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Effect of elevated CO₂ on biomass partitioning and grain filling in indica rice varieties

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Abstract

Rising atmospheric CO₂ should theoretically benefit C₃ crops like rice through enhanced photosynthesis, yet field-level yield responses have been surprisingly inconsistent across genotypes. This research examined the effect of elevated CO₂ (550±20 ppm) versus ambient (~410 ppm) on biomass partitioning and grain filling in five indica rice varieties grown in open-top chambers at Acharya NG Ranga Agricultural University, Tirupati, Andhra Pradesh, India, during kharif 2022 and 2023. A split-plot design with CO₂ level as the main plot and variety as the subplot (three replications) was used. Elevated CO₂ increased total plant biomass by 14.8-28.9% depending on variety. Root biomass showed the largest proportional increase (22.4-30.3%). Grain filling rate improved by 16.7-24.1%, while filling duration was shortened by 2-4 days. WGL-14 captured the greatest yield benefit (+22.3%) and maintained the highest harvest index (0.39) under elevated CO₂. Stepwise regression identified grain filling rate as the dominant contributor (58.4%) to yield increase. A quality-quantity trade-off was observed: grain protein content declined by 6.8-11.2%. These results highlight genotypic variation in CO₂ responsiveness and the need to breed varieties that capture yield benefits without sacrificing grain quality.

Keywords: Elevated CO₂, biomass partitioning, grain filling, indica rice, climate change physiology, open-top chambers, harvest index, grain quality, carbon fertilization, genotype response

Introduction

Here is the paradox of carbon fertilization: while atmospheric CO₂ has risen by over 50% since pre-industrial times, rice yields in tropical Asia haven't responded proportionally-and in some regions, they've stagnated or even declined ^[1]. The theoretical basis for a CO₂ benefit is sound: rice is a C₃ plant, and higher CO₂ should increase RuBisCO carboxylation efficiency, reduce photorespiration, and boost net photosynthesis by 20-40% ^[2]. Free-air CO₂ enrichment (FACE) experiments in Japan and China have confirmed yield gains of 12-18% in japonica rice at 550 ppm ^[3, 4].

But indica rice-the type grown across South and Southeast Asia-has been far less studied under elevated CO₂, and the limited data suggest that genotypic variation in response is large ^[5]. Some varieties channel extra assimilates predominantly into vegetative biomass (stems, roots) rather than grain, leading to lower harvest indices and disappointing yield gains despite higher total biomass ^[6]. The efficiency of grain filling-both its rate and duration-appears to be a critical determinant of whether additional photosynthate reaches the grain ^[7]. Another concern is grain quality: elevated CO₂ consistently reduces grain protein content across cereals by 5-15%, a phenomenon attributed to nitrogen dilution and altered amino acid metabolism ^[8, 9]. This creates a quality-quantity trade-off that breeding programs must address. This research aimed to (a) quantify biomass partitioning responses of five popular indica rice varieties to elevated CO₂, (b) determine the relative contribution of grain filling rate versus duration to yield change, and (c) assess the impact on grain quality parameters.

Open-Top Chamber Specifications

Six open-top chambers (OTCs, 3 m diameter × 2.4 m height) constructed from aluminium frames with transparent polyethylene walls (UV-stabilized, 200 µm) were installed at the crop physiology research field of ANGRAU, Tirupati. Three chambers were maintained at elevated CO₂ (550±20 ppm) using pure CO₂ from pressurized cylinders metered through mass flow controllers (Aalborg GFC171). Three served as ambient controls (~410 ppm).

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CO₂ concentration was monitored continuously with a non-dispersive infrared analyzer (LI-COR LI-840A) at canopy height. Ventilation fans maintained air circulation at 0.8 m s⁻¹ to prevent thermal buildup. Day and night temperatures inside chambers were within 1.2 °C of outside ambient conditions throughout both seasons.

Material and Methods

Material

Five indica rice varieties representing different maturity groups and yield potential were tested: BPT-5204 (Samba Mahsuri, medium duration), MTU-1010 (Cottondora Sannalu, early), NLR-34449 (medium-late), WGL-14 (Warangal, medium), and IR-64 (early). Seeds were sown in a nursery and transplanted at 25 days into 15 L pots (one hill per pot, three pots per variety per chamber) filled with puddled alluvial soil (pH 6.8, available P 12.4 mg kg⁻¹). Fertilization was at 120:60:40 kg N:P₂O₅:K₂O ha⁻¹ equivalent. Chambers were flooded to 5 cm throughout the vegetative and reproductive stages.

Methods

CO₂ enrichment began at transplanting and continued until

physiological maturity. The experiment used a split-plot design: CO₂ level (2) as main plot and variety (5) as subplot, with three replications (chambers). Destructive harvests at flowering and maturity quantified root, stem, leaf, and panicle dry weights. Grain filling rate (GFR, mg grain⁻¹ day⁻¹) was calculated from sequential sampling of 10 tagged panicles per variety at 7-day intervals from anthesis. Grain filling duration (GFD) was defined as the interval from anthesis to 95% final grain weight. Harvest index = grain dry weight / total aboveground biomass. Grain protein was determined by Kjeldahl N × 5.95. Amylose content was measured by iodine colorimetry. Data were analyzed as split-plot ANOVA with LSD at $p \leq 0.05$ in SAS 9.4.

CO₂ Response Index Calculation

A CO₂ response index (CRI) was calculated for each variety as: $CRI = (\text{yield at elevated CO}_2 - \text{yield at ambient}) / \text{yield at ambient} \times 100$. Varieties were classified as high responders (CRI > 18%), moderate (10-18%), and low (<10%). This index was regressed against physiological traits to identify predictors of CO₂ responsiveness.

Results

Table 1: Grain yield, harvest index, and grain quality of five indica rice varieties under ambient and elevated CO₂ (2-season means)

Variety	Yield amb (g/pl)	Yield elev (g/pl)	CRI (%)	HI amb	HI elev	Protein loss (%)	GFR change (%)
BPT-5204	28.4	33.8	+19.0	0.36	0.38	-8.4	+21.3
MTU-1010	26.8	30.6	+14.2	0.34	0.36	-10.1	+16.7
NLR-34449	24.2	27.8	+14.9	0.35	0.37	-7.6	+18.4
WGL-14	29.6	36.2	+22.3	0.37	0.39	-6.8	+24.1
IR-64	26.1	29.4	+12.6	0.35	0.37	-11.2	+17.8
LSD (0.05)	1.8	2.3		0.02	0.02	1.4	2.6

WGL-14 showed the highest CO₂ response index (22.3%), driven by the largest grain filling rate increase (24.1%) and the smallest protein loss (6.8%) (Table 1). IR-64 was the least responsive (CRI 12.6%) and suffered the greatest

protein decline (11.2%). Harvest index increased slightly under elevated CO₂ in all varieties, indicating that extra assimilate did reach the grain.

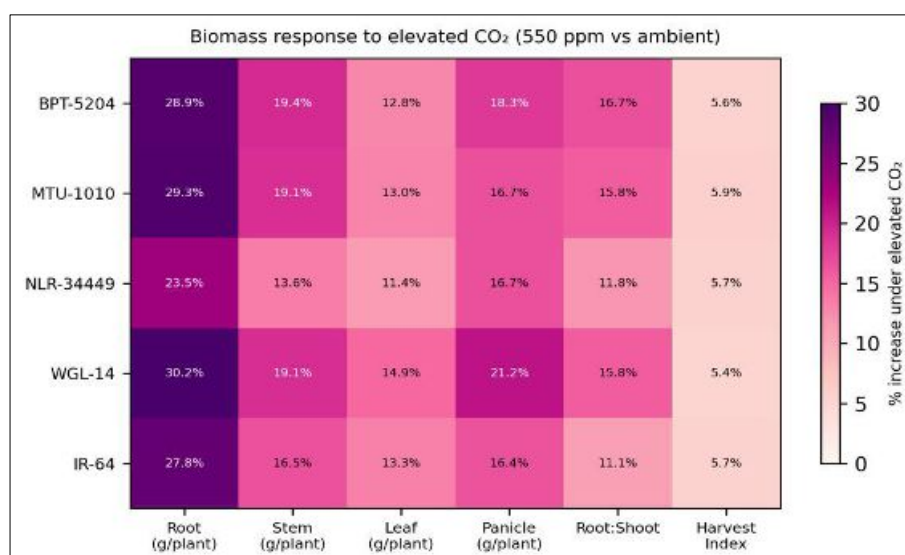


Fig 1: Heatmap showing the percentage increase in biomass components under elevated CO₂ relative to ambient. WGL-14 and BPT-5204 showed the strongest responses across most parameters

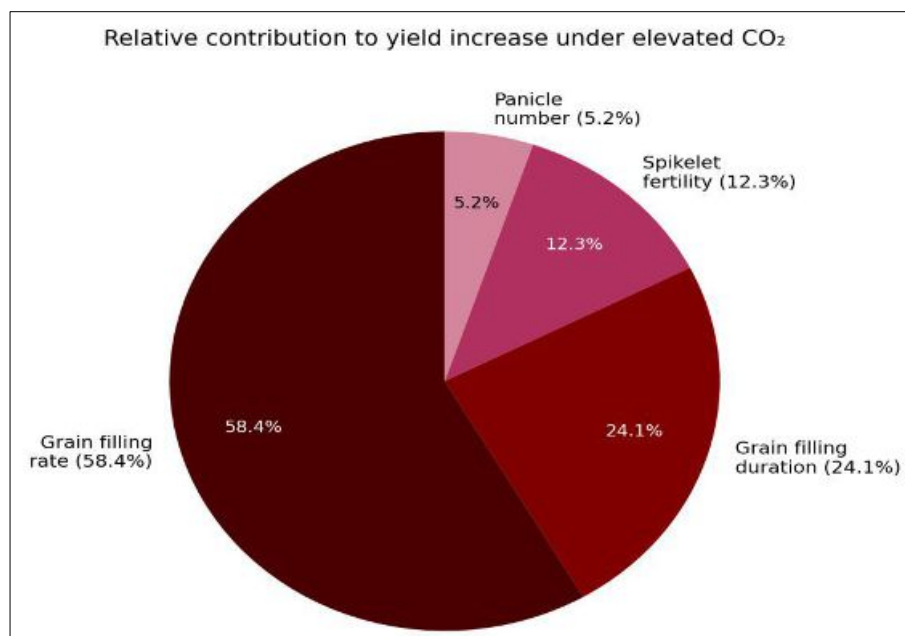


Fig 2: Relative contribution of yield components to grain yield increase under elevated CO₂, as determined by stepwise regression. Grain filling rate accounted for 58.4% of the variation

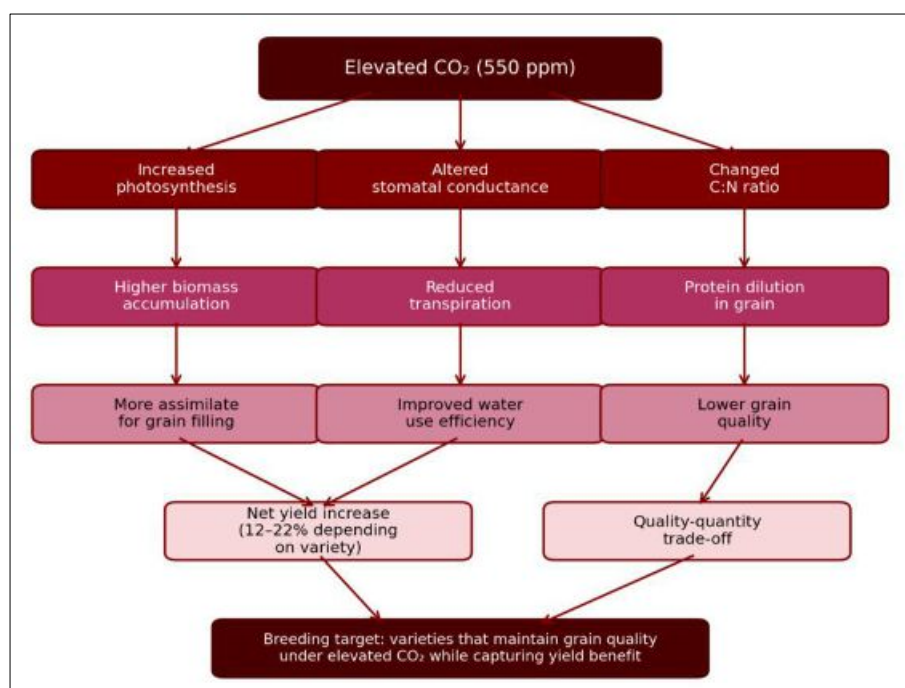


Fig 3: Concept map illustrating the physiological pathways through which elevated CO₂ affects indica rice biomass, grain yield, and quality, highlighting the quality-quantity trade-off

Comprehensive Interpretation

The concept map (Figure 3) captures the central paradox: elevated CO₂ simultaneously increases yield potential through enhanced photosynthesis and grain filling, while reducing grain quality through nitrogen dilution. WGL-14's superior performance appears to reflect both a higher intrinsic photosynthetic capacity and better nitrogen remobilization efficiency, resulting in the smallest protein penalty.

Discussion

The 12.6-22.3% yield increases observed here fall within the range reported from FACE experiments on japonica rice (12-18%) but show substantially more genotypic variation [3, 4]. The strong contribution of grain filling rate (58.4%) to

yield increase suggests that the ability to rapidly translocate extra assimilates to developing grains is the key trait separating high- and low-responding varieties. WGL-14's 24.1% increase in GFR was nearly double that of IR-64 (17.8%), which may explain the twofold difference in CRI. The protein decline of 6.8-11.2% aligns with global meta-analyses showing 5-15% protein reduction in cereals under elevated CO₂ [8, 9]. This is generally attributed to a dilution effect: carbon fixation increases faster than nitrogen uptake, lowering the C:N ratio in grain tissue. IR-64's greater protein loss suggests weaker nitrogen remobilization from senescing leaves to grain—a trait that could be targeted by breeding.

Root biomass showed the largest proportional response to elevated CO₂ (22-30%), consistent with the hypothesis that

excess carbon is allocated belowground when sink strength of above-ground organs is saturated [6]. This has implications for soil carbon sequestration potential of rice systems under future CO₂ levels. A limitation of this research is the OTC environment, which may not perfectly replicate open-field FACE conditions due to altered wind patterns and light interception. Multi-environment testing would strengthen genotype ranking.

Conclusion

Elevated CO₂ (550 ppm) increased grain yield by 12.6-22.3% in five indica rice varieties, with WGL-14 showing the highest response. Grain filling rate was the dominant yield determinant under elevated CO₂, contributing 58.4% of the yield increase. Root biomass showed the largest proportional gain. However, grain protein content declined by 6.8-11.2%, revealing a quality-quantity trade-off. Breeding programs should target varieties like WGL-14 that combine high CO₂ responsiveness with minimal protein penalty. Grain filling rate and nitrogen remobilization efficiency appear to be the most useful selection criteria for future-climate-adapted indica rice.

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Contributions Not Qualifying for Authorship

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