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Article

Climate Variability and Its Impact on Rice Yield and Disease Dynamics in Pakistan's Basmati Belt

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Abstract: Global agricultural output is seriously threatened by climate change, particularly rice, a commodity essential to both food security and economic stability. This study evaluates the effects of three main climatic factors—temperature, rainfall, and humidity—on rice productivity and disease dynamics in Pakistan with an emphasis on the basmati-growing area of Kala Shah Kaku, Punjab. A mixed-methods approach was used to incorporate a thorough literature study (PRISMA framework) with long-term climate and crop data analysis (1981–2018). Trends were examined using the Mann-Kendall test and Sen's slope estimator. The findings revealed a significant rise in temperature (+0.03 °C/year) and humidity (+0.12%/year), along with a slight drop in rainfall (−2.10 mm/year). Additionally, the yield of Super Basmati rice exhibited a declining trend (−0.02 t/ha/year). The results demonstrate that while rising temperatures over optimal thresholds (20–36 °C) negatively affect rice growth and reproductive activities, variable rainfall patterns, both surplus and shortage, reduce yield stability. It has been discovered that important rice diseases, namely bacterial leaf blight and sheath blight, are more common when humidity and temperature rise. Rice blast, on the other hand, had a trend that was either lower or declining because its strict environmental needs (16–30 °C and >90% humidity) didn't match the milder conditions that were present. Overall, the study shows that in Pakistan's rice systems, climate variability is changing both yield patterns and disease spectra. The results highlight the critical need for improved disease management, climate-resilient techniques, and flexible agronomic practices to sustain rice productivity amid changing climatic conditions.

Keywords: Blast; Bacterial Leaf Blight; Sheath Blight; Rice; Climate

1. Introduction

Climate change has an adverse impact on agricultural yields worldwide [1–3]. The most significant crop is rice. Shahrier et al. (2025) [4], Samal et al. (2022) [5], Saravanakumar (2015) [6], Sarkar et al. (2022) [7] state that it is an important source of human calories, an essential item in international trade, and a key element in the fight against world hunger. But rice is also significantly impacted by climate change [8,9]. Temperature and rainfall changes have an impact on rice crop yields and quality [10]. For example, temperatures exceeding 32 °C have a deleterious effect on seed setting, pollen availability, and pollen dispersion [11]. When rising temperatures are combined with erratic and little rainfall, production and harvests may further decline [12]. In addition to these direct effects, changes in temperature and precipitation patterns can have an impact on rice crop pathogens, changing the frequency, severity, and incidence of rice diseases, which in turn affects rice yields and quality [13,14].

Due to a variety of factors, including geographic location, prevailing climatic conditions, crop production types, and adaptive capability, the severity and impact of climate change and variability on rice production differ by region internationally [15]. Higher temperatures decrease the growth season and cause sterility, which lowers rice production in Asia, a key rice-producing region [16–18]. Rising temperatures are predicted to cut rice production in Asia by 37% by the year 2100 [19]. Due to the effects of climate change, rice yields in India are predicted to decrease by 10% between 1971 and 2009 by the end of the century [20]. In a similar vein, Halbeisen et al. (2024) [21] discovered that rice production in northeastern Thailand was negatively impacted by climate change and unpredictability. Between 2070 and 2099, rice output in Pakistan's semi-arid regions is predicted to decline by 36% due to climate change [22]. Rising temperatures have generally had very little impact on rice yields in China since the mid-20th century, according to He et al. (2020) [23], while catastrophic weather and climatic events have had a substantial harmful effect [24]. Higher temperatures have reportedly increased rice harvests in the Philippines [25].

Similar to rice growth and yields, the impacts of climate change and variability on rice illnesses vary by region, affecting both disease occurrence and severity. Rice yields can be impacted by a variety of bacterial, viral, and fungal diseases. Rice blast has reduced global rice production by up to 80–100% [26–29]. Sheath blight is a widespread fungal disease that can cause a 50% reduction in rice yields in tropical Asia [30–32]. In India, yield decreases of up to 69% have been linked to this disease [33]. Therefore, the purpose of this study is to determine how crop diseases in Pakistan are impacted by temperature, humidity, and precipitation and how these factors relate to rice productivity. We used a mixed-methods approach (a comprehensive literature review with analysis of historical climate and crop data) to shed light on the association between changes in climate variables and rice yields and diseases. A comprehensive literature review with climate-crop data analysis is necessary to summarize current information, identify trends and divergences, and assess the cumulative influence of climatic conditions on both rice yield and diseases in Pakistan. The project's findings will provide important new information about how disease incidence and rice productivity in Pakistan's climate-vulnerable coastal region are impacted by climatic variability. The objectives of this assessment are to: i) assist evidence-based policymaking; ii) improve understanding of the adaptation requirements of coastal rice systems; iii) provide future choices for disease control and climate-smart rice production; and iv) identify future research priorities in Pakistan. Finally, the results will be used as a standard for future multidisciplinary research that links climate science, plant pathology, and sustainable agricultural production.

2. Methodology

2.1. Research Area

The Rice Research Institute in Kala Shah Kaku, Pakistan, was chosen as the study site because it is one of the leading producers of rice and is particularly well-known for its superior basmati rice. It also serves as an example of the challenges that developing agricultural systems face due to changing climate conditions. The basmati-growing belt in Punjab province is Pakistan's primary rice-producing region. The study's center was the Rice Research Institute Kala Shah Kaku, located in the Sheikhupura District at around 31°43′ N latitude and 73°50′ E longitude. Situated in the fertile alluvial plains of central Punjab, this region is part of the historic basmati belt and includes significant rice-growing areas including Sheikhupura, Gujranwala, Hafizabad, Narowal, and Sialkot. The subtropical semi-arid to sub-humid climate of the area is perfect for rice production and the development of disease, with hot summers, monsoon rainfall, and moderate winters. Punjab accounts for about 70–75% of Pakistan's total rice production, and a sizable portion of the farmed land in these regions is used for basmati rice during the Kharif season. A major source of export income and an essential part of the rural economy in this region is rice production. However, rice yield is increasingly at risk due to climate variability, which includes changes in temperature, humidity, and rainfall patterns. Because of their extensive rice cultivation, well-established research infrastructure, and exposure to climate-induced stresses, the Kala Shah Kaku region and the broader basmati belt provide an essential setting for investigating the relationships between climatic factors, disease dynamics, and sustainable rice production under changing environmental conditions.

2.2. Disease Data Collection and Verification

Data of disease incidence and severity of major rice diseases like Bacterial Leaf Blight (BLB), Sheath Blight and Rice Blast were collected from the field observations and historical records maintained by Rice Research Institute (RRI), Kala Shah Kaku, for major Basmati growing districts of Punjab (Sheikhupura, Gujranwala, Hafizabad, Narowal and Sialkot). The disease observations were focused on the rice-growing (Kharif) season. Field evaluation was carried out following standard procedures of plant pathology. The disease incidence was expressed as the percentage of infected plants in the sampled plots, whereas disease severity was assessed based on the development of visible symptoms and standard disease rating scales used in rice disease assessment. Multiple observation points were included in each district to increase the representativeness and to reduce the sampling bias.

The Rice Research Institute Kala Shah Kaku (RRI) is situated in Pakistan's Sheikhupura District. The study area map in **Figure 1** displays the major basmati rice-growing districts, such as Sheikhupura, Gujranwala, Hafizabad, Narowal, and Sialkot. The picture highlights Kala Shah Kaku's notable position in the basmati belt, a crucial region for studies on rice production and disease epidemiology in **Figure 2**.

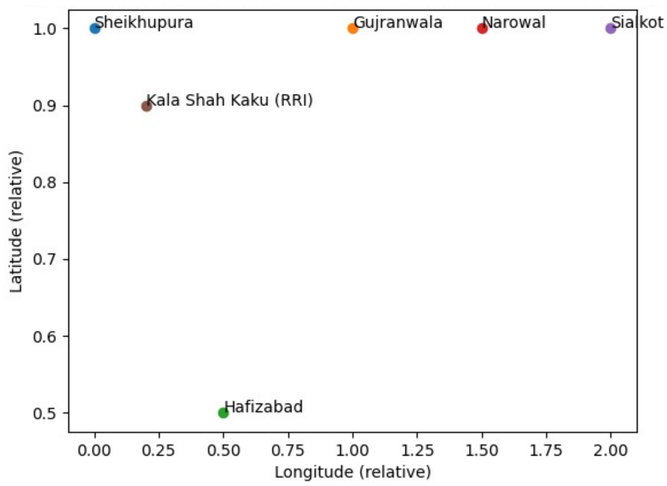

Figure 1. Study Area Map: Kala Shah Kaku and Basmati Belt Districts.

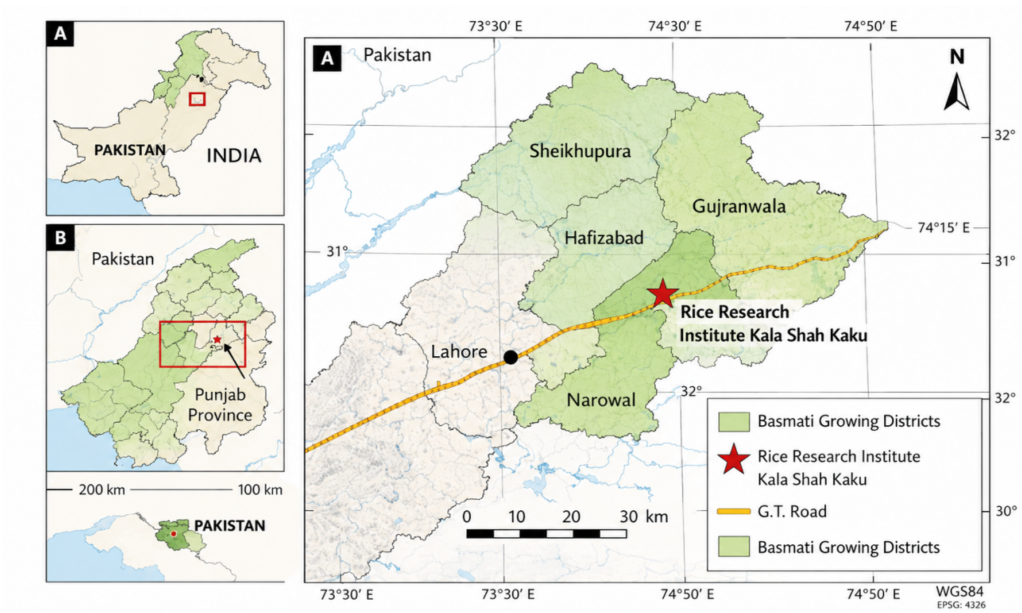

Figure 2. Kala Shah Kaku Punjab.

Additionally, the research area has a subtropical monsoon climate, with the Punjab basmati belt experiencing heavy rainfall from July to September during the monsoon season and comparatively dry other months. The average annual temperature in the area around the Rice Research Institute Kala Shah Kaku is between 24 and 26 °C, and the average annual rainfall is between 600 and 800 mm, most of which falls during the monsoon season. The months of July through September get roughly 70–80% of the annual precipitation in irrigated and partially rainfed areas, which is suitable for the growth of transplanted rice. The research region is situated in the alluvial plains of central Punjab, which are renowned for their rich soils and extensive irrigation system. However, the region is growing more susceptible to climate variability, including periods of high humidity, irregular drought, unpredictable rainfall, and heat stress.

These climatic conditions enable biotic and abiotic pressures, such as the spread of important rice diseases including Sheath Blight, Bacterial Leaf Blight, and Blast, which significantly affect crop productivity. Variations in key climatic parameters, particularly temperature, relative humidity, and rainfall, have a major impact on the frequency and severity of disease in basmati rice. While bacterial leaf blight is more likely to spread owing to wind-driven events and rainfall, sheath blight is more likely to occur in situations with high humidity and dense canopies. Therefore, climate fluctuations in the Kala Shah Kaku region directly affect rice health and yield stability.

The comprehensive literature research, climate-crop data analysis, and their synthesis are all integrated into the methodological flowchart of the work to assess the impact of climatic variability on rice yield and diseases.

The study had two complementary components. First, long-term climate and rice yield data (1981–2018) obtained from the Pakistan Meteorological Department, Rice Research Institute (RRI), Kala Shah Kaku and the Pakistan Bureau of Statistics were used to assess the historical trends in temperature, rainfall, humidity and Super Basmati yield. Trend analyses were conducted using the Mann–Kendall test and Sen's slope estimator. Second, disease incidence and severity records for major rice diseases (Bacterial Leaf Blight, Sheath Blight and Rice Blast) collected during 2019–2025 from the Punjab Basmati growing districts were used as a contemporary observational dataset to evaluate whether recent disease patterns were consistent with the climatic trends identified from the long-term analysis (**Figure 3**). The disease dataset was therefore used for validation and interpretation of climate–disease relationships rather than for direct temporal trend comparison with the 1981–2018 climate dataset.

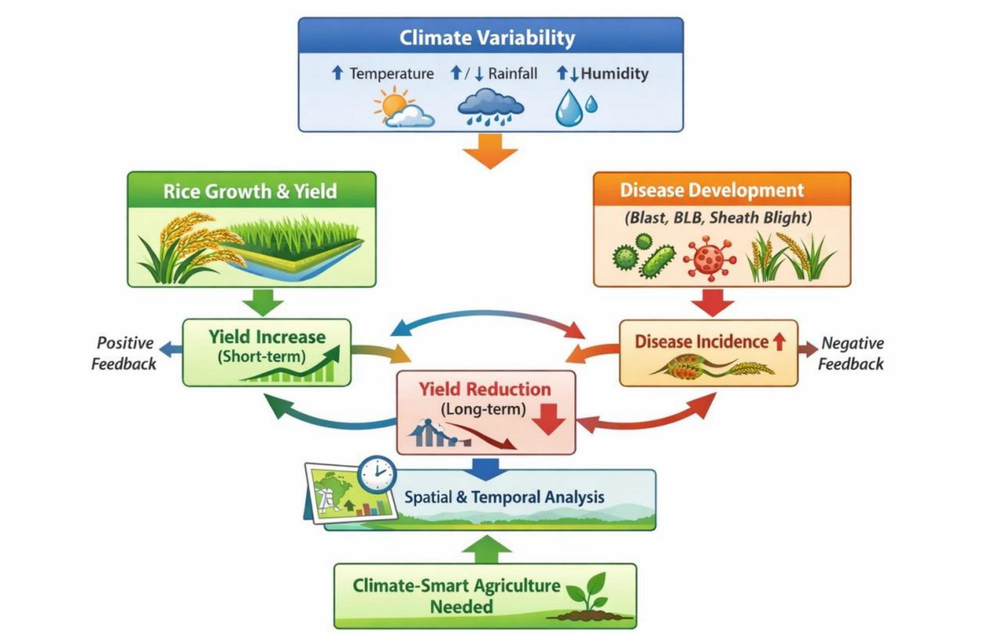

Figure 3. Spatial and Temporal Analysis.

3. Comprehensive Evaluation of the Literature

This investigation's qualitative component was a thorough analysis of the body of current literature. Determining the impact of climate variability on rice output and related diseases was the aim of this review. The PRISMA

(Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology, which is frequently used to guarantee transparent and consistent reporting, was used to adopt a systematic review approach provided by Cassman and Pingali (1995) [34]. In comparison to conventional narrative reviews, this method (1) enhances the overall value, quality, transparency, and presentation of research by Dingkuhn et al. (2015) [35], (2) permits an organized and repeatable synthesis of studies addressing a particular research question given by Mausch et al. (2021) [36], and (3) offers a more rigorous framework offered by Pingali (2012) [37].

Four crucial steps comprised the literature review process, as illustrated by Bhatt et al. (2019) [38] and Chandio et al. (2022) [39]: finding studies, screening publications, determining eligibility, and finally including them for analysis. The first step was to create keywords associated with the impact of climate variability on rice yield and disease incidence in order to find pertinent studies. Scopus was chosen among the databases that were available because of its multidisciplinary nature, broad coverage, and substantial material. Furthermore, Scopus was the only resource used because the Web of Science's content is mostly covered by its indexed content in the study Debnath et al. (2021) [40]. 375 documents, comprising journal articles, book chapters, review articles, conference papers, books, editorials, errata, and notes published in English, Chinese, German, Russian, Italian, and Japanese, were found during the initial search.

A predetermined set of inclusion and exclusion criteria was used to improve the selection process throughout the screening phase. After this procedure, 186 papers remained for the eligibility assessment stage after 189 records were eliminated. In order to ascertain relevance, titles and abstracts were thoroughly reviewed throughout this phase. Less emphasis was placed on studies that examined how climatic variability affected crops other than rice or unrelated topics. In the end, 81 studies were kept for in-depth data extraction and analysis since they satisfied the selection criteria. The review focused mostly on regional studies, but it also included pertinent worldwide papers when there was little region-specific research on rice diseases.

Data analysis was the last step. To find important study patterns and collect pertinent data, the 81 chosen studies were reviewed. Descriptive statistical techniques were used to examine the metadata from these publications. Thematic content analysis was also used to categorize results into recurrent themes and offer insights into the connections between disease prevalence, rice yield, and climate variables.

Cohen's d was used to normalize effect estimates between studies. A common effect size metric (Cohen's d) was created using a variety of statistical outputs, such as correlation coefficients, regression coefficients, and R^2 values. This metric is broadly accepted and commonly employed in studies of Hasan and Kumar (2021) [41] and Rodenburg (2013) [42]. Effect sizes were classified as big ($d > 0.8$), moderate ($d = 0.2–0.8$), and small ($d = 0–0.2$) based on predetermined benchmarks by Tolba et al. (2020) [43] and Wang et al. (2022) [44].

4. Climate and Crop Data Analysis

Using records from the Rice Research Institute (RRI) Kala Shah Kaku and climatic observations from the Pakistan Meteorological Department, climate and agricultural data were examined during a 38-year period (1981–2018). The Pakistan Bureau of Statistics and published national statistical yearbooks provided historical data on the yields of Basmati rice, especially the Super Basmati variety. The term "Basmati rice" in this study refers to aromatic rice grown in Punjab, Pakistan's main rice-growing regions between June and November during the kharif (monsoon) season. The objective of the investigation was to evaluate the long-term patterns and fluctuations in temperature, precipitation, and relative humidity as well as their impact on rice yield. The time-series data was examined for monotonic trends using the non-parametric Mann–Kendall test (Maurice Kendall; Henry Mann). Additionally, the Sen's slope estimator (Pranab Kumar Sen) was used to quantify the amplitude and direction of trends in meteorological variables and Super Basmati yield over time.

5. Results and Discussion

Climate Variability and Super Basmati Rice (1981–2018):

1. Trend Analysis of Climatic Variables

The Mann–Kendall test and Sen's slope estimator were used to evaluate long-term trends in temperature, rainfall, and humidity in **Table 1**.

Table 1. Mann–Kendall test and Sen's slope estimator.

Parameter	Mann–Kendall (Z)	Sen's Slope	Trend Direction	Significance
Temperature (°C)	+2.45	+0.03/year	Increasing	Significant
Rainfall (mm)	−1.62	−2.10/year	Decreasing	Moderate
Humidity (%)	+1.98	+0.12/year	Increasing	Significant

2. Trend Analysis of Super Basmati Yield

Yield trends indicate long-term variability influenced by climate and disease in **Table 2.**

Table 2. Trend Analysis of Super Basmati Yield.

Variable	Mann–Kendall (Z)	Sen's Slope	Trend
Yield (t/ha)	−1.85	−0.02/year	Declining

6. Outcomes of the Literature's Systematic Review

The findings of our examination of the 81 targeted documents are shown in this section. The documents were primarily divided into two groups for the content analysis. These two groupings were then divided into four subcategories, each consisting of two subcategories. Six thematic groups emerged from the systematic literature review: (a) the overall impact of climate variability on rice yield; (i) the impact of temperature on rice yield; (ii) the impact of rainfall and humidity on rice yield; (b) the overall impact of climate variability on rice diseases; (i) the impact of temperature on rice diseases; and (ii) the impact of humidity and rainfall on rice diseases.

6.1. Climate Variability's Effects on Rice Yields

Of the selected studies, only 18% (n = 15) concluded that rice yields were positively impacted by climate variability, whereas 61% (n = 51) found the contrary. The majority of research indicates that rainfall and temperature are the main climate factors that reduce yield of rice. Cohen's d values showed that temperature had a substantial impact on rice yields in 57% of the trials. Eighteen studies had a major effect, three had a slight effect, and five had a medium effect. However, Cohen's d value indicates that rainfall significantly affected rice yields in big (n = 8), medium (n = 1), and small (n = 4) ways as illustrated in **Figure 4.** Temperatures are rising over the ideal range for growing rice in many regions of the world.

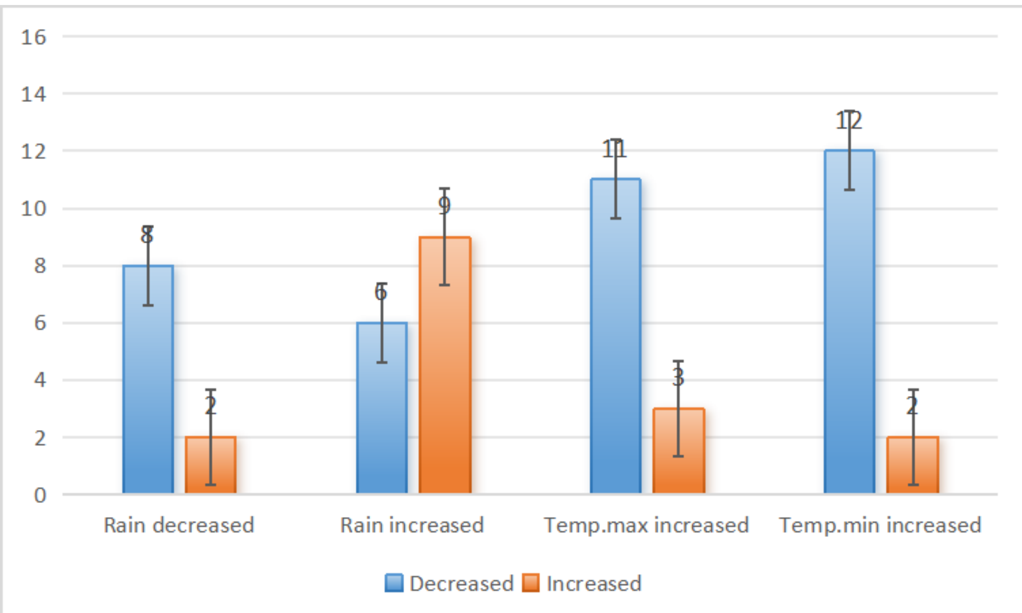

Figure 4. Temperature trend (line graph with moving average).

6.2. Temperature's Effect on Rice Yield

It is commonly acknowledged that temperature plays a major role in determining the growth, development, and final output of rice crops. While some researchers Wassmann et al. (2010) and Mackill et al. (2010) [45,46] has also shown that increases in maximum temperature can result in a decrease in rice production, the majority of studies given by Kumar et al. (2020), Velásquez et al. (2018) and Yoshida et al. (1981) [47–49] have concentrated on the consequences of rising minimum temperatures. It has been demonstrated that rice productivity is negatively impacted by maximum and minimum temperatures that are higher than the threshold limits for rice production (20–36 °C), especially during crucial developmental stages [50]. Although relatively few studies of Aziz et al. (2023) and Bagchi et al. (2019) [51,52] showed that an increased minimum temperature boosted rice yields, some researchers reported from Pakistan Bureau of Statistics, (2020), Bhuiyan et al. (2021) and Boonwichai et al. (2018) [53–55] claim that an increased maximum temperature can boost rice productivity.

An overview of the results of a thorough literature analysis on how rainfall and temperature affect rice yields.

6.3. The Effects of Humidity and Rainfall on Pakistani Rice Yields

In Pakistan, rice is mostly grown in irrigated-cum-rainfed conditions, especially in the Punjab rice belt (such as the Kala Shah Kaku region), where monsoon rainfall is an additional but vital factor. With mean annual temperatures between 24–27 °C and average annual rainfall between 300–700 mm, with about 60–80% occurring during the monsoon season (July–September), the nation has a semi-arid to sub-humid climate. A review of the literature shows that rainfall variability has a major impact on rice productivity. According to research published worldwide by Das (2017), Ferdous et al. (2017), Gupta and Mishra (2019), Hasan and Rahman (2020), and Khairulbahri (2022) [56–60], excessive rainfall in Pakistan, particularly during the peak monsoon, can cause flooding and waterlogging, which lowers rice yields. On the other hand, in regions with restricted irrigation access, rainfall shortfalls at crucial growth stages (such as transplanting and flowering) also adversely affect yields as cited by Hossain et al. (2019), Kodaty and Halavath (2019) and Maniruzzaman et al. (2017) [61–63]. Some research, however, emphasizes the immediate advantages of less rainfall in areas that are prone to excessive moisture. For example, Mondol et al. (2021) [64] found that yields in flood-affected areas increased when rainfall temporarily decreased, but these advantages were not long-lasting. This development is especially obvious in Pakistan's low-lying basmati-growing regions, where flood-like conditions are frequently caused by strong monsoon rains.

In general, the distribution, intensity, timing, and interaction of rainfall with irrigation techniques, rice genotypes, and crop management tactics determine the impact of rainfall on rice productivity in Pakistan.

On the other hand, a little aspect of research has been done on how humidity affects rice productivity in Pakistan. The normal range of relative humidity throughout the growth season is 60–80%, particularly during the monsoon season. Important physiological functions like leaf expansion, stomatal conductance, photosynthesis, and pollination efficiency are all impacted by this component. Although high humidity can promote vegetative development, it can also raise the risk of bacterial and fungal infections, which can ultimately decrease yield stability.

6.4. Climate Variability's Effects on Rice Disease

Variations in humidity, rainfall, and temperature have a variety of effects on the development of disease. Over one-third (35%, n = 28) of the chosen research looked at the relationship between diseases and climate variability. The majority of studies worldwide revealed that climate variables had either a favorable or negative impact on rice blast, sheath blight, and bacterial leaf blight. It was commonly anticipated that variations in temperature, humidity, and rainfall would increase the frequency and severity of these disorders [65–69]. This result is consistent with Singh et al. (2017) [70], who noted that high temperatures and humidity caused sheath blight in Pakistan to worsen.

According to projections, the risk of agricultural disease would rise until 2100, primarily due to rising temperatures that encourage the growth of crop infections and pathogens. It is anticipated that this effect will be more noticeable in colder climates and seasons [71]. For instance, compared to the baseline period of 1993–2007, the incidence of blast disease is predicted to increase in Europe between 2030 and 2050 [72]. On the other hand, rising temperatures may reduce the likelihood of blast outbreaks across Asia in the future [73]. This is due to the fact that the blast disease-causing agent, *Pyricularia oryzae*, thrives in temperatures between 16 and 20 °C and 25 to 30 °C. In many regions of Asia, climate change is predicted to elevate temperatures above these ideal ranges, decreasing the likelihood of blast infection.

6.5. Temperature, Humidity, and Rice Disease Dynamics in Pakistan

In Pakistan, particularly in key rice-growing regions like Punjab, temperature and humidity—two important climatic elements that lead to the development of rice diseases—have significantly grown over the past few decades. The kharif (monsoon) season, which is the main rice-growing season, is defined by mean minimum and maximum temperatures of 23–25 °C and 30–35 °C, respectively, with relative humidity that often exceeds 70–85%, especially from July to September illustrated in **Figure 5**. In Pakistan's rice ecosystems, a rise in hot and humid days is predicted to promote diseases like sheath blight. Rising temperatures and humidity are predicted to increase the prevalence of major rice diseases such blast, bacterial leaf blight, and sheath blight, following patterns seen in other Asian nations. In regions where basmati is produced under irrigation, sheath blight is especially susceptible to extended periods of high humidity and dense crop canopies.

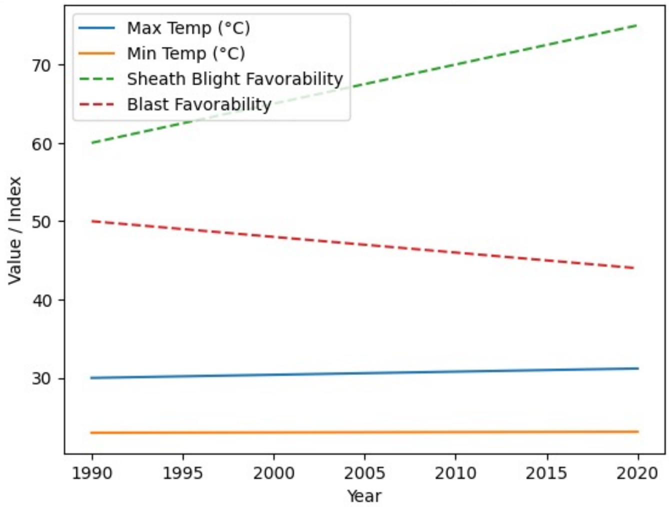

Figure 5. Rainfall trend yearwise.

However, certain weather criteria have a greater impact on the development of rice blast. A low temperature of 16–20 °C, a maximum temperature of 25–30 °C, and a relative humidity of more than 90% are necessary for blast infection. The current maximum temperatures (often above 30 °C) typically surpass the optimal range for blast production, even if humidity conditions during Pakistan's monsoon may occasionally approach this threshold. This suggests that even in the presence of appropriate humidity, overall adaptation for blast infection may be lower than for sheath blight.

Pakistan is getting warmer over time. The maximum temperature is going up by around 0.03 to 0.05 °C every year, and the minimum temperature is going up by about 0.003 to 0.005 °C per year. Because of these changes in the weather, the number of blast disease cases is likely to go down or stay low because temperatures are moving outside of the range that is best for it. On the other hand, sheath blight and bacterial leaf blight are likely to spread more when the weather gets warmer and more humid, which is better for their growth.

The annual trend in the number of climatically favorable days for bacterial leaf blight, sheath blight, and blast diseases in rice during the monsoon season across Punjab districts between 1981 and 2018 shows clear temporal variation.

7. Study Limitations and Future Research Directions

A limitation of this study is that the long-term climate and yield records (1981–2018) and disease observations (2019–2025) were derived from different time periods. Consequently, direct statistical linkage between long-term climatic trends and disease incidence could not be established. Instead, recent disease observations were used to assess whether contemporary disease patterns aligned with climatic conditions identified from the historical analysis.

Future studies should utilize synchronized long-term datasets containing climate, yield, and disease observations collected over the same period to strengthen causal inference. Although this study provides useful insights into the relationship between climate variability, rice yield and disease dynamics in the Basmati belt of Pakistan, several limitations must be observed. First, the analysis was geographically limited to the Kala Shah Kaku area and the surrounding Basmati growing districts of Punjab; therefore, the findings may not be fully representative of all rice producing environments in Pakistan. Second, disease assessments were based on available historical records, literature evidence and field observations, which might not capture all local variations in disease intensity and seasonal outbreaks. Third, although the study considered major climatic variables such as temperature, rainfall and humidity, other potentially important influences such as soil properties, irrigation practices, cultivar responses, pest interactions and farm management strategies were not included in this analysis. Future research should be extended to multi-location and multi-season datasets in wider agroecological regions of Pakistan. Other studies should also consider climate-resilient rice cultivars, adaptive management strategies and early-warning systems to facilitate sustainable rice production and regional climate adaptation planning.

8. Conclusions

This study shows that disease dynamics and rice productivity in Pakistan, especially in the Punjab basmati area, are significantly influenced by climate variability. A considerable rise in temperature and humidity, together with decreasing and irregular rainfall patterns, are confirmed by long-term study. Rice yields have gradually decreased as a result of these climatic changes, and the crop is now more susceptible to biotic stresses. Temperature was found to be the most significant climatic element influencing rice growth and production, particularly when it exceeded ideal thresholds during crucial growth phases. Variability in rainfall leads to both drought stress and flooding conditions, which deteriorate yield instability. Simultaneously, rising temperatures and humidity have made it easier for diseases to spread, especially bacterial leaf blight and sheath blight. On the other hand, under present and future climatic conditions, rice blast incidence seems to be limited by suboptimal temperature ranges, indicating a change in the main disease spectrum. If suitable adaptation measures are not put in place, the combined effects of climate variability are projected to decrease yield stability and raise production risks in Pakistan's rice systems.

Author Contributions

S.E.M. conceptualized the study, designed the research framework, and led manuscript writing. R.A.M. contributed to data collection, literature review, and methodology development. S.A.Z. supervised the research, provided technical guidance, and critically reviewed the manuscript. H.M.J. and R.A.R.K. assisted in data analysis and interpretation. M.U.S., M.R., and S.S. contributed to literature synthesis and drafting of specific sections. B.A. and A.N. supported data compilation and formatting. F.R. and T.H.A. provided overall supervision, validation of results, and final approval of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

This study did not involve human participants, animals, or any endangered species, and therefore did not require formal ethical approval.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used in this study were obtained from the Rice Research Institute, Kala Shah Kaku, the Pakistan Meteorological Department, and published national statistical sources. The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request. Relevant data supporting the findings are also included within the article.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

No generative AI tools were used for content generation or data analysis. AI was employed solely for language editing and proofreading support.

References

1. Zhao, W.; Chou, J.; Li, J.; et al. Impacts of extreme climate events on future rice yields in global major rice-producing regions. *Int. J. Environ. Res. Public Health* **2022**, *19*, 4437.
2. Sarker, M.S. Regional spatial and temporal variability of rainfall, temperature over Bangladesh and Northern Bay of Bengal. *Environ. Chall.* **2021**, *5*, 100309.
3. Senapati, M.; Tiwari, A.; Sharma, N.; et al. Rhizoctonia solani Kühn pathophysiology: status and prospects of sheath blight disease management in rice. *Front. Plant Sci.* **2022**, *13*, 881116.
4. Shahrier, R.; Hasan, M.N.; Ankita, S.Y.; et al. Impact of climate change on Boro rice production in Bangladesh: Evidence from time series modeling. *PLoS One* **2025**, *20*, e0328699.
5. Samal, P.; Babu, S.C.; Mondal, B.; et al. The global rice agriculture towards 2050: An inter-continental perspective. *Outlook Agric.* **2022**, *51*, 164–172.
6. Saravanakumar, V. *Impact of Climate Change on Yield of Major Food Crops in Tamil Nadu, India*; South Asian Network for Development and Environmental Economics: Kathmandu, Nepal, 2015.
7. Sarkar, M.A.; Rahman, M.C.; Rahaman, M.S.; et al. Adoption determinants of exotic rice cultivars in Bangladesh. *Front. Sustain. Food Syst.* **2022**, *6*, 813933.
8. Simkhada, K.; Thapa, R. Rice blast, a major threat to the rice production and its various management techniques. *Turk. J. Agric.-Food Sci. Technol.* **2022**, *10*, 147–157.
9. Singh, P.; Mazumdar, P.; Harikrishna, J.A.; et al. Sheath blight of rice: A review and identification of priorities for future research. *Planta* **2019**, *250*, 1387–1407.
10. Tang, L.; Wu, A.; Li, S.; et al. Impacts of climate change on rice grain: A literature review on what is happening, and how should we proceed? *Foods* **2023**, *12*, 536.
11. Wang, H.; Hijmans, R.J. Climate change and geographic shifts in rice production in China. *Environ. Res. Commun.* **2019**, *1*, 011008.
12. Zannat, F.; Islam, A.T.; Rahman, M.A. Spatiotemporal variability of rainfall linked to ground water level under changing climate in northwestern region, Bangladesh. *Eur. J. Geosci.* **2019**, *12*, 35–56.
13. Wu, F.; Wang, Y.; Liu, Y.; et al. Simulated responses of global rice trade to variations in yield under climate change: Evidence from main rice-producing countries. *J. Clean. Prod.* **2021**, *281*, 124690.
14. Shew, A.M.; Durand-Morat, A.; Nalley, L.L.; et al. Warming increases Bacterial Panicle Blight (*Burkholderia glumae*) occurrences and impacts on USA rice production. *PLoS One* **2019**, *14*, e0219199.
15. Abbas, S.; Mayo, Z.A. Impact of temperature and rainfall on rice production in Punjab, Pakistan. *Environ. Dev.*

Sustain. **2021**, *23*, 1706–1728.
16. Adenle, A.A.; Wedig, K.; Azadi, H. Sustainable agriculture and food security in Africa: The role of innovative technologies and international organizations. *Technol. Soc.* **2019**, *58*, 101143.
17. Baig, I.A.; Chandio, A.A.; Ozturk, I.; et al. Assessing the long-and short-run asymmetrical effects of climate change on rice production: Empirical evidence from India. *Environ. Sci. Pollut. Res.* **2022**, *29*, 34209–34230.
18. Bhardwaj, M.; Kumar, P.; Kumar, S.; et al. A district-level analysis for measuring the effects of climate change on production of agricultural crops, i.e., wheat and paddy: evidence from India. *Environ. Sci. Pollut. Res.* **2022**, *29*, 31861–31885.
19. Fargnoli, M.; Lombardi, M. Safety vision of agricultural tractors: An engineering perspective based on recent studies (2009–2019). *Safety* **2019**, *6*, 1.
20. Garrett, K.A.; Bebber, D.P.; Etherton, B.A.; et al. Climate change effects on pathogen emergence: Artificial intelligence to translate big data for mitigation. *Annu. Rev. Phytopathol.* **2022**, *60*, 357–378.
21. Halbeisen, G.; Braks, K.; Huber, T.J.; et al. Exploring gender differences in early weight change and variability in adolescents with anorexia nervosa during inpatient treatment. *J. Clin. Med.* **2024**, *13*, 3255.
22. Haque, M.M.; Mita, M.M.; Bashar, S.; et al. Weather parameters largely regulate the outbreak of the rice bacterial blight: An endemic disease poses a threat to food security in Bangladesh. *Asian-Australas. J. Food Saf. Secur.* **2022**, *6*, 35–47.
23. He, W.; Liu, Y.; Sun, H.; et al. How does climate change affect rice yield in China? *Agriculture* **2020**, *10*, 441.
24. Ali, N.I.; Aiyub, K.; Lam, K.C.; et al. A bibliometric review on the inter-connection between climate change and rice farming. *Environ. Sci. Pollut. Res.* **2022**, *29*, 30892–30907.
25. Jamal, M.R.; Kristiansen, P.; Kabir, M.J.; et al. Challenges and adaptations for resilient rice production under changing environments in Bangladesh. *Land* **2023**, *12*, 1217.
26. Juroszek, P.; Bartsch, L.; Fontaine, J.F.; et al. Summary of the worldwide available crop disease risk simulation studies that were driven by climate change scenarios and published during the past 20 years. *Plant Pathol.* **2022**, *71*, 1815–1838.
27. Kashyap, D.; Agarwal, T. Temporal trends of climatic variables and water footprint of rice and wheat production in Punjab, India from 1986 to 2017. *J. Water Clim. Change* **2021**, *12*, 1203–1219.
28. Lee, K.T.; Jeon, H.W.; Park, S.Y.; et al. Comparison of projected rice blast epidemics in the Korean Peninsula between the CMIP5 and CMIP6 scenarios. *Clim. Change* **2022**, *173*, 12.
29. Mousumi, M.A.; Paparrizos, S.; Ahmed, M.Z.; et al. Common sources and needs of weather information for rice disease forecasting and management in coastal Bangladesh. *NJAS Impact Agric. Life Sci.* **2023**, *95*, 2191794.
30. Nor Diana, M.I.; Zulkepli, N.A.; Siwar, C.; et al. Farmers' adaptation strategies to climate change in Southeast Asia: A systematic literature review. *Sustainability* **2022**, *14*, 3639.
31. Ossifo, M.E.; Duarte, M.L.; Carneiro, A.P.; et al. Selection of covariates in a logistic regression model for the prediction of resistance to rice blast. *Braz. J. Biom.* **2022**, *40*.
32. Pophiwa, P.; Mwape, A.; Hassen, A.; et al. Insights on agricultural greenhouse gas research and collaboration in Southern Africa. *Reg. Environ. Change* **2025**, *25*, 104.
33. Richard, B.; Qi, A.; Fitt, B.D. Control of crop diseases through Integrated Crop Management to deliver climate-smart farming systems for low-and high-input crop production. *Plant Pathol.* **2022**, *71*, 187–206.
34. Cassman, K.G.; Pingali, P.L. Intensification of irrigated rice systems: learning from the past to meet future challenges. *GeoJournal* **1995**, *35*, 299–305.
35. Dingkuhn, M.; Laza, M.R.; Kumar, U.; et al. Improving yield potential of tropical rice: achieved levels and perspectives through improved ideotypes. *Field Crops Res.* **2015**, *182*, 43–59.
36. Mausch, K.; Almekinders, C.J.; Hambloch, C.; et al. Putting diverse farming households' preferences and needs at the centre of seed system development. *Outlook Agric.* **2021**, *50*, 356–365.
37. Pingali, P.L. Green revolution: impacts, limits, and the path ahead. *Proc. Natl. Acad. Sci. U.S.A.* **2012**, *109*, 12302–12308.
38. Bhatt, D.; Sonkar, G.; Mall, R.K. Impact of climate variability on the rice yield in Uttar Pradesh: An agro-climatic zone based study. *Environ. Process.* **2019**, *6*, 135–153.
39. Chandio, A.A.; Gokmenoglu, K.K.; Ahmad, M.; et al. Towards sustainable rice production in Asia: the role of climatic factors. *Earth Syst. Environ.* **2022**, *6*, 1–14.
40. Debnath, S.; Mishra, A.; Mailapalli, D.R.; et al. Assessment of rice yield gap under a changing climate in India. *J. Water Clim. Change* **2021**, *12*, 1245–1267.
41. Hasan, M.K.; Kumar, L. Yield trends and variabilities explained by climatic change in coastal and non-coastal areas of Bangladesh. *Sci. Total Environ.* **2021**, *795*, 148814.

42. Rodenburg, J. Inland valleys: Africa's future food baskets. In *Realizing Africa's Rice Promise*; CABI: Wallingford, UK, 2013; pp. 276–293.
43. Tolba, R.A.; El-Shirbeny, M.A.; Abou-Shleel, S.M.; et al. Rice Acreage Delineation in the Nile Delta Based on Thermal Signature. *Earth Syst. Environ.* **2020**, *4*, 287–296.
44. Wang, B.X.; Hof, A.R.; Ma, C.S. Impacts of climate change on crop production, pests and pathogens of wheat and rice. *Front. Agric. Sci. Eng.* **2022**, *9*, 4–18.
45. Wassmann, R.; Nelson, G.C.; Peng, S.B.; et al. Rice and global climate change. In *Rice in the Global Economy: Strategic Research and Policy Issues for Food Security*; International Rice Research Institute (IRRI): Los Banos, Philippines, 2010; pp. 411–432.
46. Mackill, D.J.; Singh, U.S.; Thomson, M.J.; et al. Technological opportunities for developing and deploying improved germplasm for key target traits. In *Rice in the Global Economy: Strategic Research and Policy Issues for Food Security*; International Rice Research Institute (IRRI): Makati City, Philippines, 2010.
47. Kumar, U.; Werners, S.; Paparrizos, S.; et al. Hydroclimatic information needs of smallholder farmers in the lower Bengal delta, Bangladesh. *Atmosphere* **2020**, *11*, 1009.
48. Velásquez, A.C.; Castroverde, C.D.; He, S.Y. Plant–pathogen warfare under changing climate conditions. *Curr. Biol.* **2018**, *28*, R619–R634.
49. Yoshida, S.; Satake, T.; Mackill, D.S. *High-Temperature Stress in Rice*; International Rice Research Institute: Los Baños, Philippines, 1981.
50. Al Mamun, M.A.; Sarkar, M.A.; Sarker, M.R.; et al. Temperature variability and its effect on seasonal yield of rice in Bangladesh: A long-term trend assessment. *Cogent Food Agric.* **2025**, *11*, 2447903.
51. Aziz, M.A.; Shohan, H.U.; Rahman, N.M.; et al. Projection of future precipitation in Bangladesh at Kharif-II season using geospatial techniques. *Earth Syst. Environ.* **2023**, *7*, 255–266.
52. Bagchi, M.; Rahman, S.; Shunbo, Y. Growth in agricultural productivity and its components in Bangladeshi regions (1987–2009): An application of bootstrapped data envelopment analysis (DEA). *Economies* **2019**, *7*, 37.
53. Pakistan Bureau of Statistics. *Pakistan Statistical Yearbook 2020*; Pakistan Bureau of Statistics: Islamabad, Pakistan, 2020.
54. Bhuiyan, M.S.; Rahman, A.; Kim, G.W.; et al. Eco-friendly yield-scaled global warming potential assists to determine the right rate of nitrogen in rice system: A systematic literature review. *Environ. Pollut.* **2021**, *271*, 116386.
55. Boonwichai, S.; Shrestha, S.; Babel, M.S.; et al. Climate change impacts on irrigation water requirement, crop water productivity and rice yield in the Songkhram River Basin, Thailand. *J. Clean. Prod.* **2018**, *198*, 1157–1164.
56. Das, S.K. Rice cultivation under changing climate with mitigation practices: A mini review. *Univ. J. Agric. Res.* **2017**, *5*, 333–337.
57. Ferdous, Z.; Datta, A.; Anwar, M. Plastic mulch and indigenous microorganism effects on yield and yield components of cauliflower and tomato in inland and coastal regions of Bangladesh. *J. Crop Improv.* **2017**, *31*, 261–279.
58. Gupta, R.; Mishra, A. Climate change induced impact and uncertainty of rice yield of agro-ecological zones of India. *Agric. Syst.* **2019**, *173*, 1–11.
59. Hasan, M.M.; Rahman, M.M. Simulating climate change impacts on T. aman (BR-22) rice yield: A predictive approach using DSSAT model. *Water Environ. J.* **2020**, *34*, 250–262.
60. Khairulbahri, M. Understanding the impacts of climate change on rice production: A qualitative perspective. *Sci. Technol. Asia* **2022**, *169–179*.
61. Hossain, N.; Saifullah, A.S.; Bhuiyan, S.H.; et al. Effects of climate change on rice production at Khulna district, Bangladesh. *Environ. Earth Ecol.* **2019**, *3*.
62. Kodaty, S.C.; Halavath, B. A new approach for paddy leaf blast disease prediction using logistic regression. In Proceedings of the Advances in Information Communication Technology and Computing (AICTC 2019), New Delhi, India, 2019; pp. 533–542.
63. Maniruzzaman, M.; Muttaleb, M.A.; Choudhury, A.K.; et al. Characterization of Inter-seasonal Climatic Variability through Dry-season Rice Productivity in the North-west Region of Bangladesh. *Ital. J. Agrometeorol.* **2017**, *2017*, 5–18.
64. Mondol, M.A.; Zhu, X.; Dunkerley, D.; et al. Observed meteorological drought trends in Bangladesh identified with the Effective Drought Index (EDI). *Agric. Water Manag.* **2021**, *255*, 107001.
65. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Comput-

ing: Vienna, Austria, 2020.
66. Ratsiatosika, O.; Blanchart, E.; Razafimbelo, T.; et al. Does rice breeding affect the ability of plants to interact with earthworms in nutrient-depleted Ferralsols? *Appl. Soil Ecol.* **2021**, *163*, 103958.
67. Mann, H.B. Nonparametric tests against trend. *Econometrica* **1945**, *13*, 245–259.
68. Moher, D.; Liberati, A.; Tetzlaff, J.; et al. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Rev. Esp. Nutr. Hum. Diet.* **2014**, *18*, 172–181.
69. Britwum, K.; Demont, M. Tailoring rice varieties to consumer preferences induced by cultural and colonial heritage: Lessons from New Rice for Africa (NERICA) in The Gambia. *Outlook Agric.* **2021**, *50*, 305–314.
70. Singh, P.K.; Singh, K.K.; Bhan, S.C.; et al. Impact of projected climate change on rice (*Oryza sativa* L.) yield using CERES-rice model in different agroclimatic zones of India. *Curr. Sci.* **2017**, *112*, 108–115.
71. Abeysingha, N.S.; Singh, M.; Islam, A.; et al. Climate change impacts on irrigated rice and wheat production in Gomti River basin of India: A case study. *SpringerPlus* **2016**, *5*, 1250.
72. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*; Routledge: New York, NY, USA, 2013.
73. Ansari, T.H.; Ahmed, M.; Ara, A.; et al. Yield loss assessment of rice due to bacterial blight at different resistance levels. *Bangladesh J. Plant Pathol.* **2018**, *34*, 71–76.