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Investigating the Impact of Climate Change Impacts on Direct-seeded Rice Production in Middle Gujarat Using the InfoCrop-rice Model

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Rice (*Oryza sativa* L.) is a global food staple, essential for human nutrition and calorie intake, particularly in low- and middle-income countries. This study assesses the impact of climate change on direct-seeded rice (DSR) production in Middle Gujarat (India) using the InfoCrop-Rice model. The study evaluates potential climate scenarios under Representative Concentration Pathways (RCP) 4.5 and RCP 8.5, focusing on projected changes in temperature, rainfall, and sunshine hours, and their effects on rice yield and phenology. Field data from Kharif 2023 were used to calibrate the model, which projected significant increases in maximum and minimum temperatures, variable changes in rainfall, and consistent reductions in sunshine hours. By 2100, maximum temperatures are expected to rise by up to 6°C under RCP 8.5, and minimum temperatures could

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increase by as much as 7.5°C. Rainfall projections show high variability, with potential reductions and increases depending on the scenario and time period. Sunshine hours are projected to decline by approximately 6.6% under both RCP scenarios. The model simulations indicate a notable decline in rice yields, with reductions ranging from 18% to 36% by 2100. These results underscore the severe impact of climate change on DSR productivity. The study highlights the need for adaptive strategies, including improved water management, resilient crop varieties, and sustainable agricultural practices, to mitigate the adverse effects of climate change and ensure the sustainability of direct seeded rice production in Middle Gujarat.

Keywords: Direct-seeded rice; InfoCrop model; rcp scenarios; impact assessment of climate change.

1. INTRODUCTION

Rice (*Oryza sativa* L.) is a crucial global food staple, providing essential nutrients and accounting for 20% of human calorie intake, primarily in low- and middle-income countries. It is almost exclusively consumed by humans and is known for its high nutritional quality and digestibility [1,2]. For example, 100 grams of cooked white Indian rice contains 130 kcal of energy and 28.17 grams of carbohydrates [3]. India is a leading rice producer, contributing 22.81% to global production, with Gujarat playing a significant role by dedicating 7-8% of its gross cropped area to rice. In 2020, Gujarat produced 19.8 lakh tons of rice, with the Kheda district contributing 17.14% of the state's total rice production in 2021-22 [4]. Rice cultivation requires specific temperature ranges: 20-22°C at sowing, 23-25°C during growth, 27-29°C for flower initiation, and 25-30°C at harvesting, along with high humidity and around 1250mm of rainfall [5]. Climate change poses significant threats to rice cultivation, with elevated temperatures, altered precipitation patterns, and increased extreme weather events impacting growth and yield (IPCC). Representative Concentration Pathways (RCP) data are essential for assessing climate change impacts on crops. RCP 4.5 assumes moderate emissions reductions, stabilizing greenhouse gas concentrations by the century's end, while RCP 8.5 describes a high-emission scenario with continued reliance on fossil fuels [6,7]. These scenarios help simulate potential climate change effects on crop production, guiding adaptation strategies and policy decisions. Crop simulation models, such as InfoCrop, developed by Aggarwal et al. [8], are vital for simulating crop growth under varying conditions. InfoCrop covers 12 crops, including rice, and aids in assessing climate variability and climate change impacts. This study utilizes the InfoCrop-Rice model to simulate climate change impacts on direct-seeded rice (DSR) production in Middle Gujarat (India). DSR is valued for its water efficiency, labor reduction, and adaptability to variable climates. Using RCP scenarios, this research projects the effects of climate change on rice yield and phenology, providing insights into rice cultivation in Middle Gujarat's Agro-climatic Zone III.

2. MATERIALS AND METHODS

2.1 Field Experimental Detail

For the climate change impact assessment on direct-seeded rice (DSR) production, we selected one representative farmer's field from a pool of 20 fields in Middle Gujarat. This selection was based on specific criteria, including soil type, historical yield data, and overall field management practices. The study utilized the InfoCrop-Rice model to simulate rice yields under future climate scenarios. The model was calibrated using field data collected during the Kharif season of 2023, and the baseline yield was taken by model simulation for the period of 1976 to 2005 for future projected yield comparison. Key parameters such as soil characteristics, crop management practices, and local weather data were input into the model to ensure accurate simulation. The InfoCrop model ran simulations using these future climate datasets to project rice yields under anticipated climate conditions. The projected future yields were then compared to the baseline yield. This comparison aimed to quantify the potential impacts of climate change on DSR production in the region. The analysis focused on key yield components, phenological stages, and overall crop performance under varying climate scenarios. By integrating field data with advanced crop simulation models, this study provides valuable insights into the potential effects of climate change on direct seeded rice production in Middle Gujarat, aiding in the development of effective adaptation strategies.

2.2 Description of Model

Crop growth simulation models are essential for evaluating the impact of climate change on crop production stability under different management scenarios [9]. These models offer a cost-effective alternative to field experiments by simulating how climate affects soil conditions, crop development, productivity, and long-term agricultural viability. Over the past two decades, a range of models has been developed to describe the complex soil-water-plant-atmosphere system, covering major field crops and some horticultural cultivars. The InfoCrop-Rice model, coded in Fortran Simulation Translator (FST/FSE) and developed by Wageningen University [10], is a dynamic simulation tool recognized by the International Consortium for Agricultural Systems Application (ICASA) [11]. This model is designed to simplify agricultural research and development for users with limited programming expertise [12]. It integrates soil characteristics, daily weather patterns, crop management practices, and pest dynamics to simulate their collective effects on crop growth, yield, soil carbon content, and greenhouse gas emissions. The model accurately captures variations in grain and biomass yields, emissions of greenhouse gases, and yield losses due to pests. InfoCrop-Rice (v2.1) encompasses a comprehensive simulation of crop growth and development processes, including interactions related to soil water, nitrogen, carbon, and crop-pest dynamics. It simulates the effects of temperature, water availability, and nutrient levels on crop growth, with processes such as phenology, photosynthesis, respiration, leaf area expansion, and nutrient distribution. The model includes components for soil water balance, soil nitrogen balance, and soil organic carbon dynamics. It can simulate various annual crops and includes a detailed database of Indian soil types. Crop phenology is modeled based on temperature, photoperiod, water availability, nutrients, and specific varietal traits, with development measured as thermal time accumulation above a base temperature threshold.

2.3 Projection Scenario of Climate Change

In climate science, Representative Concentration Pathways (RCPs) project future climate conditions based on different greenhouse gas emission scenarios, with RCP 4.5 and RCP 8.5 representing moderate and high-emission pathways, respectively. Climate change projections were sourced from the Indian Institute of Tropical Meteorology (IITM) in Pune, using the RegCM4-4CCCma-CanESM2 model from the Canadian Centre for Climate Modelling and Analysis. Data on maximum and minimum temperatures, rainfall, and bright sunshine hours under RCP 4.5 and RCP 8.5 scenarios, covering 2006 to 2100 and baseline data for period 1976 to 2005 were downloaded from IITM's Centre for Climate Change Research. RCP 4.5, developed by the MiniCAM team at the Pacific Northwest National Laboratory, aims to stabilize radiative forcing before 2100 through various technologies and GHG reduction strategies. In contrast, RCP 8.5, developed by the MESSAGE team at the International Institute for Applied Systems Analysis (IIASA), Austria, is characterized by increasing GHG emissions, leading to high concentration levels. The projected values for minimum temperature, maximum temperature, bright sunshine hours, and rainfall through 2100.

3. RESULTS AND DISCUSSION

3.1 Projected Trends of Key Climatic Variables under RCP 4.5 and RCP 8.5 scenarios (2025-2100)

To comprehensively understand the projected climate change impacts on direct seeded rice in Middle Gujarat, it is crucial to analyze the trends of key climatic variables over the projection period from 2025 to 2100. This analysis involves examining the trends of minimum temperature, maximum temperature, bright sunshine hours (BSS), and rainfall under two Representative Concentration Pathways (RCPs): RCP 4.5 and RCP 8.5. The RCP 4.5 scenario represents a moderate climate change trajectory with stabilization of greenhouse gas emissions, while RCP 8.5 represents a high-emission scenario with minimal mitigation efforts. Fig. 1 illustrates the trend of minimum temperature (°C) under RCP 4.5 and RCP 8.5 scenarios during the projection period. The analysis of this trend is essential as it impacts various physiological processes in rice, including germination, growth, and yield. An increase in minimum temperature can accelerate phenological stages, potentially reducing the overall growing period. Fig. 2 shows the trend of maximum temperature (°C) under RCP 4.5 and RCP 8.5 scenarios during the projection period. Maximum temperature plays a significant role in crop evapotranspiration rates and stress tolerance. Elevated maximum temperatures can lead to heat stress, affecting the photosynthetic efficiency and overall productivity of rice. Fig. 3 presents the trend of bright sunshine hours (BSS) under RCP 4.5 and RCP 8.5 scenarios during the projection period. Bright sunshine hours are indicative of solar radiation availability, which directly influences photosynthesis and biomass accumulation. Variations in BSS can impact the growth and development of rice plants, affecting yields. Fig. 4 depicts the trend of rainfall under RCP 4.5 and RCP 8.5 scenarios during the projection period. Rainfall is a critical factor for rice cultivation, particularly in rainfed regions. Changes in rainfall patterns and amounts can influence water availability, irrigation needs, and overall crop productivity. In the subsequent section, a detailed analysis is provided through a table indicating the reduction in all these parameters compared to the baseline period of 1976 to 2005. This comparison helps in understanding the magnitude of changes and their potential impact on rice cultivation in Middle Gujarat.

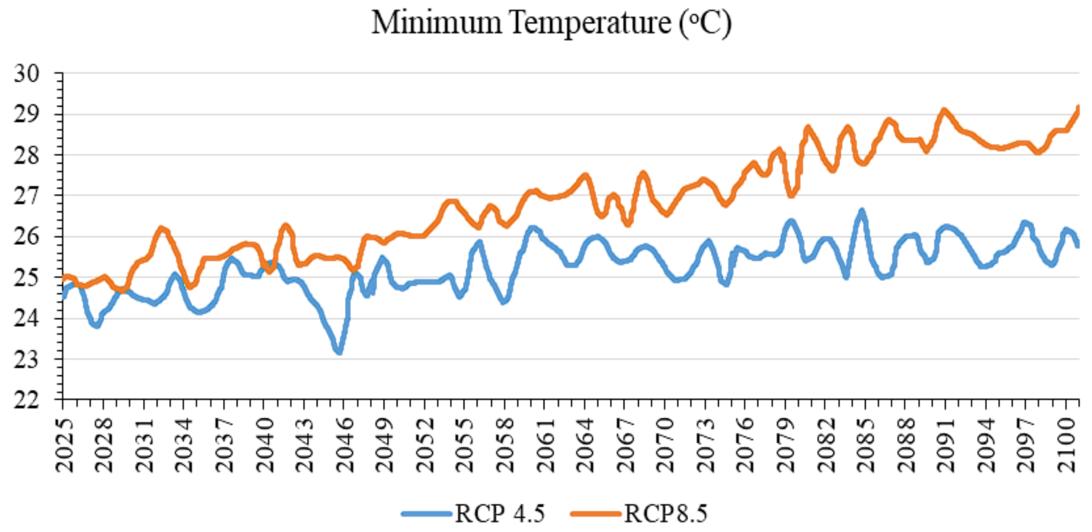

Fig. 1. Trend of minimum temperature (°C) under RCP 4.5 and RCP 8.5 scenarios during projection period (2025-2100)

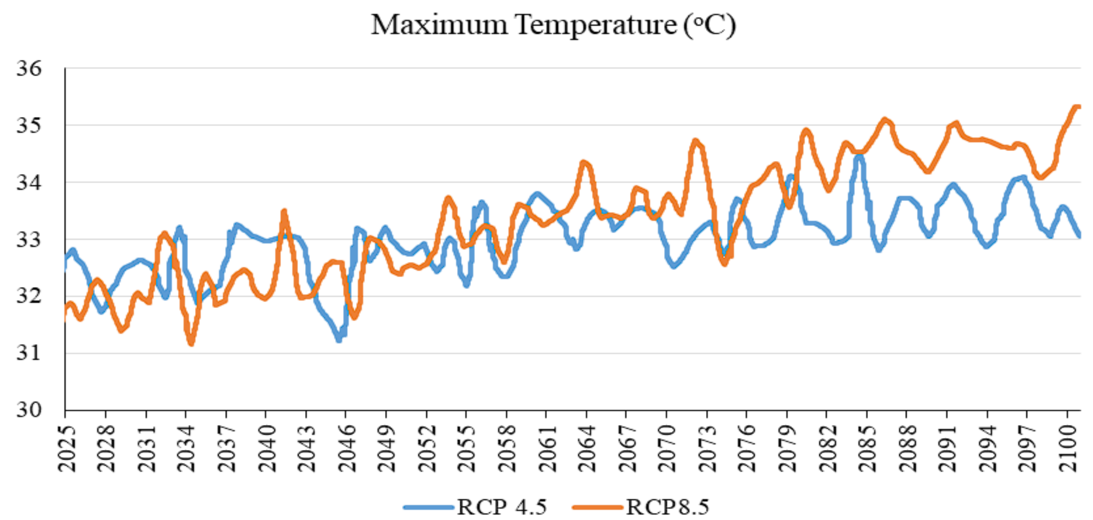

Fig. 2. Trend of maximum temperature (°C) under RCP 4.5 and RCP 8.5 scenarios during projection period (2025-2100)

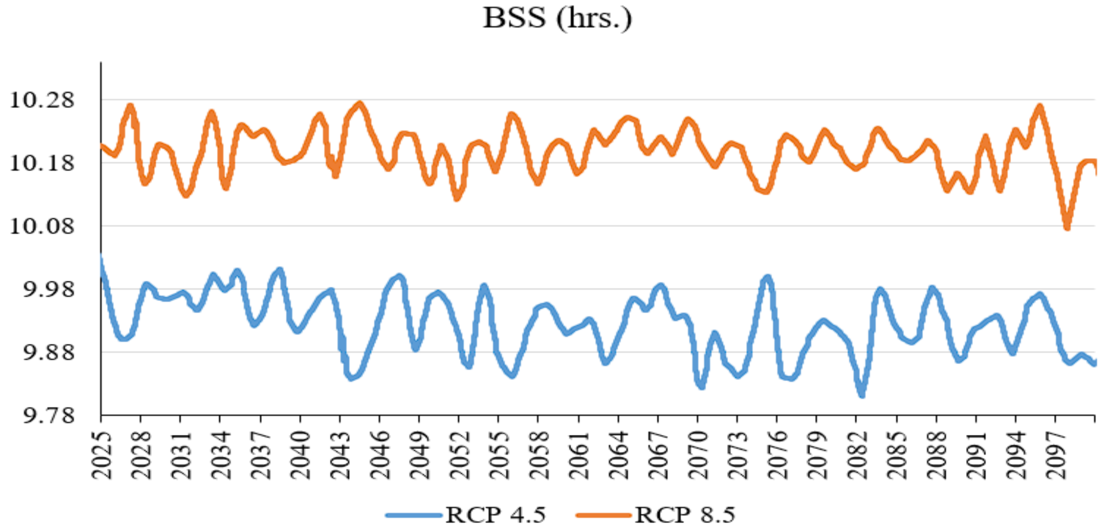

Fig. 3. Trend of Bright Sunshine Hours (BSS) under RCP 4.5 and RCP 8.5 scenarios during projection period (2025-2100)

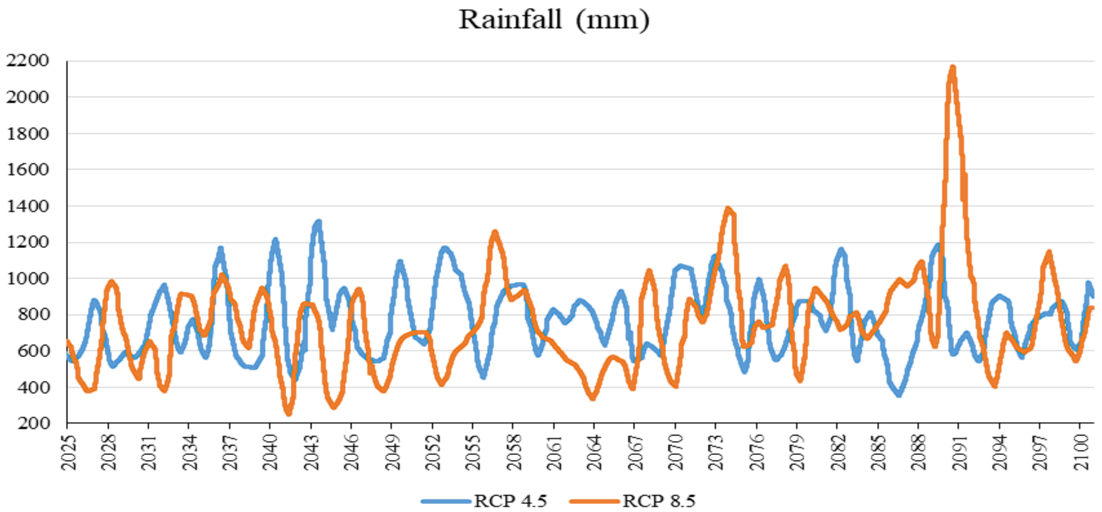

Fig. 4. Trend of rainfall under RCP 4.5 and RCP 8.5 Scenarios during projection period (2025-2100)

Table 1. Projected changes in maximum temperature (ºC) under different RCP scenarios

Time Period	Maximum Temperature during Baseline period (1976-2005) (ºC)	Maximum Temperature under RCP 4.5 (ºC)	Difference (ºC)	Maximum Temperature under RCP 8.5 (ºC)	Difference (ºC)
2025-2040	30.3	33.0	2.7	32.8	2.5
2041-2060		33.7	3.4	33.8	3.5
2061-2080		33.3	3.0	34.6	4.3
2081-2100		33.0	2.7	36.3	6.0

Table 2. Projected changes in minimum temperature (ºC) under different RCP scenarios

Time Period	Minimum Temperature during Baseline period (1976-2005) (ºC)	Minimum Temperature under RCP 4.5 (ºC)	Difference (ºC)	Minimum Temperature under RCP 8.5 (ºC)	Difference (ºC)
2025-2040	21.3	25.4	4.1	24.8	3.5
2041-2060		25.9	4.6	26.9	5.6
2061-2080		25.9	4.6	26.4	5.1
2081-2100		25.6	4.3	28.8	7.5

The projected changes in maximum temperature under different RCP scenarios are depicted in Table 1 it is indicate a significant increase in maximum temperature over time. By 2040, the maximum temperature is projected to rise by 2.7°C under RCP 4.5 and by 2.5 °C under RCP 8.5 from the baseline value of 30.3°C. The increases continue, with temperatures under RCP 4.5 rising by 3.4°C by 2060, 3.0°C by 2080, and 2.7°C by 2100. Under RCP 8.5, the temperature increases are more pronounced, with projected rises of 2.5°C by 2040, 3.5°C by 2060, 4.3°C by 2080, and a substantial increase of 6.0°C by 2100. These projections highlight the significant warming expected under both scenarios, with more extreme increases under RCP 8.5, emphasizing the urgent need for adaptation and mitigation strategies to address the impacts of rising temperatures on agriculture and other sectors.

The projected changes in minimum temperature under different RCP scenarios are depicted in Table 2 it is indicate a significant increase in minimum temperature indicate substantial increases over time. By 2040, the minimum temperature is projected to rise by 4.1°C under RCP 4.5 and by 3.5°C under RCP 8.5 from the baseline period value of 21.3°C. The increases continue, with temperatures under RCP 4.5 rising by 4.1°C in 2040, 4.6°C in both 2060 and 2080, and 4.3°C in 2100. Under RCP 8.5, the temperature increases are more pronounced, with projected rises of 5.6°C by 2060, 5.1°C by 2080, and a substantial increase of 7.5°C by 2100. These projections highlight significant warming trends, particularly under the more extreme RCP 8.5 scenario.

The projected changes in rainfall under different RCP scenarios indicate varying trends over time (Table 3). By 2040, the projections show a contrasting pattern, with an increase of 44.4% under RCP 4.5 and a substantial decrease of 44.5% under RCP 8.5. By 2060, rainfall is projected to slightly decrease by 1.4% under RCP 4.5, while a significant reduction of 40.2% is expected under RCP 8.5. The trends continue to vary, with a 14.0% decrease under RCP 4.5 and a 13.2% increase under RCP 8.5 by 2080. By 2100, rainfall is projected to increase by 17.7% under RCP 4.5 and by 4.3% under RCP 8.5. These projections highlight the complex and uncertain nature of future rainfall patterns, with potential for both significant decreases and increases depending on the scenario, underscoring the need for flexible and adaptive water management strategies to cope with the anticipated changes in precipitation.

Table 3. Projected changes in rainfall (mm) under different RCP scenarios

Time Period	Rainfall during Baseline period (1976-2005) (mm)	Rainfall under RCP 4.5 (mm)	Deviation (%)	Rainfall under RCP 8.5 (mm)	Deviation (%)
2025-2040	838.7	1211.5	44.4	465.4	-44.5
2041-2060		826.9	-1.4	501.2	-40.2
2061-2080		721.1	-14.0	949.6	13.2
2081-2100		987.5	17.7	874.6	4.3

Table 4. Projected Bright Sunshine Hours (hrs.) under different RCP scenarios

Time Period	BSS during Baseline period (1976-2005) (hrs.)	BSS under RCP 4.5 (hrs.)	Deviation (%)	BSS under RCP 8.5 (hrs.)	Deviation (%)
2025-2040	10.6	9.9	-6.6	10	-5.7
2041-2060		9.9	-6.6	10	-5.7
2061-2080		9.9	-6.6	9.9	-6.6
2081-2100		9.9	-6.6	9.9	-6.6

Table 4 shows the projected changes in bright sunshine hours under different RCP scenarios from 2025 to 2100. Compared to the baseline average of 10.6 hours per day (1976-2005), both RCP 4.5 and RCP 8.5 scenarios predict a decline in bright sunshine hours. By 2025, sunshine hours are expected to decrease to 9.9 hours under RCP 4.5 and RCP 8.5, representing reductions of 6.6% in both scenarios. This trend continues with sunshine hours remaining at 9.9 hours per day for both scenarios from 2040 to 2100, maintaining a consistent reduction of approximately 6.6% from the baseline. These projections indicate a steady decrease in solar radiation, which could have implications for agricultural productivity and environmental conditions.

3.2 Impact of Climate Change on Direct Seeded Rice Productivity

Climate change significantly impacts direct seeded rice, influencing its growth and yield. Rising temperatures can accelerate the phenological stages, potentially leading to shorter growing periods and affecting grain filling. Increased frequency and intensity of extreme weather events, such as droughts and floods, can cause considerable stress on rice crops, reducing overall productivity. Additionally, changes in precipitation patterns can disrupt water availability, further challenging rice cultivation. Understanding these impacts is crucial for developing adaptive strategies to ensure sustainable rice production under changing climatic conditions.

Future climate scenario data for RCP 4.5 and RCP 8.5 were input into the InfoCrop model. The model results, shown in Table 5, indicate a reduction in rice yield in future years due to changing weather patterns. Table 5 compares the simulated rice yields under both climate scenarios.

The simulated yield data in Table 5 presents a comparison of baseline and projected direct seeded rice yields under RCP 4.5 and RCP 8.5 scenarios from 2025 to 2100. Under RCP 4.5, the simulated yields show significant declines from the baseline, with percent yield changes ranging from -18.2% in period of 2061-2080 and in 2081-2100 it is expected decrease -28.3%. The simulated yields under RCP 8.5 also indicate considerable reductions, with percent yield changes ranging from -25.3% in period of 2041-2060 and in 2081-2100 it is expected decrease -35.6%. These results reflect the negative impacts of climate change on rice yields, underscoring the importance of implementing effective adaptation strategies to mitigate these losses and sustain rice production in the future. This data illustrates the potential negative impact of climate change on rice yields, with more severe reductions under higher emission scenarios (RCP 8.5). The similar results was found by Kawasaki et al*.* [13], Krishnan et al*.* [14], Elanchezhian et al*.* [15], Patel et al*.* [16] and Gupta et al*.* [17], [18].

Table 5. Comparison of baseline and simulated direct seeded rice yields under RCP 4.5 and RCP 8.5 scenarios

Time Period	Baseline Yield (kg/ha)	Simulated Yield (kg/ha) under RCP 4.5	Percent Yield reduction under (RCP 4.5)	Simulated Yield under (kg/ha) RCP 8.5	Percent Yield reduction under (RCP 8.5)
2025- 2040	5204.9	3820	-26.6	3711	-28.7
2041-2060		4195	-19.4	3888	-25.3
2061-2080		4258	-18.2	3545	-31.9
2081-2100		3732	-28.3	3352	-35.6

4. CONCLUSION

This study, utilizing the InfoCrop-Rice model, provides crucial insights into the potential impacts of climate change on direct-seeded rice (DSR) production in Middle Gujarat. The analysis of projected trends in key climatic variables under RCP 4.5 and RCP 8.5 scenarios from 2025 to 2100 reveals a significant warming trend, with minimum temperatures expected to rise by 4.1°C to 7.5°C and maximum temperatures projected to increase by 2.7°C to 6.0°C, particularly under the more extreme RCP 8.5 scenario. This substantial warming is likely to accelerate the phenological stages of rice, potentially reducing the overall growing period and increasing heat stress, which could adversely affect photosynthesis and overall productivity. Rainfall projections display contrasting trends, with potential increases of up to 44.4% under RCP 4.5 and significant decreases of up to 44.5% under RCP 8.5 by 2040, indicating a highly uncertain future for water availability crucial for rice cultivation. Additionally, a consistent reduction in bright sunshine hours is predicted, with a decrease of approximately 6.6% from the baseline period, which could further impact photosynthesis and biomass accumulation. The InfoCrop model simulations indicate considerable reductions in rice yields, with decreases ranging from 18.2% to 28.3% under RCP 4.5 and 25.3% to 35.6% under RCP 8.5 by the end of the century. These projections underscore the negative impacts of climate change on rice production in Middle Gujarat, highlighting the urgent need for effective adaptation and mitigation strategies to sustain rice yields and ensure agricultural resilience in the face of changing climatic conditions.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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