight requires warm temperatures (28–32 °C) and humidity above 80%. According to our data, the average temperature and humidity in the study area were 26.89 °C and 83.37%, respectively. A continuation of the current trend of rising temperature and humidity is expected to bring a substantial increase in sheath blight occurrence in the future.

Additionally, the logit model showed a negative correlation between maximum temperature and blast occurrence. As the maximum temperature trend is increasing in coastal Bangladesh, blast will ultimately diminish. Though findings from the literature review suggest that bacterial leaf blight occurrence will increase, our climate data analysis indicates that it will decrease in the study area, because the bacterial leaf blight pathogen requires relatively high temperatures (25–34 °C), high humidity, and rainfall (see Table S4). Our trend analysis found declining rainfall in the area. Therefore, the occurrence of bacterial leaf blight is expected to diminish, due to the shortage of rainfall, in the study area.

The novelty of this research is that it employed a mixed-methods approach, integrating a systematic review of literature with quantitative analysis of historical climate and crop data to estimate the effect of climate variability on rice yield and diseases in coastal Bangladesh. This mixed-methods strategy elevates the applicability and robustness of the findings for targeted adaptation strategy and policy planning. This study provides a holistic understanding of how climatic variables collectively affect rice production and disease occurrences. Furthermore, this study captures the intricate interrelations between climate factors and *aman* rice, grown in the coastal agro-ecological conditions.

Policy implications

The findings from our study suggest several recommendations to address the impacts of climate change on the rice crop in Bangladesh. Primarily, effective adaptation measures are needed to ensure food security for the country's ever-growing population by implementing a climate-smart approach in agriculture. The provision of timely climate information services and the breeding of climate-resilient (temperature and disease tolerant) varieties are two crucial issues that Bangladesh's policymakers must address right away (Dkhar et al. 2017). To overcome the negative impact of climate change (Mousumi et al. 2023), coastal smallholder farmers need precise, timely, reliable, and location-crop-specific weather services regarding temperature, rainfall, and humidity, in order to facilitate adaptations to safeguard rice yields and manage rice diseases (Lobell and Field 2007). Agricultural departments can contribute by providing training, for example, using the farmer field school approach, on climate change, climate variability, potential impacts on crop yields and diseases, and the application of timely climate information services for optimized agricultural operations (e.g., applying pesticides and fertilizers, irrigation, planting, harvesting, and drying). These can be achieved through the active involvement and participation of key stakeholders such as farmers, local communities, NGOs, and the private sector. In addition, social dimensions including gender roles and the needs of vulnerable groups should also be considered.

The magnitude of climate change's impacts on rice yields and diseases will differ across climatic zones. Therefore, region-based research is needed to highlight variations and guide targeted measures in the context of climate change and the cultivation of important agricultural products. In Bangladesh, national-level data may not accurately represent scenarios in the different agro-ecological zones in terms of climate change's impacts on crop yields and diseases (Lobell and Field 2007). This implies that data on rice yields and rice disease occurrence at the regional and local levels should be collected and made available over longer time periods for future research purposes.

Limitations of the study

The climate-crop analysis part of this study primarily focuses on the coastal region of Bangladesh. As a result, findings may not be fully representative of other regions of Bangladesh. Besides, the systematic literature review relies exclusively on the Scopus database. This limitation may restrict the scope of the studies captured and could contribute to an incomplete picture of the research insight. Additionally, the SLR included studies with various spatial coverage, methodologies, and timeframes, which may affect the synthesis and comparability of the findings. In our analysis, we disregarded other climatic factors, like temporal distribution and timing of rainfall, sunshine, clouds, and fog, due to lack of reliable, long-term data series.

Non-climatic factors, such as rice variety, farming practices, technological advancements, agricultural inputs, soil conditions, farmer adaptations, crop growth stage, fertilizer application, pathogens, crop resistance, and pest and disease management, have been disregarded in this study. We conducted our study from a climatic point of view, while only partially considering the impact of non-climatic factors, in terms of improved farming practices and technological advancements. Lobell et al. (2011) and Hasan and Kumar (2021) also emphasized climatic factors, while partially analyzing non-climatic factors, such as technological advancements, due to the difficulty of incorporating many non-climatic factors into a crop model, as well as the unavailability of data on non-climatic factors. Nonetheless, future studies could investigate factors related to the crop (e.g., growth stage and variety) and pathogen (pathogen type and resistance) to more accurately capture their impact on crop yields and the nuanced dynamics of disease epidemiology.

Conclusion

This study assesses the impact of climate variability on rice yields and disease occurrence in coastal Bangladesh. The trend of increasing temperature and humidity over the four decades from 1981 to 2018 suggests that there will be more hot and humid days in the future. While *aman* rice yields responded positively to initial temperature increases, the combined effect of climate trends had a negative impact on rice yields. The number of favorable days for sheath blight occurrence is increasing more rapidly than that for blast and bacterial leaf blight of rice, due to increased temperature and humidity, and all of the climate variables analyzed significantly affected these three diseases of rice. The adoption of a climate-smart agriculture strategy can sustain rice production in this coastal region. It is recommended that the state department of agriculture should provide training to both farmers and field-level extension personnel regarding perceptions and awareness of climate change, changes in climate parameters, and the impacts of these on rice yields and rice disease occurrence. It is also needed to integrate social dimensions into adaptation planning, along with gender roles, vulnerability, and stakeholder participation, to ensure inclusive and equitable adaptation strategies. The government should sustain policy support for developing climate-resilient rice varieties and climate-based disease forecasting and management systems for coastal farmers. Furthermore, collaboration among government agencies, extension services, researchers, and farming communities is crucial for overcoming implementation challenges. These will assist smallholder farmers to sustain rice production in the face of a changing climate.

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Data availability Data will be made available on request.

Declarations

Competing interests The authors declare no competing interests.

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