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Effects of Elevated CO_2 on Rice Harvest Components

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ABSTRACT

Rice (Oryza sativa L.) has long been a staple food for people across various nations, particularly in Asia. Climate change and rising atmospheric carbon dioxide (CO_2) levels now have diverse impacts on crop performance worldwide. Since CO_2 is a key factor in photosynthesis, it enhances productivity and yield. This study investigated the effects of elevated CO_2 (eCO_2) on rice yield improvement. Using a novel approach, rice seedlings were only exposed to high CO_2 levels during the early vegetative stage. The treatments included eCO_2 (600 to 800 µmol mol⁻¹), ambient CO_2 [aCO_2 (410-415 µmol mol⁻¹)], and a control under field conditions. Following treatment with eCO_2, the seedlings were transplanted into a rain shelter in a two-factorial randomized complete block design (RCBD). Results showed that tiller number per plant, panicle number per plant, and panicle length increased by 18.38%, 20.96%, and 14.15%, respectively, with eCO_2. Additionally, filled grain per panicle and grain yield increased by 15.30% and 47.48%, respectively. In conclusion, eCO_2 treatment significantly improved rice yield components during the seedling stage. Applying eCO_2 sustainably could increase rice yield, supporting Afghanistan in achieving rice self-sufficiency in the future. Temporary eCO_2 treatment on rice seedlings may enhance rice production, improving farmers' incomes and living standards.

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Introduction

Rice has been a vital staple food for humanity for centuries, with the two most widely consumed species being *Oryza sativa* L. and *Oryza glaberrima* L. *Oryza sativa*, the most common type, now serves as the staple food for nearly 4 billion people globally, expanding beyond Asia to become a staple in Africa, Latin America, and Australia (Maity et al., 2019).

The populations of rice-producing and consuming nations have increased significantly, necessitating a substantial rise in food production to meet growing demand. According to Khush (2005), rice production needs to increase by 40% by 2030 to address the rising population and prevent malnutrition in the developing world. Research estimates project a global population of 8 billion by 2025, primarily concentrated in developing countries.

In Afghanistan, the Ministry of Agriculture, Irrigation, and Livestock reported a 2023 rice production total of 400,000 tonnes against a demand of 688,500 tonnes. There is thus an urgent need to boost rice production to meet national demand. Sustainable rice production methods offer a promising path to achieve this.

South Asia, including Afghanistan, is among the regions most impacted by climate change (Omerkhil et al., 2020). Afghanistan frequently experiences drought and other challenges due to rising temperatures and reduced precipitation, adversely affecting crop production (Sarwary et al., 2023). For example, climate change has shortened the duration of rice growth (Sarwary et al., 2023).

The rise in atmospheric CO_2, a principal contributor to global warming, is occurring at an unprecedented rate, with current levels at approximately 416 μmol mol^{-1} and expected to double by the end of the century (Long et al., 2004). Higher CO_2 concentrations could positively impact crop productivity by increasing photosynthetic rates and reducing water use (Hasegawa et al., 2013).

Plants' primary response to elevated atmospheric CO_2 is increased growth and yield (Wohlfahrt et al., 2018). Despite CO_2's role as a greenhouse gas, it enhances photosynthesis and water-use efficiency in crops such as rice (Hasegawa et al., 2013). For instance, eCO_2 has been shown to boost rice seedling growth, germination rates, vigor, and mineral uptake, increasing rice yield by up to 25.5% with recommended nitrogen levels (Abzar et al., 2017; Guo, 2015; Raj et al., 2019; Lieffering, 2004).

The ongoing challenge of increasing rice production on limited arable land underscores the need for innovative approaches. As conventional methods approach production plateaus, alternatives like eCO_2 treatment can improve yields. Limited research has been conducted on the impact of eCO_2 exposure during the seedling stage only, followed by field growth. Thus, this study examines the efficacy of eCO_2 treatment during the seedling stage in enhancing rice yield components in field conditions.

Methods and Materials

Experimental site and location

The experiment was conducted at Field 15 Research Farm, Faculty of Agriculture, University Putra Malaysia (UPM), Serdang, Selangor, Malaysia, located at 2°59′0.42″ N latitude and 101°44′104″ E longitude, 30 m above sea level. The experiment was conducted under a rain shelter with average temperatures ranging from 26 to 37 ºC and humidity levels between 60% and 80% during the study.

Experimental Design, Treatments, and Agronomical Practices

A two-factorial RCBD was used, with CO_2 treatment and rice variety as factors, replicated four times. Each replication included two pots containing two rice plants each. Treatments consisted of aCO_2, control, and eCO_2, with varieties MR219 and Sri Malaysia 1. Seedlings were grown under ambient and eCO_2 conditions in growth chambers before being transplanted to the rain shelter.

Seedlings were manually transplanted with two plants per hill in pots at a density of 25 plants per square meter. Pots (25 cm depth, 30 cm diameter) were filled with 3.5 kg of clay loam paddy soil. On the third day post-transplanting, a 5 cm water layer was maintained until 10 days before harvest. Fertilizers were applied during the vegetative, tillering, and panicle initiation stages, and weekly hand weeding was performed during vegetative growth.

Measurements

The tiller and non-productive tiller numbers were counted manually after the maximum tillering stage and before harvesting. The panicle number was manually counted for both plants, and the average was calculated. Furthermore, the panicle height (cm) was measured and recorded. The panicles were separated from the rest of the plants and were dried for 24 hours at 40°C in the oven. The grain was separated from the husk manually. Then, the filled grain per panicle and non-filled grain per panicle of each plant's panicles were separated manually, and the grain was counted using an electronic seed counter machine.

Moreover, the record of filled grain per panicle and non-filled grain for each panicle per plant in both varieties and all treatments was added and calculated separately to obtain the spikelet per panicle. Furthermore, the grain yield per plant was weighed using an electronic laboratory balance (Kern & Sohn, PCE-ABT 220, Germany) for all treatments and varieties. Finally, 1000 grain weight (g) was recorded using a seed counting machine and weighed by an electronic laboratory balance.

Components of yield were measured to determine grain yields, such as the average number of panicles per area (m^2), average field grain per panicle, and weight of grain was calculated from 1000 grain weight for both MR219 and Sri Malaysia 1 rice varieties in the study and all a CO_2, control, and eCO_2 treatments separately according to the obtained data from the survey. All these parameters were used to estimate grain yield (t/ha). The average panicle number per m^2 was calculated using the study's data and 25 plants per m^2. The average kernel weight was recorded from 1000 grain weight. The parameters mentioned below were calculated separately for both varieties' ambient, control, and eCO2. Below is the formula to estimate grain yield (t/ha) from the yield components measured (IRRI, 2013):

$$Grain\ yield = No.of\,\frac{panicle}{\mathrm{m2}} \times\ No.of\ filled\,\frac{grain}{panicle} \times weight\ of\ grain$$

Data Analysis

All data were analyzed using analysis of variance (ANOVA) in SAS (Statistical Analysis Software, Version 9.4) software (SAS ®, SAS Institute Inc, NC, USA). The normality and homogeneity of variance were assessed to check if the data followed the assumptions of ANOVA. Significant differences were considered at a significance level of $p<0.05$, and the LSD (least significant difference) post-hoc test was conducted when there was a significant difference between the means.

Results

Significant differences were observed between CO_2 treatments in all tiller-panicle properties parameters except for panicle length, demonstrating significant differences in CO_2 treatments and varieties at $p<0.05$ (Table 1).

Table 1: The effects of elevated CO_2 and variety on tiller-panicle properties of rice

Treatment	Tiller no. per plant	Panicle no. per plant	Non-productive TNPP	Panicle length (cm)
CO_2				
Ambient CO_2	9.43 ± 0.29^{ab}	7.43 ± 0.29^{a}	2.62 ± 0.18^{a}	24.25 ± 1.65^{b}
Control	8.81 ± 0.58^{b}	6.87 ± 0.22^{b}	2.53 ± 0.24^{a}	23.81 ± 0.89^{b}
Elevated CO_2	10.43 ± 0.29^{a}	8.31 ± 0.33^{a}	1.75 ± 0.21^{b}	27.18 ± 0.65^{a}
Varieties				
MR219	9.95 ± 0.28^{a}	7.75 ± 0.30^{a}	2.08 ± 0.21^{a}	27.29 ± 0.47^{a}
Sri Malaysia1	9.16 ± 0.25^{a}	7.33 ± 0.25^{a}	2.52 ± 0.21^{a}	22.87 ± 0.45^{b}
Significance level				
CO_2	*	*	*	*
Variety	ns	ns	ns	*
CO_2*Variety	ns	ns	ns	ns

Within the column, means with the same letter are not significantly different at $p<0.05$ using LSD. Values are the mean ± SE of two plants derived from four blocks (n= 8) for all groups of treatments and varieties.
TNPP tiller number per plant
* Significantly different at $p<0.05$
ns Not significantly different at $p>0.05$

Significant differences between eCO_2 and control treatments were recorded; however, there were no significant differences between eCO_2 and aCO_2 and aCO_2 and control (Table 1). The tiller number per plant significantly increased by 18.38% in eCO2 treatment compared to the control. Panicle number demonstrated a significant difference between eCO_2 and control treatment, although there was no significant difference between eCO_2 and aCO_2 (Table 1). Panicle number per plant also increased significantly under eCO_2 treatment by 20.96% compared to the control plants. Significant differences were detected in non-productive tiller numbers between eCO_2 and other treatments, and there were no significant differences between aCO_2 and control (Table 1). Elevated CO_2 significantly decreased the non-productive tiller number per plant by 30.83% compared to control. The greatest panicle length was recorded in MR219, and the lowest was for Sri Malaysia1 (Table 1). The greatest panicle length was also obtained for eCO_2 treatment (Table 1). Panicle length significantly increased by 14.15% under the eCO2 condition compared to the control treatment.

Moreover, significant main effects between CO_2 treatments were detected at $p<0.05$ for all parameters except for 1000 grain weight, resulting in significant differences between varieties. The highest filled grain per panicle was observed in eCO_2, followed by a control (Table 2).

Table 2: The effects of elevated CO_2 and variety on grain-panicle properties of rice

Treatment	No of filled grain per panicle	No of non-filled grain per panicle	No of spikelet per panicle	1000 grain weight (g)	Grain yield (t/ha)
CO_2					
Ambient CO_2	50.9 ± 0.95^a	44.9 ± 3.76^a	82.7 ± 1.54^b	22.2 ± 0.52^a	2.1 ± 0.05^b
Control	47.3 ± 0.95^b	51.7 ± 2.11^a	79.8 ± 0.54^b	21.9 ± 0.37^a	1.7 ± 0.05^c
Elevated CO_2	54.6 ± 1.40^a	30.7 ± 1.96^b	101.7 ± 2.76^a	23.2 ± 0.46^a	2.6 ± 0.07^a
Varieties					
MR219	50.9 ± 1.18^a	44.1 ± 2.53^a	88.7 ± 3.99^a	23.2 ± 0.32^a	2.3 ± 0.08^a
Sri Malaysia1	50.9 ± 1.16^a	40.8 ± 2.60^a	87.4 ± 3.94^a	21.7 ± 0.32^b	2.0 ± 0.08^b
Significance level					
CO_2	*	**	**	ns	**
Variety	ns	ns	ns	*	*
CO_2*Variety	ns	ns	*	ns	ns

Within the column, means with the same letter are not significantly different at $p<0.05$ using LSD. Values are the mean ± SE of two plants derived from four blocks (n= 8) for all groups of treatments and varieties.
*, ** Significantly different at $p < 0.05$ and $p < 0.01$, respectively.
ns Not significantly different at $p > 0.05$

The number of filled grains per panicle was significantly increased by 15.30% by eCO_2 compared to the control. A significant difference was observed between CO_2 treatments in the number of non-filled grains per panicle (Table 2). The lowest non-filled grain per panicle was recorded in eCO_2, followed by the aCO_2 and control. However, no significant differences between the aCO_2 and control were observed, as presented in Table 2. The number of non-filled grains per panicle of eCO_2 treatments was significantly decreased by 42.04% compared to the control. There were significant differences in 1000-grain weight between varieties but no significant differences among CO_2 treatments at $p<0.05$. A greater 1000-grain weight was recorded in MR219 compared to Sri Malaysia1 (Table 2). Significant differences in grain yield for both varieties and CO_2 treatments were detected at $p<0.05$. Greater grain yield was recorded in MR219, followed by the Sri Malaysia1 variety. For CO_2 treatments, the highest grain yield was recorded in eCO_2, followed by the aCO_2 and control, as presented in Table 2. Grain yield in the eCO_2 increased significantly by 47.48% compared to the control (Table 2)

Table 3: Interaction effects between elevated CO_2 and variety on the number of spikelet's per panicle of rice

Within the column, means with the same letter are not significantly different at $p<0.05$ using LSD. Values are the mean ± SE of two plants derived from four blocks (n=8) for all groups of treatments and varieties.

Significant interaction effects for spikelet per panicle between CO_2 treatments and varieties were observed at $p < 0.05$. Although the interaction between CO_2 and variety is significant, the greatest number of spikelets per panicle was recorded in eCO_2 treatment in MR219 and Sri Malaysia varieties (Table 3).

CO_2 treatment	Variety MR219	Sri Malaysia1
	------------- No. spikelet per panicle-----------------	
Ambient CO_2	80.50 ± 2.10^b	85.00 ± 1.82^b
Control	79.25 ± 0.85^b	80.50 ± 0.64^b
Elevated CO_2	106.49 ± 3.55^a	96.91 ± 2.79^a

For MR219, the highest panicle number was recorded for eCO_2, followed by aCO_2 and control; eCO_2 increased spikelet per panicle by 34.27% to control. For Sri Malaysia1, the highest spikelet per panicle was for eCO_2, followed by aCO_2 and control. The eCO_2 treatment increased by 20.37% in comparison to control (Table 3)

Discussion

The increment in tiller number per plant may be due to rice's high growth and seedlings' capacity, while a similar result was reported by Raj et al. (2019) and Maity et al. (2019). Panicle number was also increased by 20.96% under eCO_2, possibly due to the high photosynthetic rate, which brings about fast plant growth and produces a high tiller number. Similar results were reported by Wang et al. (2015). Interestingly, the non-productive tiller number significantly decreased in eCO2 by 30.83% compared to the control, likely due to the increase in panicle number. Within each CO_2 treatment, the non-productive tiller per plant is about 17% in eCO_2 compared to 27 and 28% in aCO_2 and control treatments, respectively.

Filled grain per panicle and yield were significantly higher under eCO_2, whereas filled grain per panicle increased by 15.30% under eCO2 conditions compared to the control. Yoshida (1973) reported that the 30-day enrichment of rice plants after flowering increased grain yield by 10% due to the production of high-filled grain per panicle. Nonetheless, Satapathy et al. (2015) reported that eCO_2 in the open-top chamber decreased grain per panicle. Furthermore, the number of spikelets per panicle was also increased in eCO_2 compared to the control for both MR219 and Sri Malaysia 1 rice varieties by 34.25% and 20.37%, respectively. Moreover, grain yield was also significantly increased by 47.48% by eCO_2 due to high growth, high tiller number, and high panicle number along with high filled grain per panicle. A similar result was reported by Seneweera (2011), which was that eCO_2 increased yield by 27%. Elevated CO_2 treatment increased the plant`s potential to improve grain yield. Thus, it is suggested that the above-mentioned sustainable method be used to increase rice yield by rice farmers worldwide, including Afghan rice farmers.

Conclusion

Rice (*Oryza sativa* L.) is one of the *Poaceae* family`s members, and it is a semi-aquatic annual grass plant. Since ancient times, rice has been the staple food for individuals in different nations. Rice is one of the world's most important crops and the first staple food in Asia, providing nutrition for many populations. Current changes in climate and rising atmospheric CO_2 concentration have different global impacts on crop performance. Since CO_2 is one of the limiting factors in photosynthesis, any increase in its concentration would improve carboxylation activity. Instead of constantly adding CO_2, the current study employed a new approach in which elevated CO_2 (eCO_2) enriches the rice plant only during its early vegetative stage before being transplanted into a typical cultivation area. Rice seedlings were germinated and grown in the eCO_2 condition for four weeks. Then, the eCO_2-treated seedlings were transplanted in the bucket containing soil and placed in the rain shelter using a randomized completely block design (RCBD) arrangement.

After being transplanted into the field, the rice plant harvest components improved significantly even though they were no longer treated with eCO_2. The tiller and panicle numbers per plant were increased by 18.38% and 20.96%, respectively. Filled grain per panicle increased by 15.30%. On the other hand, eCO_2 decreased the non-productive tiller number by 30.30% and the number of non-filled grains per panicle by 42.04% than the control. The grain yield increased by the eCO_2 treatment compared to the control by 47.48%. In a nutshell, this experiment showed some positive effects on rice yield. Hence, the application of eCO_2 on rice seedlings before field cultivation is considered a promising method that may have the potential to be used by farmers in improving rice yield components. This new cultivation technique may facilitate farmers not only growing rice with high yield to cater to the demand for rice supply but also increasing their income and improving their livelihood.

Rice has been cultivated in Afghanistan by conventional methods. Based on the achievement from the current study, instead of continuously enriching rice plants with CO_2 during all growth stages, which is expensive and not applicable in the field by farmers in Afghanistan, treating rice seedlings only during the seedling stage in the nursery with CO_2 from sustainable sources (yeast and sugar) will increase rice yield. Thus, applying the above-mentioned new method in rice production in Afghanistan will improve rice yield sustainably and farmers' incomes, result in self-sufficient Afghanistan in rice production in the future, and promote Afghanistan’s agriculture sectors. It is recommended that more research be conducted in the field conditions of rice cultivation areas in the country.

Conflict of Interst: The author(s) declared no conflict of interest.

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