



Influence of Elevated CO₂ and Temperature on Yield Attributes of Rice and Wheat in Central India

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Authors' contributions

This work was carried out in collaboration between all authors. Author RP, SCG, BK, SRM designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors MHD, NA, AB and IM, SC, KA managed the analyses of the study. Author SKT, SSY, PAK managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Elevated CO₂ and rising temperature are the major climate changing drivers to attain sustainability in agriculture. The current experiment was carried out to evaluate the extent of impact of climate changing factors on rice and wheat crop. Field experiment was carried out under a Free Air CO₂ Enrichment (FACE) condition. The treatments consisted of ambient CO₂ and temperature, elevated CO₂ of 600ppm + ambient temperature, ambient CO₂ + elevated temperature (+2°C), ambient CO₂+elevated temperature (+3°C), elevated CO₂ of 600 ppm + elevated temperature (+2°C) and elevated CO₂ 600ppm + elevated temperature (+3°C). The plant yield attributes were biomass, tillers per plant, productive tillers per plant, failure tillers per plant, total number of grains per panicle, failure grains per panicle and test weight. Elevated CO₂ stimulated biomass and other yield attributes in both crops. However, elevated temperature inhibited yield attributes. Elevated CO₂ enhanced biomass but elevated temperature reduced biomass of crops. Elevated CO₂ influenced tillers per plant in rice by -26.9% to 16.6% and in wheat by 3.7% to 25.9%. Elevated temperature affected number tillers up to 26.9%. Number of productive tillers in rice ranged from -28.5% to 21.4% and in wheat by -29.1% to 36%. In wheat the number of grains per panicle varied from -24.3% to 6%. Test weight of grains varied from -9.1% to 4.6% in rice. Combined effect of elevated CO₂ and elevated temperature had differential effect on crops. Study highlights that yield attributes and productivity of rice and wheat crop will be affected under elevated CO₂ and rising temperature in central part of India and warrants necessary interventions to alleviate climate stress.

Keywords: Elevated CO₂; temperature; rice-wheat; yield, India.

1. INTRODUCTION

Climate change refers to long-term alterations in the average weather patterns and conditions on Earth, typically observed over decades or longer. It includes changes in temperature, precipitation, wind patterns, and other aspects of the Earth's climate system. The primary driver of recent climate change is the increase in greenhouse gases (GHGs), particularly concentration of atmospheric CO₂ is escalating rapidly at a rate of 3% per year [1]. Projections indicate that even with rigorous greenhouse gas (GHG) emission controls, CO₂ levels could reach 550-700 ppm by 2050 and 650-1200 ppm by 2100 [2,3,4]. This increase in GHGs is expected to raise the average global temperature by up to 2.5°C by 2050 and up to 6.4°C by the century's end [5,6]. A CO₂ concentration of 450 ppm is anticipated to elevate atmospheric temperatures by 2°C. Currently, the atmospheric CO₂ concentration stands at 421 parts per million (ppm), marking it to increase 50% from the era of industrial revolution [7]. This shift is may lead to severe extreme climatic events, such as heat waves and droughts, which may affect agriculture severely [8,9].

While rising temperatures may adversely affect plant growth, elevated CO₂ levels could enhance photosynthesis, thereby boosting net primary productivity. Increased biomass promotes root

exudation, which in turn supports greater microbial abundance.

Wheat (*Triticum aestivum*) and rice (*Oryza sativa*), are the primary food crops which feeds about 90% of the world's population, are vulnerable to climate change impacts [10]. Food production need to rise 70% by 2050 to meet population demands. Understanding how wheat and rice respond to elevated CO₂ and temperature becomes imperative for addressing food security [11]. Several experiments have been carried out to understand the climate impact [12,13,14,15,16,17,18]. For evaluating the impact of climate changing factors on crop yield, Free Air CO₂ enrichment (FACE) system is preferred as it offers more realistic insights into crop responses [19,20,21]. Higher CO₂ concentration in air can enhance leaf photosynthesis of C₃ species, including wheat, rice, and many other cereal crops, leading to increased yields [22,23]. Enhanced yield due to elevated CO₂ levels interpretation cautiously for two primary reasons. First, higher CO₂ often comes with rising air temperatures. This temperature increase typically accelerates the developmental of crops. Warming found to shorten the growth periods of rice crop by about 2.7 days per degree Kelvin rise for early cultivars. It may delay 4.8 days per degree Kelvin for late rice varieties. Secondly, crop yields respond less favorably to elevated CO₂ levels. This discrepancy could be attributed to a

phenomenon known as photosynthetic acclimation to elevated CO₂. Research suggests that over time, plants adjust to elevated CO₂ levels, leading to a diminished response in terms of crop yield [24,25].

Differences in the responses of wheat and rice to elevated CO₂ and temperature underscore the need for tailored mitigation strategies. Wheat may exhibit a more positive response to elevated CO₂ than rice, but the impact of temperature may vary between the two crops [14,26]. An experiment indicate that the stimulation observed in crop yield under elevated CO₂ was attributed to higher photosynthesis [27,28]. Impact of elevated CO₂ on rice differs depending on growth phase of crop [29,14]. Similarly, wheat also exhibit differential response to climate factors. Understanding the complexities of yield component responses to elevated CO₂ and temperature for both rice and wheat is important to address food security under climate change [30].

However, it is unclear how biomass yield and yield attributes occur in rice and wheat under elevated CO₂ and temperature in central India. In central India, cultivation of rice and wheat is increasing during recent years. To predict the real response of rice and wheat under elevated CO₂ and temperature in vertisol of central India in future climate, it is pertinent to study the effect in rice and wheat under elevated CO₂ and temperature.

The current experiment was undertaken with a primary objective to evaluate the influence of climate factors on yield of rice and wheat. Study also aims to evaluate whether the elevated CO₂ levels can mitigate the adverse effects of temperature on wheat and rice.

2. MATERIALS AND METHODS

2.1 Experimental Site and Weather Conditions

The FACE system was established at ICAR-Indian Institute of Soil Science, situated in the Bhopal district of Madhya Pradesh, India. Positioned between latitudes 21°6'N - 26°30'N, this area experiences a semi-dry tropical monsoon climate. With a mean annual temperature of 28°C (ranging from 11°C to 45°C) and precipitation ranging from 1000 to 1200 mm during the period of 2018–2023, it lies centrally within the country. The soil type is black (Vertisol) and is used for continuous rice–wheat rotation.

2.2 Soil Physico-chemical Properties

The soil is a heavy clayey vertisol and the experimental site was characterized by 5.7 g kg⁻¹ organic carbon, 225 mg kg⁻¹ available N, 12.75 mg kg⁻¹ available P, and 230 mg kg⁻¹ available K. The soil had sand 15.2%, silt 30.3%, clay 54.5%. The electrical conductivity (EC) was 0.43 dS m⁻¹, and the pH of soil was 7.5.

2.3 Free Air CO₂ Enrichment (FACE) System

FACE system comprised was comprised of eight octagonal rings fitted on fields across various sites, each with comparable agronomic practices. The CO₂ exposure system was meticulously designed and assembled using cutting-edge technology. It involved CO₂ gas cylinders fitted with two-stage regulators connected to a gas mixing compressor (Elgi, India), which was directly connected to CO₂ exposure system of FACE system rings in experimental field. These FACE system rings were tailored to meet the specific requirements of experimental crops, featuring 8-meter-diameter 'rings' covering an area of 50 square meters per plot.

To ensure uniform CO₂ concentration within the rings, one E-sense extended-range 10000 ppm CO₂ sensor (Senseair, part of the Asahi Kasei Group, headquartered in Delsbo, Sweden) was installed above the canopy in each plot, evenly distributed in two concentric circles, facilitating automatic CO₂ pumping control. The consistency of CO₂ concentration within the rings was maintained through automatic adjustments controlled through pneumatic valves installed on each field.

For infrared heating, facility was designed following the principles outlined by [31]. Each field had eight infrared heaters (1000 W, 240 V, 45 cm long, 10 cm wide; Elestein-FSR/1, Elstein-Werk M. Steinmetz GmbH & Co. KG, Northeim, Germany), which were adjusted weekly to maintain a height of 1.2 m above the crop canopy during the growth cycle. The shading effect of these heaters over the open circle (50 m²) was approximately 5.5%.

The infrared thermometers used were sensitive to radiation in the range of 8.0–14 μm, minimizing interference from atmospheric absorption or emission bands outside this range. Thus, the heaters fitted generally did not emit short wavelengths radiation those might be

influence photosynthesis. Crop canopy temperature was measured by sensors (PT 500, Sensography International, Pune, India) fitted at the top of the canopy. Readings of both CO₂ and temperature were automatically monitored and recorded at every minute using a data-logger (TC-800, Ambetronics Scientific Inc., Maharashtra, India). All these components were interconnected through WiFi. System was operated by using software programs (InduSoft Web Studio v8.1 and USR-VCOM, M/s Moreson, India) placed in a control room.

2.4 Experimental Set Up

The experiment was conducted to simulate future climate conditions anticipated for the period 2040-2050. This projection included atmospheric CO₂ levels ranging between 550-650 ppm and a corresponding rise in global mean surface air temperature of 2-3 °C under the A2 emission scenario.

Initially, during the first two years (2019-20 and 2020-21), each of the treatments (T1, T2, T3, and T5) were replicated in two rings with identical infrastructure, following a block split-plot design. After two years (2021-22 and 2022-23), experiments were conducted with six treatments (T1-T6), each with a single replication. Carbon dioxide enrichment was implemented during daytime, with canopy temperature regulated both during the day and night. To prevent potential artifacts arising from heterogeneity among crop seedlings during the winter phase of wheat and any effects of transplanting shock in rice, CO₂ and temperature treatments were initiated within the FACE system only after the crops had established well and achieved homogeneity within each plot, typically at the early tillering stage of crop [32].

2.5 Crop Cultivation and Agronomical Practices

In each experimental season, plots were planted with winter wheat, HI-1605 (Pusa Ujala) and rice,

PB-1 (Pusa Basmati-1). Standard cultivation practices were performed in all experimental plots. For wheat, seeds were sown in rows 10-12 cm apart at a rate of 120 kg seed per ha, resulting in a plant density of approximately 250-300 plants /m². For rice, direct seeded rice (DSR) method was used. Spacing of hills was maintained at 12 x 22.4 cm (equivalent to 37 hills / m²). Fertilizer dose followed as recommended dose of fertilizer (RDF) at 120:60:40 kg/ha of N:P:K respectively. About 50 percent of nitrogen and 100 percent of P and K were applied at sowing time (basal dose). Remaining doses of nitrogen was applied as two split at different growth stages of both crop.

2.6 Yield Attributes

Agronomical data was collected by using standard agronomical methods during the experimental years. Biomass yield was estimated as total biomass, straw weight and grain yield at the end of every cropping season and represented as quintal per hectare or Q/ha in rice and wheat during 2019-23. The rice and winter wheat were harvested at the maturity stage from 1 m² area of experimental plot and converted in biomass yield Q/ha [33].

Yield attributes were estimated as number of tillers per plant, productive tillers per plant, failure tillers per plant, total number of grains per panicle, failure grains per panicle and test weight (g/1000 grains). The parameters were estimated at the end of every cropping season in rice and wheat. The five plants sample were collected randomly from each plot and their number of tillers, productive tillers and failure tillers estimated. From these plant sample five randomly selected panicles for measuring number of grains per panicle from each plot were counted carefully and averaged to obtain during investigation. The thousand grains randomly selected and counted from each plot for test weight in both crop [34].

List 1. The experiment comprised six treatments

Treat No.	Treatment combination for Rice and wheat
T ₁	ambient CO ₂ & ambient Temperature
T ₂	Elevated CO ₂ (600ppm) & ambient Temperature
T ₃	Ambient CO ₂ & elevated Temperature (+ 2°C)
T ₄	Ambient CO ₂ & elevated Temperature (+ 3°C)
T ₅	Elevated CO ₂ (600ppm) & elevated Temperature (+ 2°C)
T ₆	Elevated CO ₂ (600ppm) & elevated Temperature (+3°C)

3. RESULTS

The economic yields of crops depend on a number of characters which are known as yield attributes. Yield attributing characters were estimated as plant biomass, number of tillers per plant, productive tillers per plant, failure tillers per plant, total number of grains per panicle, failure grains per panicle and test weight (g/1000 grains). The parameters were estimated at the end of every cropping season in rice and wheat during 2019-23.

Biomass (BM) yield was estimated as total biomass, straw wt. and grain yield at the end of every cropping season and represented as q/ha. in rice and wheat during 2019-23. Plant total biomass, straw weight and grain yield were estimated at the harvest stage of crop and represented as q/ha. In rice, total biomass varied from 63.7 to 121.1, straw weight varied from 45.12 to 74.85 and grain yield varied from 17.6 to 47 (Fig. 1) or (Tables 1 & 2). In case of wheat total biomass was in the range of 87.4 to 151.22, straw weight 62 to 87.4 and grain yield ranged by 22.87 to 61.82 during the cropping period (Fig. 2) or (Tables 1 & 2). In both crop, total biomass, straw biomass and grain yield was highest in treatment T2 and lowest in treatment T4.

Total number of tillers occurred differently in both crops (Fig. 3). In rice, total number of tillers per plant varied from 8.75 to 12.25 in 2019, 9.5 to 13 in 2020, 9.5 to 13 in 2021 and it was in the range of 9 to 14 in 2022. Similarly, in wheat, total number of tillers varied from 6 to 9 in 2020, 5 to 8.5 in 2021, 5.5 to 8.25 in 2022 and 5 to 8.5 in 2023.

Number of productive tillers varied in both crops under the influence of climate changing factors (Fig. 3). In rice, productive tillers per plant varied from 8.25 to 11.25 in 2019, 8.25 to 12.75 in 2020, 8.5 to 12.5 in 2021 and it was in the range of 7.5 to 12.75 in 2022. Similarly, in wheat, productive tillers varied from 5.25 to 8.5 in 2020, 4.25 to 8 in 2021, 5.25 to 7.75 in 2022 and 4.5 to 8.25 in 2023.

Number of failure tillers estimated to define relative failure of tillers in the crops (Fig. 3). In rice, number of failure tillers per plant varied from 0.5 to 1.25 in 2019, 0.25 to 1.25 in 2020, 0.25 to 1.5 in 2021 and it was in the range of 1.25 to 2.75 in 2022. Similarly, in wheat, failure tillers varied from 0.5 to 0.75 in 2020, 0.5 to 0.75 in

2021, 0.25 to 0.5 in 2022 and 0.25 to 0.5 in 2023.

Total number of grains per panicle estimated to indicate crop yield per panicle (Fig. 4) or (Table 3). Number of grains per panicle estimated from a randomly selected individual productive tiller of a plant. In rice, it varied from 122.75 to 172 in 2019, 123.75 to 167.75 in 2020, 119.5 to 168.25 in 2021 and 113.25 to 168.5 in 2022. In wheat, it varied from 35.25 to 44.5 in 2020, 34.25 to 42.5 in 2021, 31 to 42.75 in 2022 and 32 to 43.5 during 2023.

Number of failure grains/ panicle was estimated as the difference between total number of grains and number of healthy grains per panicle (Fig. 4) or (Table 3). It is an indicator of grain yield reduction under kind of stresses of plant. In rice, number of failure grains/panicle varied from 8.75 to 13.25 in 2019, 7.5 to 12.5 in 2020, 6 to 16.25 in 2021 and 4.25 to 15 in 2022. Similarly, in wheat, it varied from 1.25 to 2.25 in 2020, 1.75 to 2.5 in 2021, 1.25 to 3 in 2022 and 1.75 to 2.75 in 2023.

In rice, test weight varied from 20.27 to 22.3 in 2019, 20.4 to 22.6 in 2020, 20.2 to 22.45 in 2021 and 19.8 to 22.4 in 2022 (Fig. 5) or (Table 4). Similarly, in wheat, the value varied from 39 to 41.8 in 2020, 39 to 41.8 in 2021, 37.1 to 42.7 in 2022 and 37.9 to 41.77 in 2023.

Yield attributes of crops under different treatments were compared over control (T1) to evaluate how climate factors affected yield. In rice the effect of climate factors on number of tillers varied from -26.9% to 16.6%. Total number of tillers was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 2% to 26.9%. Stimulation was up to 16.6%. Maximum stimulation was observed in T2 and maximum inhibition was in T6. In wheat the effect of climate factors on number of tillers varied from -25.9% to 33.3%. In wheat, total number of tillers was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 3.7% to 25.9%. Stimulation varied from 13.7% to 33.3%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T4. In case of elevated temperature (T3 and T4) and combined effect of elevated CO₂ of 600ppm + elevated temperature (T5, and T6) had negative effect on this parameter in both crops. In rice the effect of climate factors on number of productive tillers ranged from -28.5% to 21.4%.

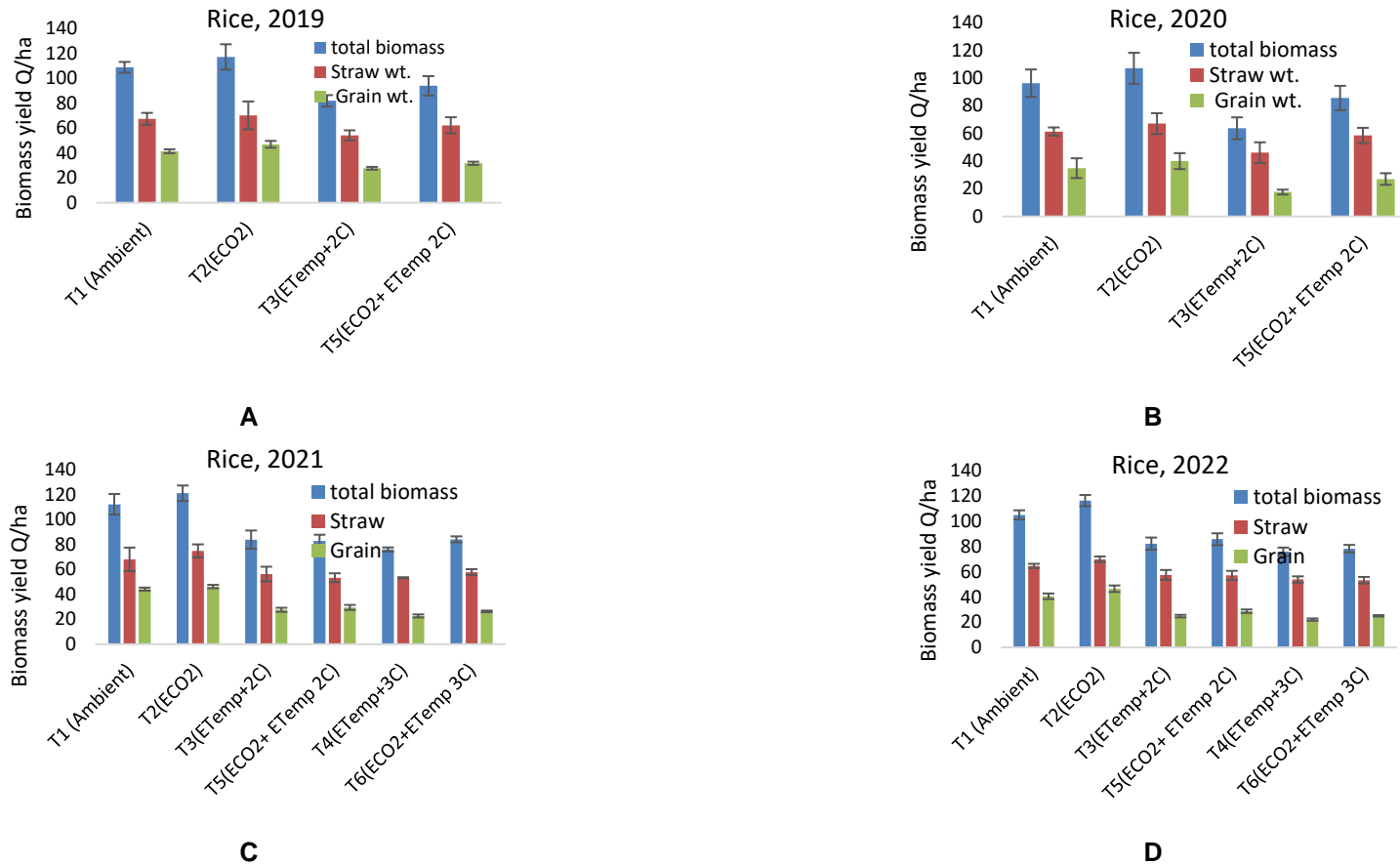


Fig. 1. Influence of climate changing factors on yield parameters of rice. Rice was cultivated under Free Air CO₂ Enrichment (FACE) system with different treatments. The treatments were ambient condition (T1), elevated CO₂ of 600 ppm (T2), elevated temperature (+2°C) (T3), elevated CO₂ of 600 ppm + temperature (+2°C) (T5), elevated temperature (+3°C) (T4), elevated CO₂ (600 ppm) + elevated temperature (+3°C). Plant samples were collected at maturity stage of crop. Parameters total biomass, straw yield, and grain yield were estimated during different years (A-2019, B-2020, C-2021, D-2022). X axis represents different climate changing factors. Y axis represents yield in quintal per hectare (Q/ha). Each data point represents arithmetic mean and standard deviation as error bar of 4 replicated observations

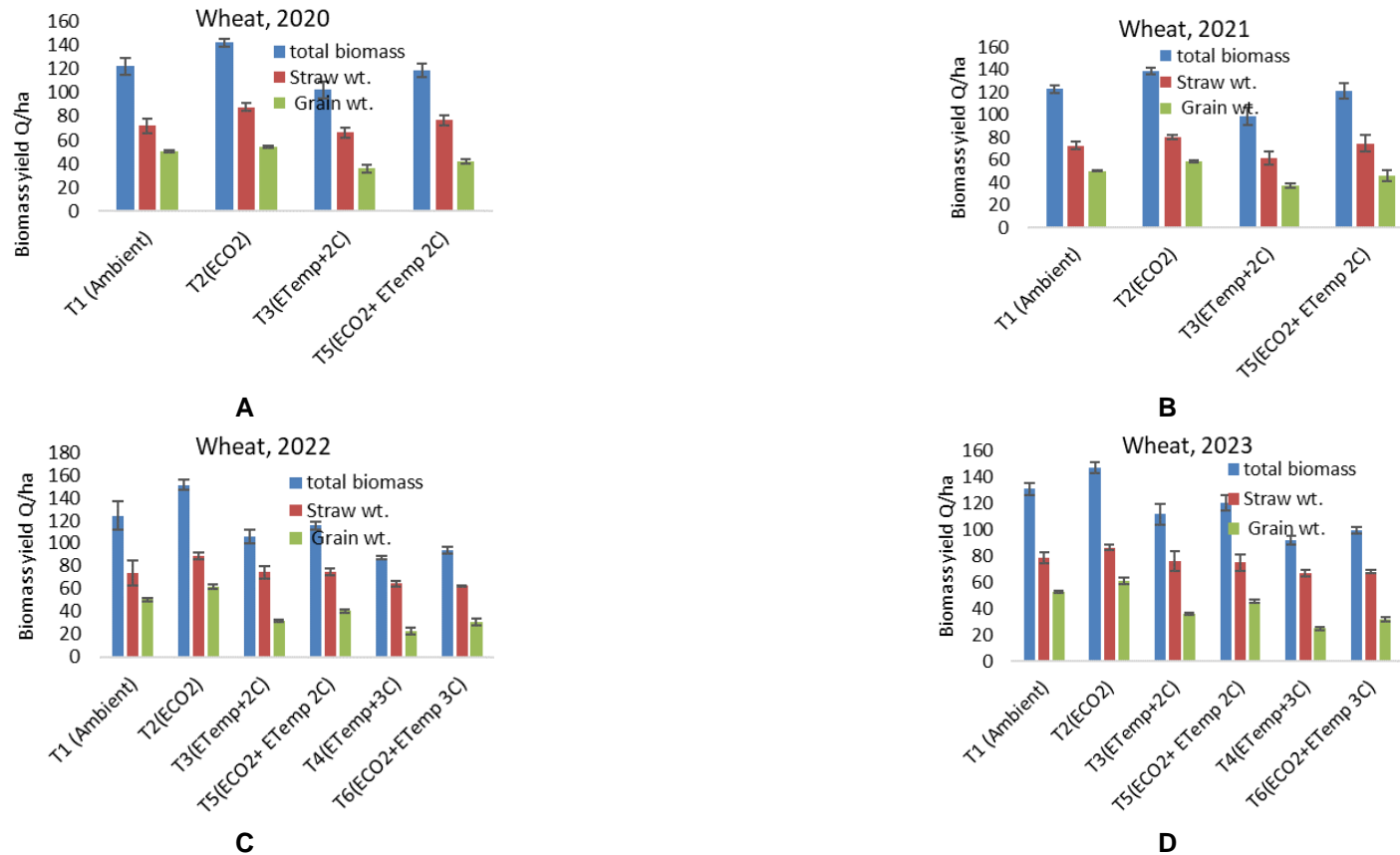
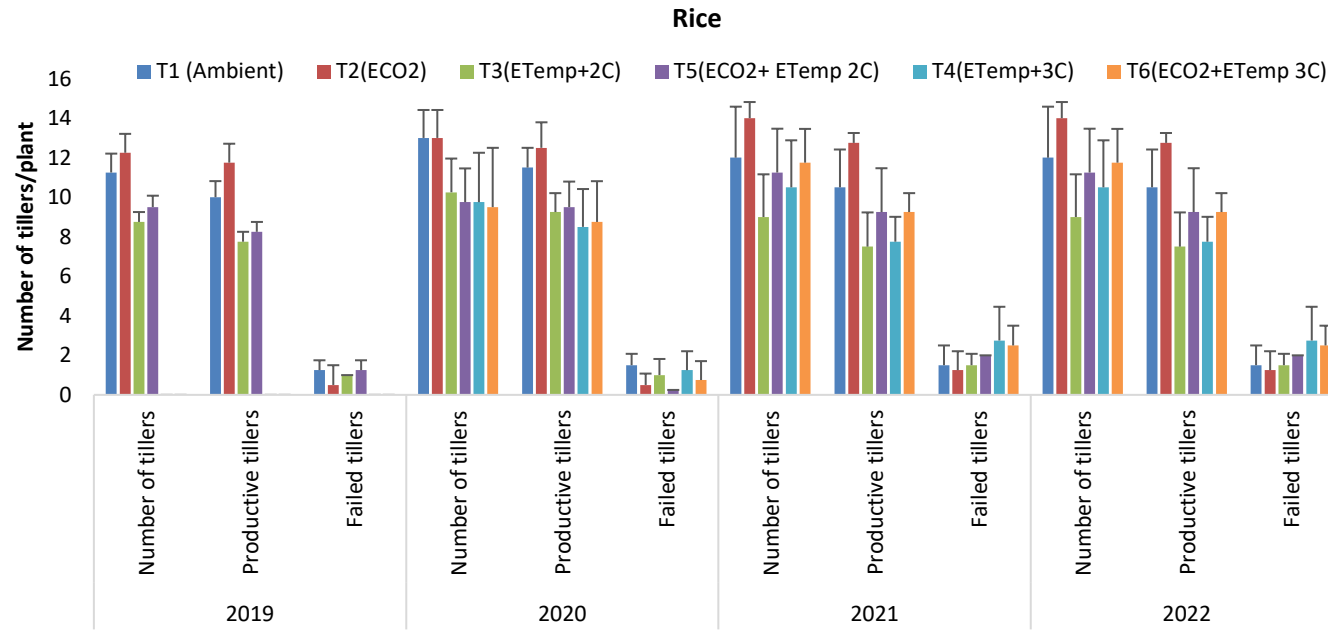


Fig. 2. Influence of climate changing factors on yield parameters of wheat. Wheat was cultivated under Free Air CO₂ Enrichment (FACE) system with the different treatments. The treatments were ambient (T1), elevated CO₂ 600 ppm (T2), elevated temperature (+2°C) (T3), elevated CO₂ (600 ppm) +temperature (+2°C) (T5), elevated temperature (+3°C) (T4), elevated CO₂ (600 ppm) + elevated temperature (+3°C). Plant sample were collected at maturity stage of crop. Parameters total biomass, straw yield, and grain yield were estimated during different years (A-2020, B-2021, C-2022, D-2023). X axis represents different climate changing factors. Y axis represents yield in quintal per hectare (Q/ha). Each data point represents arithmetic mean and standard deviation as error bar of 4 replicated observations



A

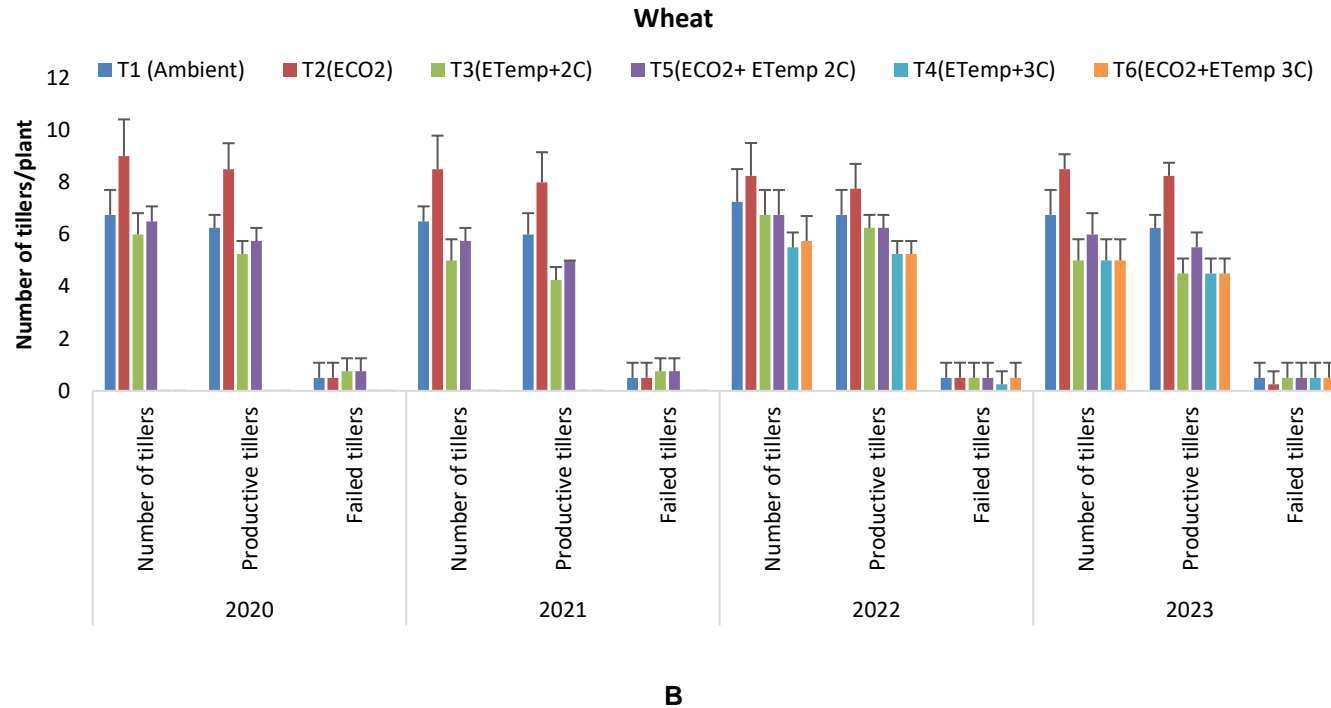
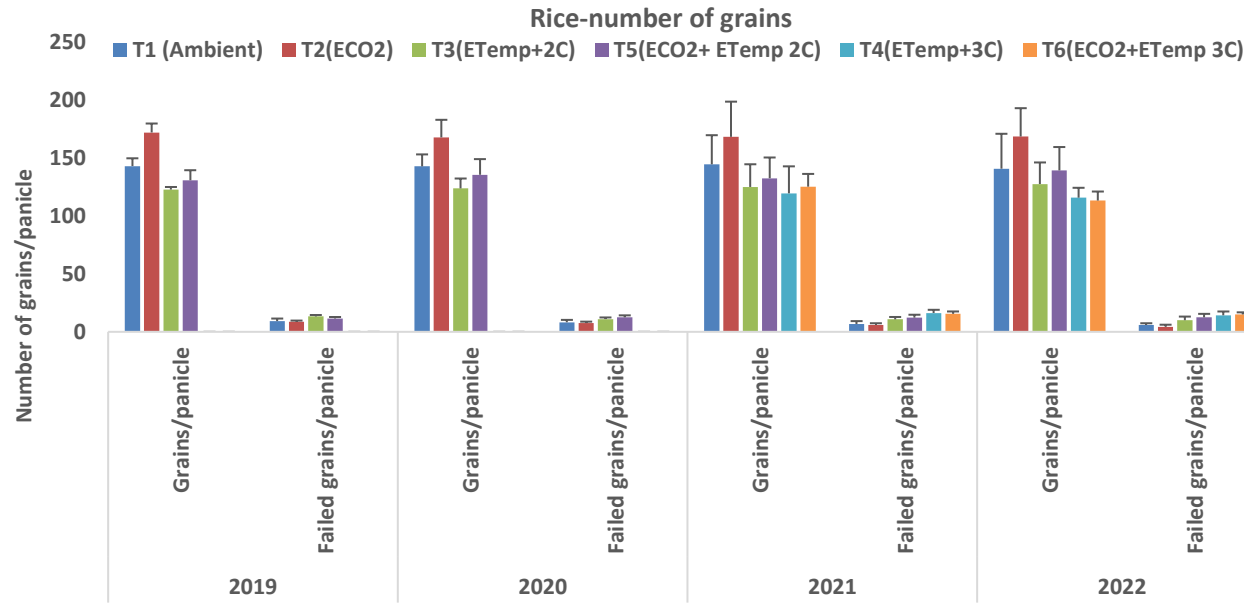


Fig. 3. Effect of climate changing factors on tillers of rice (A) and wheat (B). Tillers were estimated as number of tillers, productive tillers and failed tillers. Rice and wheat were cultivated under Free Air CO₂ Enrichment (FACE) system with the different treatments. The treatments were ambient (T1), elevated CO₂ 600 ppm (T2), elevated temperature (+2°C) (T3), elevated CO₂ (600 ppm) +temperature (+2°C) (T5), elevated temperature (+3°C) (T4), elevated CO₂ (600 ppm)+elevated temperature (+3°C). Plant samples were collected at maturity stage of crop grown during different years. X axis represents different cropping years. Y axis represents number of tillers/plant. Each data point represents arithmetic mean and standard deviation as error bar of 4 replicated observations



A

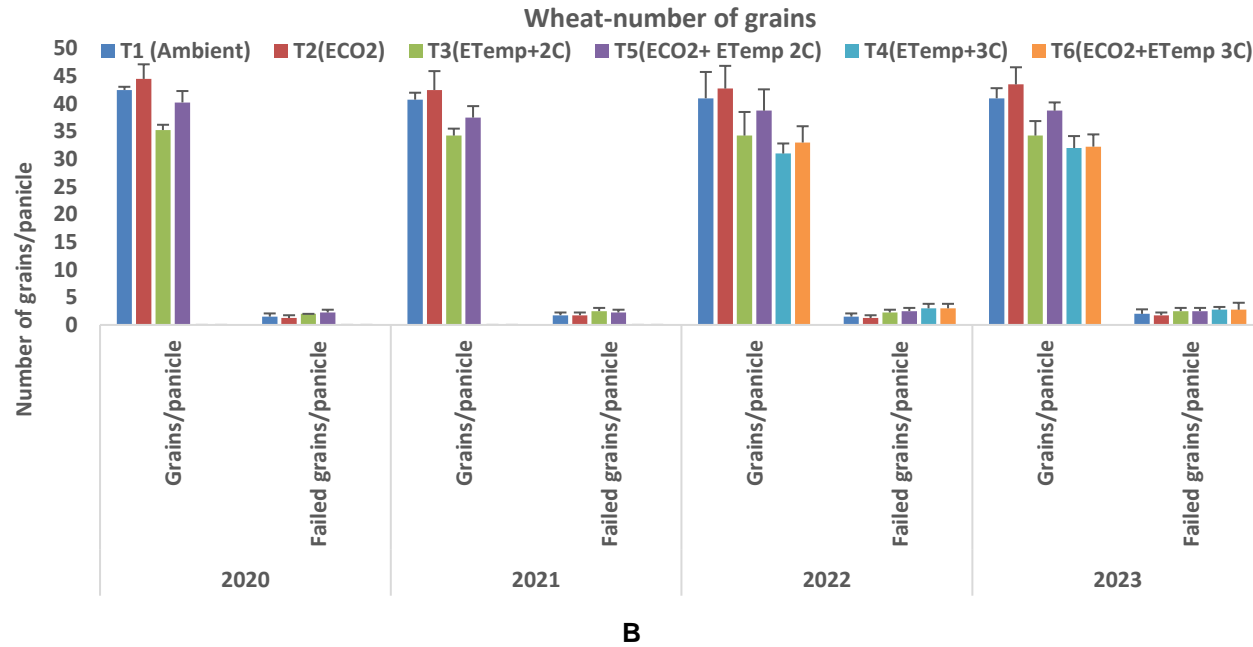


Fig. 4. Effect of climate changing factors on number of grains and failed grains per panicle in rice (A) and wheat (B). Rice and wheat were cultivated under Free Air CO₂ Enrichment (FACE) system with the different treatments. The treatments were ambient (T1), elevated CO₂ 600 ppm (T2), elevated temperature (+2°C) (T3), elevated CO₂ (600 ppm) +temperature (+2°C) (T5), elevated temperature (+3°C) (T4), elevated CO₂ (600 ppm) + elevated temperature (+3°C). Plant samples were collected at maturity stage of crops grown at different years. Parameters were number of grains and failed grains per panicle. X axis represents different cropping years. Y axis represents grains per panicle. Each data point represents arithmetic mean and standard deviation as error bar of 4 replicated observations

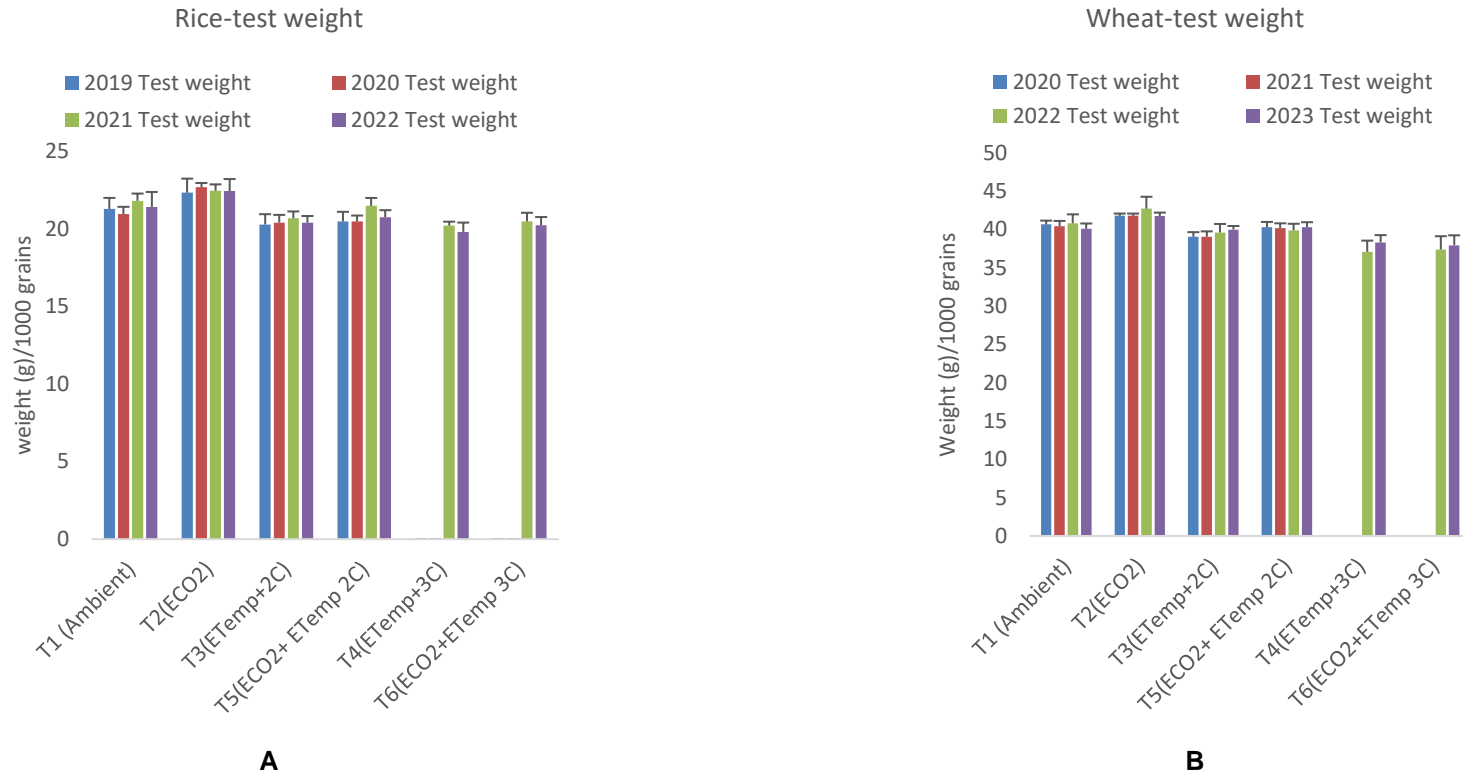


Fig. 5. Effect of climate changing factors on test weight of rice (A) and wheat (B). Rice and wheat were cultivated under Free Air CO₂ Enrichment (FACE) system with the different treatments. The treatments were ambient (T1), elevated CO₂ 600 ppm (T2), elevated temperature (+2°C) (T3), elevated CO₂ (600 ppm) +temperature (+2°C) (T5), elevated temperature (+3°C) (T4), elevated CO₂ (600 ppm) + elevated temperature (+3°C). Grain samples were collected after harvesting of crop from each treatment and test weight estimated as weight(g)/1000 grains. Crops were grown during different years. X axis represents different treatments. Y axis represents test weight. Each data point represents arithmetic mean and standard deviation as error bar of 4 replicated observations

Table 1. Biomass yield of rice. Rice cultivated under Free Air CO₂ Enrichment (FACE) system under different treatments. The treatments were T1 - ambient, T2 - elevated CO₂ (600 ppm), T3 - elevated temperature (+2°C), T4 - elevated temperature (+3°C), T5 - elevated CO₂ (600 ppm) + elevated temperature (+2°C), T6 - elevated CO₂ (600 ppm) + elevated temperature (+3°C). Plant samples were collected at maturity stage of crops. Parameters total biomass, straw yield, and grain yield were estimated during different years. Each data point represents arithmetic mean, ± standard deviation as error bar of 4 replicated observations

Year	Yield parameters	Biomass yield in Q./hac.					
		T1	T2	T3	T4	T5	T6
2019	total biomass	108.9±4.35	117.25±10.18	81.9375±4.61	-	94.0075±7.79	-
	Straw wt.	67.465±4.81	70.25±11.16	54.2025±4.06	-	62.27±6.50	-
	Grain wt.	41.435±1.54	47±2.75	27.735±1.12	-	31.7375±1.30	-
2020	total biomass	96.4±9.91	107.1725±11.21	63.7675±7.92	-	85.655±8.84	-
	Straw wt.	61.45±2.95	67.145±7.53	46.125±7.51	-	58.5725±5.53	-
	Grain wt.	34.95±7.15	40.0275±5.79	17.6425±1.79	-	27.0825±4.20	-
2021	total biomass	112.25±8.26	121.1±6.20	83.9±7.30	75.9775±1.65	82.9±4.93	84.1±2.44
	Straw	68.05±9.45	74.85±5.25	56.3±5.89	53.2775±0.45	53.375±3.54	57.775±2.40
	Grain	44.2±1.23	46.25±1.39	27.6±1.65	22.7±1.24	29.525±2.03	26.325±0.67
2022	total biomass	105.075±3.61	116.4±4.44	82.275±4.82	75.85±3.30	85.76±4.70	78.3±2.93
	Straw	64.565±1.70	69.9±2.22	57.475±3.90	53.8±2.54	57.06±3.62	53.275±2.57
	Grain	40.51±2.22	46.5±2.60	24.8±1.01	22.05±0.90	28.7±1.37	25.025±0.54

(-) = Not done

Table 2. Biomass yield of wheat. Wheat cultivated under Free Air CO₂ Enrichment (FACE) system under different treatments. The treatments were T1 - ambient, T2 - elevated CO₂ (600 ppm), T3 - elevated temperature (+2°C), T4 - elevated temperature (+3°C), T5 - elevated CO₂ (600 ppm) + elevated temperature (+2°C), T6 - elevated CO₂ (600 ppm) +elevated temperature (+3°C). Plant samples were collected at maturity stage of crops. Parameters total biomass, straw yield, and grain yield were estimated during different years. Each data point represents arithmetic mean, ± standard deviation as error bar of 4 replicated observations

Year	Yield parameters	Biomass yield in Q./hac.					
		T1	T2	T3	T4	T5	T6
2020	total biomass	122.5±7.05	142.325±3.34	102.35±6.90	-	118.725±5.47	-
	Straw wt.	71.975±6.53	87.975±3.51	66.2975±4.29	-	76.85±4.40	-
	Grain wt.	50.7±1.01	54.35±1.08	35.8275±3.49	-	41.875±2.15	-
2021	total biomass	123.125±3.42	138.825±2.68	99.15±7.78	-	121.225±7.13	-
	Straw wt.	72.925±3.30	79.9725±2.06	62.05±5.96	-	74.9±7.05	-
	Grain wt.	50.2±0.62	58.8525±1.02	37.1±2.13	-	46.325±5.08	-
2022	total biomass	124.05±12.57	151.225±4.66	106.25±5.97	87.4±1.66	115.5±3.42	93.475±3.03
	Straw	73.675±11.20	89.4±3.01	74.45±5.10	64.525±2.74	74.925±2.87	62.725±0.59
	Grain	50.375±1.73	61.825±1.73	31.8±0.91	22.875±2.71	40.575±1.36	30.75±2.92
2023	total biomass	130.575±4.26	147.05±4.02	111.375±7.59	91.4±3.36	120.25±5.91	99.475±2.31
	Straw	78.1±4.13	86.075±2.19	75.6±7.43	66.65±2.53	74.8±6.24	67.625±1.21
	Grain	52.475±0.88	60.975±2.19	35.775±0.95	24.75±1.42	45.45±1.14	31.85±1.73

(-) = Not done

Table 3. Number of grains/panicle of rice and wheat. Crop was cultivated under Free Air CO₂ Enrichment (FACE) system under different treatments. The treatments were T1 - ambient, T2 - elevated CO₂ (600 ppm), T3 - elevated temperature (+2°C), T4 - elevated temperature (+3°C), T5 - elevated CO₂ (600 ppm) + elevated temperature (+2°C), T6 - elevated CO₂ (600 ppm) + elevated temperature (+3°C). Plant samples were collected at maturity stage of crops. Parameters number of Grains/panicle and failed grains/panicle were estimated during different years. Each data point represents arithmetic mean, ± standard deviation as error bar of 4 replicated observations

Crop & Year	Parameters	Number of Grains/panicle					
		T1	T2	T3	T4	T5	T6
Rice 2019	Grains/panicle	143±6.73	172±7.75	122.75±2.22	-	130.75±8.69	-
	Failed grains/panicle	9.25±2.22	8.75±0.96	13.25±1.26	-	11.5±1.29	-
2020	Grains/panicle	142.75±10.34	167.75±15.17	123.75±8.54	-	135.5±13.53	-
	Failed grains/panicle	8.25±2.06	7.5±1.29	11±1.41	-	12.5±1.73	-
2021	Grains/panicle	144.5±25.15	168.25±30.36	125±19.58	119.5±23.27	132.5±17.92	125.25±11.00
	Failed grains/panicle	6.75±2.50	6±1.41	10.75±2.06	16.25±2.75	12.25±2.50	15.5±2.08
2022	Grains/panicle	140.75±30.14	168.5±24.47	127.5±18.65	115.75±8.54	139.25±20.19	113.25±7.80
	Failed grains/panicle	6±1.41	4.25±1.89	10±3.16	14.25±3.30	12.5±3.00	15±1.83
Wheat 2020	Grains/panicle	42.5±0.58	44.5±2.65	35.25±0.96	-	40.25±2.06	-
	Failed grains/panicle	1.5±0.58	1.25±0.50	2±0.00	-	2.25±0.50	-
2021	Grains/panicle	40.75±1.26	42.5±3.42	34.25±1.26	-	37.5±2.08	-
	Failed grains/panicle	1.75±0.50	1.75±0.50	2.5±0.58	-	2.25±0.50	-
2022	Grains/panicle	41±4.76	42.75±4.11	34.25±4.27	31±1.83	38.75±3.86	33±2.94
	Failed grains/panicle	1.5±0.58	1.25±0.50	2.25±0.50	3±0.82	2.5±0.58	3±0.82
2023	Grains/panicle	41±1.83	43.5±3.11	34.25±2.63	32±2.16	38.75±1.50	32.25±2.22
	Failed grains/panicle	2±0.82	1.75±0.50	2.5±0.58	2.75±0.50	2.5±0.58	2.75±1.26

(-) = Not done

Table 4. Test weight of rice and wheat. Rice and wheat were cultivated under Free Air CO₂ Enrichment (FACE) under different treatments. The treatments were T1 - ambient, T2 - elevated CO₂ (600 ppm), T3 - elevated temperature (+2°C), T4 - elevated temperature (+3°C), T5 - elevated CO₂ (600 ppm) + elevated temperature (+2°C), T6 - elevated CO₂ (600 ppm) + elevated temperature (+3°C). Plant samples were collected at maturity stage of crops. Test weight was estimated during different years. Each data point represents arithmetic mean, ± standard deviation as error bar of 4 replicated observations

Crop	Years	Weight	Test weight (g/1000 grains)					
			T1	T2	T3	T4	T5	T6
Rice	2019	Test wt	21.28±0.71	22.33±0.91	20.28±0.67	-	20.48±0.62	-
	2020	Test wt	20.95±0.47	22.68±0.28	20.40±0.50	-	20.48±0.38	-
	2021	Test wt	21.80±0.47	22.45±0.41	20.68±0.44	20.20±0.26	21.48±0.51	20.48±0.56
	2022	Test wt	21.41±0.96	22.43±0.78	20.40±0.42	19.80±0.60	20.74±0.46	20.23±0.53
Wheat	2020	Test wt	40.68±0.50	41.80±0.29	39.05±0.61	-	40.30±0.70	-
	2021	Test wt	40.45±0.68	41.80±0.29	39.08±0.69	-	40.20±0.62	-
	2022	Test wt	40.83±1.16	42.73±1.56	39.63±1.11	37.10±1.46	39.90±0.86	37.40±1.74
	2023	Test wt	40.10±0.70	41.78±0.44	40.00±0.47	38.33±0.95	40.33±0.64	37.95±1.30

(-) = Not done

It was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 11.9% to 28.5%. Stimulation varied from 8.6% to 21.4%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T3. In wheat the effect of climate factors on number of productive tillers ranged from -29.1% to 36%. It was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 7.4% to 29.1%. Stimulation varied from 14.8% to 36%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T3.

In case of elevated temperature (T3, and T4) and combine effect of elevated CO₂ 600ppm + elevated temperature (T5, and T6) had positive effect on failed tillers in both crops.

In rice the effect of climate changing drivers on number of grains per panicle was with the factor of -19.5% to 20.2%. It was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 5% to 19.5%. Stimulation varied from 16.4% to 20.7%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T6. In wheat the effect of climate changing drivers on number of grains per panicle was with the factor of -24.3% to 6%. It was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 5.2% to 24.3%. Stimulation varied from 4.2% to 6%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T4.

In rice the effect of climate changing drivers on number of failure grain per panicle varied by -29.1% to 150%. In T2, was negatively affected by 5.4% to 29.1%. It was stimulated by treatments T3, T5, T4, and T6 and was inhibited by treatments T2. Inhibition ranged from 5.4% to 29.1%. Stimulation varied from 24.3% to 150%. Maximum stimulation was in the treatment T6 and maximum inhibition was in T2. In wheat the effect of climate changing drivers on number of failure grain per panicle varied by -16.6% to 100%. In T2, was negatively affected by 0% to 16.6%. It was stimulated by treatments T3, T5, T4, and T6 and was inhibited by treatments T2. Stimulation varied from 25% to 100%. Maximum stimulation was in the treatment T4. In T2 (elevated CO₂ 600ppm) had negative effect on both crops. In case of elevated temperature (T3, and T4) and combine effect of elevated CO₂ 600ppm + elevated temperature (T5, and T6) had positive effect on both crops.

In rice the effect of climate changing factors on test weight was varied from -7.5% to 8.2%. It was stimulated by treatments T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 1.4% to 7.5%. Stimulation varied from 2.9% to 4.9%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T4. In wheat the effect of climate changing factors on test weight was varied from -9.1% to 4.6%. It was stimulated by treatment T2 and was inhibited by treatments T3, T5, T4 and T6. Inhibition ranged from 0.2% to 9.1%. Stimulation varied from 2.7% to 4.6%. Maximum stimulation was in the treatment T2 and maximum inhibition was in T4.

In rice, under ambient condition (T1), test weight was decreased by 0.6% to 2.4% during 2020-22. In T2, it was increased by 0.4% to 1.5%. In T3, it increased by 0.6% to 1.9%. In T5, test weight was increased by a factor of 0% to 4.8%. In T4, it was decreased by a factor of 1.9% in 2022. In T6, it was decreased with the value of 1.2% in 2022. In case of wheat, in T1, test weight was decreased by 0.3% to 1.4% over the years. In T2, it was increased by a factor of 2.2% over the years. In T3, test weight was increased 2.4% during the years. In T5, it was decreased by 0.9% during 2021-23. In T4, test weight was increased by a factor of 3.3% during 2023. In T6, it was increased by 1.4% during 2023.

4. DISCUSSION

The economic output of crops relies on various traits, often referred to as yield attributes or yield-contributing characteristics. Yield-contributing traits result from the accumulation of dry matter in plants and its subsequent translocation to develop yield attributes. In rice and wheat, yield is influenced by indirect traits such as tillering ability, seed setting rate, and grains per panicle, as well as direct traits like the number of panicles per unit area or per plant, the number of filled grains per panicle, and the weight of 1000 grains [35,36].

Climate change significantly impacts crop yield attributes and biomass yield. It is estimated that a 1°C increase in temperature can reduce global crop yields by 10–20% [37]. By the end of this century, global atmospheric temperatures are expected to rise by 2–4°C or more, posing a threat to crop production [38]. Changes in daily weather conditions could lead to permanent extreme climate shifts, affecting agriculture worldwide [39]. These extreme temperature changes, especially during sensitive stages like

flowering, anthesis, and the milking stage, significantly impact wheat and rice yield, grain weight, and other yield attributes at the end of the season [40,41]. For instance, when temperatures reached $36 \pm 2^\circ\text{C}$ during anthesis, wheat yield decreased by 13%, with most grains becoming sterile [42]. Such temperature increases can lead to heat stress, a severe threat to rice and wheat production, particularly during reproductive and grain-filling phases [43]. Previous studies have shown that exposure to temperatures above the optimum range for wheat at anthesis and grain-filling stages (12 to 20°C) can significantly reduce grain yield by more than 20% [44]. All physiological processes of wheat and rice plants are sensitive to temperature and can suffer permanent damage from heat. Heat stress during anthesis can increase floret abortion, and temperatures over 30°C during floret formation may lead to complete sterility [45,46]. Heat stress during the reproductive stage can result in pollen sterility, tissue dehydration, lower CO_2 assimilation, increased photorespiration, and reduced resource capture due to accelerated growth and senescence, consequently reducing yield [47,43]. While increased CO_2 levels can enhance the rate of photosynthesis and water efficiency, this does not necessarily lead to higher yield or biomass in C_3 plants like wheat [48]. Wheat yield depends not only on the rate of photosynthesis but also on the duration of the active photosynthetic phase and the grain's sink capacity [49].

In rice the effect of elevated temperature and elevated CO_2 on total biomass, straw yield and grain yield varied from -33.8% to 11.17%, -24.9% to 9.99% and 49.5% to 14.7%, respectively during 2019-22. Similarly, in wheat the yield parameters were affected by 19.4% to 21.9%, 14.9% to 22.2% and -54.5% to 22.7%, respectively during 2020-23. Under elevated temperature, biomass and grain yield reduced in both crops. Results indicated that means elevated temperature inhibited plant growth by altering various enzymatic and physiological processes in plant. Photosystem II (PSII) is the most sensitive component of the photosynthetic apparatus [50]. Heat-induced oxidative stress causes the dissociation of the oxygen-evolving complex (OEC) in PSII, inhibiting electron transport from the OEC to the acceptor side of PSII [51]. Rubisco is the key enzyme that converts carbon dioxide into carbohydrates during photosynthesis [52,53]. However, as temperatures rise, Rubisco "relaxes," causing its CO_2 -binding pocket to become less precise [54].

Over control under elevated CO_2 condition, total biomass, straw yield and grain yield increased in some extent by stimulating photosynthesis and stomata conductance mechanisms in both crops. Rising CO_2 levels in the atmosphere drive an increase in plant photosynthesis, a phenomenon called the carbon fertilization effect [48,55]. Most of this increase in photosynthesis is attributed to carbon dioxide fertilization. Enhanced photosynthesis leads to greater growth in some plants.

Current study highlighted that elevated CO_2 (eCO_2) significantly promoted rice tillering. Similar results were observed in rice under elevated CO_2 [56]. In an experiment with rice-wheat systems, eCO_2 positively improved the number of grains per panicle and improved test weight in both crops [57].

Experiments on wheat production have shown that high temperatures combined with increased CO_2 concentrations can be harmful and decline the crop yield attributes [58]. Elevated CO_2 levels increases nitrogen sink capacity but also shorten the photosynthetic period, resulting in poor growth and reduced yield [59]. Increase in CO_2 concentration and temperature can disrupt positive aspects of crop growth [60]. A study revealed that doubling CO_2 and raising temperatures by 1.5 to 4°C negatively impacted the wheat yield attributes [61].

Increasing atmospheric carbon dioxide levels have led to higher photosynthetic rates, increased biomass growth, and greater numbers of tillers, grains per panicle, and improved test weight [62,27], ultimately boosting seed yield for many globally important C_3 food and feed crops [63,64]. Rising CO_2 levels in the atmosphere drives plant photosynthesis, which is referred as the carbon fertilization effect [4,55]. It is reported that during the period of 1982 and 2020, global plant photosynthesis has increased by 12 %, in correlation to 17% increase in atmospheric CO_2 levels [65]. Most of this increase in photosynthesis is attributed to CO_2 fertilization, which enhances growth and yield attributes in some plants.

Elevated temperatures (eTemp) negatively affect yield attributes by various means. One is through disrupting enzymes involved in photorespiration and photosynthesis (Rubisco) [66]. Rubisco plays key role to convert CO_2 to carbohydrates during photosynthesis [52,53]. However, as temperatures rises, conformation of Rubisco

enzyme changes making it unable to capture CO₂ [64]. In this case Rubisco fixes O₂ instead of CO₂ [67]. At even higher temperatures, Rubisco enzyme is completely deactivated [68]. Under higher nitrogen fertilizer application Rubisco content of plant increases. Thus higher N fertilizer application may alleviate negative effect of elevated temperature on photosynthesis [69]. Heat stress can also damage the permeability of the thylakoid membrane and affect photosynthesis [70]. This results in decreased chlorophyll content in plant [50]. Negative effect of climate changing drivers on plant yield attributes could be the result of declined plant photosynthesis [71-73].

5. CONCLUSION

Climate changing drivers had differential impact on yield parameters of rice and wheat. Treatment T2 (elevated CO₂ at 600ppm) had positive effect on plant biomass, number of tillers in both crops. In case of elevated temperature (T3, and T4) and combined effect of elevated CO₂ 600ppm + elevated temperature (T5, and T6), number of tillers declined in both crops. Elevated CO₂ was beneficial for both crops. Hence, it stimulated yield attributes in rice and wheat. But warming had negative effect on yield attributes of both rice and wheat crops. Study concluded that climate changing factors will affect the yield of rice and wheat by declining the parameters including biomass, tillers, grains per panicle, and grain weight. Further research warranted to evaluate strategies to offset the negative effect of elevated temperature for sustainable production of rice and wheat under climate change in central India.

6. CHALLENGES AND FUTURE PROSPECTS

Our finding highlights the challenges posed by rising temperatures for rice and wheat production in central India. Breeding programs focused on genotypes that can withstand higher temperatures without compromising yield are essential. Evaluating and implementing improved water management strategies, planting dates, and nutrient application techniques can help mitigate heat stress impacts. Researching and introducing drought-resistant and heat-tolerant alternative crops could provide additional options for farmers in a changing climate.

By addressing these challenges, we can develop strategies to maintain and improve rice and

Wheat production in central India despite the threats posed by climate change.

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.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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