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Response of Mungbean (Vigna radiata L.) Growth and Biomass Allocation to Elevated CO_2 Levels[1]

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Abstract

Rising atmospheric carbon dioxide (CO_2) concentration is a key driver of global climate change and has profound implications for the growth and productivity of C_3 crops. Mungbean (Vigna radiata L.), an important pulse crop valued for its high protein content and short growth duration, is expected to respond positively to CO_2 enrichment. The present study examines the effects of different elevated CO_2 levels on growth performance and biomass allocation of mungbean grown under open top chamber (OTC) conditions. Observations on root, shoot and leaf dry weight, leaf area, total biomass and root–shoot ratio were recorded at 30 days after sowing (DAS) and at maturity. Elevated CO_2 significantly enhanced dry matter accumulation in all plant parts, with a more pronounced effect during the early growth stage. Biomass partitioning was altered under elevated CO_2, showing increased allocation towards roots and shoots, indicative of improved sink strength and carbon assimilation efficiency. Enhanced leaf area and total biomass under CO_2 enrichment contributed to improved overall plant growth. The findings suggest that mungbean exhibits strong positive growth and biomass responses to elevated CO_2, highlighting its potential adaptability and resilience under future climate change scenarios characterized by increased atmospheric CO_2 levels.

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Keywords

Elevated CO_2, Mungbean, Dry matter partitioning, Biomass allocation, Climate change.

1. Introduction

Atmospheric carbon dioxide (CO_2) concentration has increased substantially since the onset of the industrial revolution, primarily due to intensified anthropogenic activities such as large-scale combustion of fossil fuels, deforestation, rapid industrialization, and expanding urbanization. From a pre-industrial level of approximately 280 ppm, atmospheric CO_2 concentrations have risen steadily and are currently exceeding 420 ppm. Climate model projections indicate that CO_2 levels may reach 550–600 ppm by the middle of the twenty-first century, coinciding with a rise in global mean temperatures and increased climatic variability. These concurrent changes are expected to exert profound influences on terrestrial ecosystems and agricultural systems, with direct implications for crop growth, productivity, and the efficient use of resources such as water and nutrients.

Plant responses to elevated atmospheric CO_2 are largely governed by their photosynthetic pathways, physiological traits, and adaptive capacities. Crops following the C_3 photosynthetic pathway generally exhibit a stronger positive response to CO_2 enrichment than C_4 plants. This is primarily because elevated CO_2 reduces the oxygenation reaction of ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco), thereby suppressing photorespiration and enhancing carboxylation efficiency. Consequently, increased CO_2 availability often leads to higher rates of net photosynthesis, greater accumulation of carbohydrates, and improved biomass production in C_3 crops. In addition, partial stomatal closure under elevated CO_2 conditions can reduce transpirational water loss, thereby improving water-use efficiency. However, the magnitude and sustainability of these responses vary widely among species, genotypes, and developmental stages and are strongly influenced by environmental factors such as nutrient availability, soil moisture, temperature, and light conditions.

Mungbean (*Vigna radiata* L.) is a short-duration, self-pollinated C_3 legume crop extensively cultivated in tropical and subtropical regions, particularly across South and Southeast Asia, including India. It is valued for its high protein content, balanced amino acid composition, easy digestibility, and relatively low input requirements. In addition to its nutritional importance, mungbean contributes to soil health and sustainability through biological nitrogen fixation, making it an integral component of cereal-based cropping systems and crop rotations. Owing to its rapid growth cycle, high photosynthetic efficiency, and sensitivity to environmental changes, mungbean is considered a suitable model crop for examining the impacts of elevated atmospheric CO_2 on growth dynamics, carbon assimilation, and dry matter production.

Biomass production and its partitioning among different plant organs are critical determinants of crop performance, stress tolerance, and yield potential. The allocation of assimilated carbon between roots, stems, leaves, and reproductive organs determines canopy architecture, root system development, and overall source–sink relationships. Under elevated CO_2 conditions, changes in carbon allocation patterns can significantly influence plant morphology and physiology. Enhanced

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allocation of assimilates to root systems may improve nutrient and water uptake, thereby supporting sustained growth under resource-limited conditions. Similarly, increased shoot and leaf biomass can expand the photosynthetically active surface area, further reinforcing carbon gain. However, disproportionate vegetative growth without corresponding enhancement of reproductive sinks may limit yield benefits, highlighting the importance of understanding biomass partitioning responses under CO_2 enrichment.

Although several experimental studies have documented positive growth responses of legumes to elevated CO_2, comprehensive information on dry matter accumulation and biomass partitioning in mungbean remains limited, particularly under Indian agro-climatic conditions characterized by diverse soil types, temperature regimes, and moisture availability. Most existing studies have focused on overall growth or yield responses, with relatively less emphasis on organ-specific biomass distribution and its implications for crop productivity. Therefore, a detailed evaluation of mungbean growth and biomass allocation under elevated CO_2 environments is essential to bridge this knowledge gap.

In this context, the present study was undertaken to evaluate the effects of different elevated CO_2 levels on growth characteristics and biomass partitioning of mungbean using open top chamber (OTC) conditions. By analyzing dry matter accumulation in various plant components, the study aims to enhance understanding of mungbean's physiological adaptability under future climate change scenarios and to provide scientific insights for the development of climate-resilient and sustainable pulse production systems.

2. Literature Review

Rising atmospheric carbon dioxide (CO_2) concentration is one of the most significant components of global climate change and has profound implications for agricultural productivity. Extensive research over the past few decades has focused on understanding plant responses to elevated CO_2, particularly in relation to growth, biomass accumulation, and yield. As mungbean (*Vigna radiata* L.) is a C_3 legume crop, its physiological and morphological responses to CO_2 enrichment have received increasing attention.

Early studies established that elevated CO_2 generally enhances photosynthetic rates in C_3 plants by increasing the availability of CO_2 for carboxylation and reducing photorespiration (Kimball, 1983; Pearcy & Björkman, 1983). This enhanced photosynthesis often translates into increased dry matter production, larger leaf area, and improved plant growth. Long et al. (2004) and Ainsworth and Long (2005) reported that CO_2 enrichment significantly improves biomass accumulation and canopy development in several C_3 crops, although the magnitude of response varies among species and environmental conditions.

Leguminous crops, owing to their ability to fix atmospheric nitrogen, are considered particularly responsive to elevated CO_2. Rogers et al. (2009) suggested that legumes may have a competitive advantage under CO_2-enriched conditions due to enhanced carbon supply supporting greater nitrogen fixation and sink development. Studies on soybean, cowpea, and mungbean have consistently reported increases in plant height, leaf area, and dry matter accumulation under elevated CO_2 (Bhattacharya et al., 1985; Cure et al., 1989; Srivastava et al., 2002).

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Research specifically on mungbean indicates a strong positive growth response to elevated CO_2. Uprety et al. (1996) observed enhanced photosynthetic rates, increased root and shoot growth, and greater total biomass in mungbean under elevated CO_2 conditions. Similarly, Chowdhury et al. (2005) reported significant improvements in mungbean growth and productivity under CO_2 enrichment, attributing these responses to faster photosynthesis and improved carbon assimilation efficiency. Das et al. (2000) further noted that early exposure to elevated CO_2 resulted in greater vegetative growth and higher yield components in mungbean.

Biomass partitioning is a critical determinant of crop performance, as it governs the distribution of assimilated carbon among roots, shoots, and leaves. Several studies have reported altered biomass allocation patterns under elevated CO_2, often characterized by increased root biomass and higher root:shoot ratios, particularly during early growth stages (Poorter, 1993; Baxter et al., 1997). Enhanced root growth under CO_2 enrichment has been linked to improved nutrient and water uptake, which can support sustained above-ground growth and yield formation. Srivastava et al. (2001) observed increased allocation of dry matter to roots, stems, and leaves in mungbean under elevated CO_2, indicating improved sink strength and growth efficiency.

Leaf area development is another important response to elevated CO_2. Increased leaf area under CO_2 enrichment has been widely reported and is associated with improved light interception and photosynthetic capacity (Cure et al., 1989; Pal et al., 2004). However, some studies have also noted reductions in leaf nitrogen concentration under elevated CO_2, which may influence long-term photosynthetic performance and crop quality (Conroy, 1992; Bloom et al., 2010). Despite this, many legumes appear capable of sustaining growth responses due to their nitrogen-fixing ability and flexible sink–source relationships.

While the beneficial effects of elevated CO_2 on growth and biomass production are well documented, several authors have emphasized that these responses are strongly influenced by interacting factors such as nutrient availability, water supply, and temperature (Fangmeier et al., 2002; Leakey et al., 2009). Under nutrient- or water-limited conditions, the positive effects of CO_2 enrichment may be reduced. Therefore, understanding crop-specific responses under controlled and semi-controlled environments remains essential.

In summary, the existing literature indicates that elevated CO_2 generally enhances growth, biomass accumulation, and alters biomass partitioning in C_3 legumes, including mungbean. However, variability in responses due to growth stage and environmental conditions highlights the need for crop- and region-specific studies. The present investigation builds upon earlier findings by examining the effects of elevated CO_2 on growth and biomass allocation in mungbean under open top chamber conditions, thereby contributing to a better understanding of its adaptive potential under future climate change scenarios.

3. Materials and Methods

3.1 Experimental Site

The field experiment was conducted during the **kharif season of 2019–20** at the experimental farm of the **Department of Environmental Sciences, College of Agriculture, Rajmata Vijayaraje Scindia**

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Krishi Vishwa Vidyalaya (R.V.S.K.V.V.), Gwalior, Madhya Pradesh, India. The experimental site is located in the **north-central part of India** and falls under a **subtropical agro-climatic zone**, characterized by hot summers, mild winters, and a monsoon-driven rainfall pattern.

The region experiences high temperatures during the summer months, while winter temperatures remain moderate. The average annual rainfall ranges between **600–800 mm**, most of which is received during the southwest monsoon season. During the experimental period, meteorological parameters such as maximum and minimum temperature, relative humidity, rainfall, and sunshine hours were recorded regularly from the nearby agrometeorological observatory. These climatic conditions remained favourable for mungbean growth and development throughout the cropping season, ensuring minimal climatic stress on the crop.

3.2 Experimental Design and CO_2 Treatments

The experiment was conducted using **open top chambers (OTCs)** to study the response of mungbean to varying atmospheric CO_2 concentrations under semi-controlled field conditions. OTCs were constructed using transparent polyvinyl chloride (PVC) sheets supported by a metal framework, allowing natural solar radiation while maintaining controlled CO_2 levels within the chambers.

The study was laid out in a **completely randomized design (CRD)** with appropriate replications to ensure statistical validity. The treatments consisted of:

- **Ambient CO_2 concentration (control)**, representing the prevailing atmospheric CO_2 level, and
- **Elevated CO_2 treatments**, where CO_2 concentration was maintained above ambient levels inside the OTCs.

Elevated CO_2 was supplied from compressed CO_2 cylinders and regulated through a controlled delivery system. The CO_2 concentration inside the chambers was continuously monitored using a CO_2 analyser to maintain the desired concentration throughout the crop growth period. Uniform exposure of plants to CO_2 was ensured by proper mixing of air inside the chambers and regular calibration of monitoring instruments.

3.3 Crop Material and Cultural Practices

Mungbean (*Vigna radiata* L.) variety **TJM-3** was selected for the experiment owing to its adaptability to the agro-climatic conditions of the region and its widespread cultivation. Seeds were sown at the recommended spacing to ensure optimum plant population and uniform crop stand.

Standard agronomic practices recommended for mungbean cultivation in the region were followed uniformly across all treatments. A **uniform basal dose of fertilizers** was applied to all plots to avoid nutrient limitation and to isolate the effects of CO_2 treatments on crop growth. Irrigation was provided as and when required to prevent moisture stress. Weeding and intercultural operations were carried out manually at critical growth stages. Plant protection measures were adopted uniformly to safeguard the crop from pests and diseases, ensuring that treatment effects were solely due to CO_2 concentration.

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3.4 Observations on Growth and Biomass Parameters

Observations on growth and biomass parameters were recorded at two critical growth stages, namely **30 days after sowing (DAS)** and **physiological maturity**, to assess early growth response and final biomass accumulation. Representative plants were carefully uprooted from each treatment without disturbing the root system.

The plants were washed gently under running water to remove adhering soil particles and then separated into **roots, shoots, and leaves**. Each plant component was dried in a **hot air oven at 65 ± 2 °C** until constant weight was attained. The dried samples were weighed using a precision balance to record dry matter accumulation.

The following growth and biomass parameters were measured:

- Root dry weight (g plant^{-1})
- Shoot dry weight (g plant^{-1})
- Leaf dry weight (g plant^{-1})
- Total biomass (g plant^{-1})
- Root length and shoot length (cm)
- Leaf area (cm^2 plant^{-1})
- Root:shoot ratio

3.5 Measurement of Leaf Area

Leaf area was determined using a **leaf area meter**, ensuring accurate measurement of individual leaves and total leaf area per plant. In cases where direct measurement was not feasible, the **graphical method** was employed to validate the observations. Leaf area index (LAI) and total leaf area per plant were calculated following standard procedures described in agronomic literature. Leaf area data were used to assess the photosynthetic potential and canopy development of mungbean under different CO_2 treatments.

3.6 Statistical Analysis

The data collected from the experiment were subjected to **analysis of variance (ANOVA)** to evaluate the significance of treatment effects on growth and biomass parameters. Treatment means were compared using the **critical difference (CD) test at the 5% level of significance.** Standard error of mean (SEm ±) and **coefficient of variation (CV)** were calculated to assess experimental precision and reliability of the results. All statistical analyses were carried out following standard statistical procedures applicable to completely randomized design experiments.

4. Results

The influence of elevated atmospheric CO_2 levels on growth, dry matter accumulation, and biomass partitioning in mungbean is presented in this section. Observations were recorded at **30 days after sowing (DAS)** and at **physiological maturity** to assess both early vegetative responses and final

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biomass outcomes. Overall, mungbean exhibited a strong positive response to CO_2 enrichment, with significant improvements observed in growth parameters and dry matter allocation.

4.1 Effect of Elevated CO_2 on Root Dry Weight

Root dry weight of mungbean was significantly influenced by elevated CO_2 levels at both growth stages. At **30 DAS**, plants grown under elevated CO_2 recorded markedly higher root dry weight compared to those grown under ambient CO_2 conditions. This enhancement indicates increased allocation of photosynthetically assimilated carbon towards below-ground plant parts during early vegetative growth, promoting better root development.

At **physiological maturity**, root dry weight remained significantly higher under elevated CO_2; however, the magnitude of increase was comparatively lower than that observed at 30 DAS. This suggests that CO_2 enrichment primarily stimulates early root growth, which subsequently supports overall plant development throughout the crop life cycle.

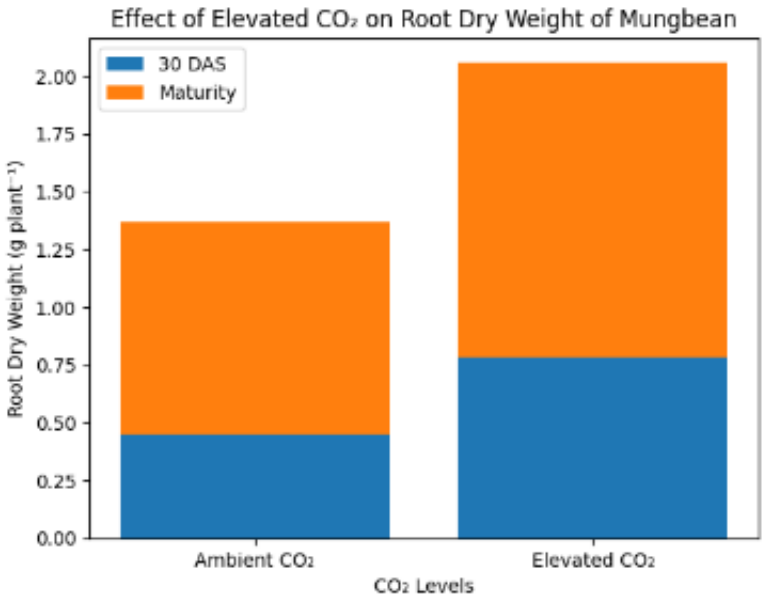


Figure 1. Effect of elevated CO_2 levels on root dry weight (g plant^{-1}) of mungbean at 30 DAS and at maturity.

4.2 Effect of Elevated CO_2 on Shoot Dry Weight

Shoot dry weight responded positively and significantly to elevated CO_2 levels at both observation stages. At **30 DAS**, plants exposed to elevated CO_2 showed substantially greater shoot dry matter accumulation than those under ambient CO_2. The enhanced shoot biomass reflects increased photosynthetic efficiency, accelerated vegetative growth, and greater carbon availability under CO_2-enriched conditions.

At **maturity**, shoot dry weight continued to remain significantly higher under elevated CO_2, indicating sustained carbon assimilation and translocation to above-ground plant parts throughout the growing

period. The continued increase in shoot biomass suggests that elevated CO_2 supports prolonged vegetative vigour in mungbean.

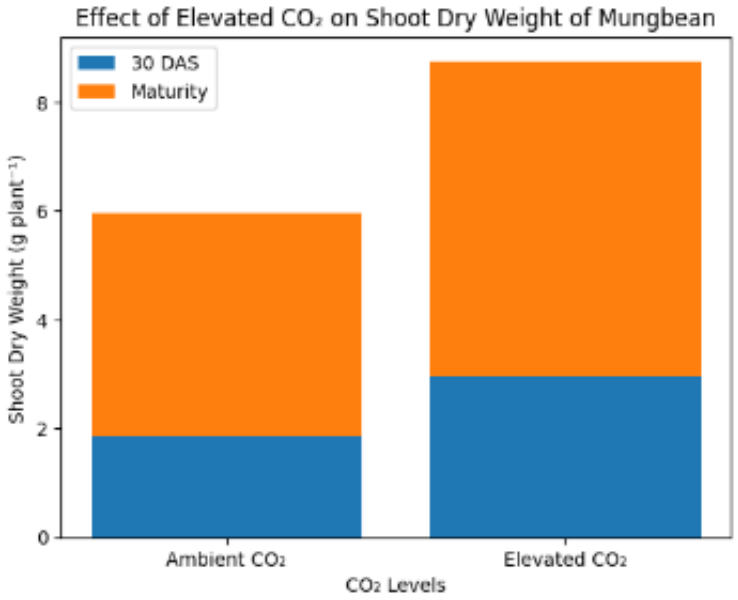


Figure 2. Effect of elevated CO_2 levels on shoot dry weight (g plant^{-1}) of mungbean at different growth stages.

4.3 Effect of Elevated CO_2 on Leaf Dry Weight

Leaf dry weight was significantly enhanced under elevated CO_2 at both 30 DAS and maturity. The increase was more pronounced at the early growth stage, indicating rapid leaf initiation and expansion under CO_2 enrichment. Increased leaf biomass under elevated CO_2 contributed to improved canopy development and a larger photosynthetic surface area.

At maturity, although the rate of increase in leaf dry weight was comparatively lower, plants under elevated CO_2 still maintained significantly higher leaf biomass than those under ambient conditions. This enhanced leaf development played a crucial role in supporting higher total biomass production.

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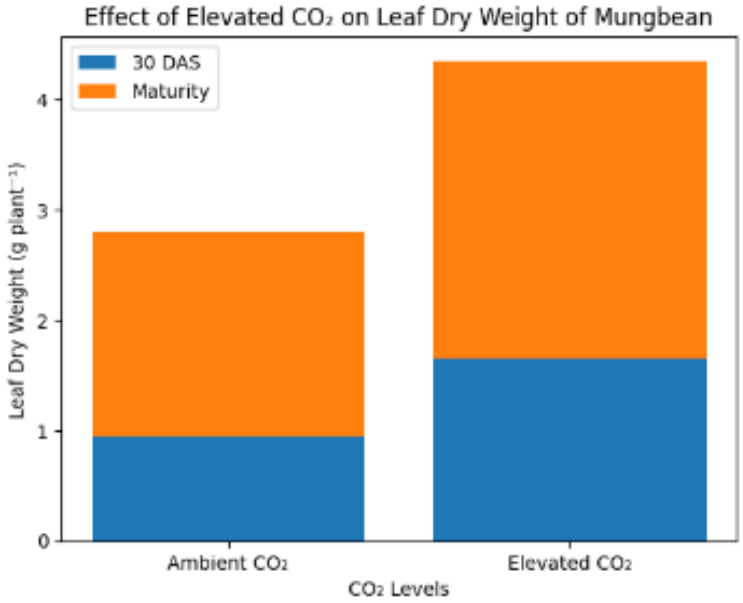


Figure 3. Effect of elevated CO_2 levels on leaf dry weight (g plant^{-1}) of mungbean.

4.4 Total Biomass Accumulation

Total biomass per plant was significantly increased under elevated CO_2 conditions at both stages of crop growth. At **30 DAS**, elevated CO_2 treatments recorded substantially higher total biomass compared to ambient CO_2, highlighting the strong stimulatory effect of CO_2 enrichment during early vegetative growth.

At **maturity**, the cumulative effect of enhanced growth resulted in significantly greater total biomass under elevated CO_2 levels. This increase in total biomass reflects the combined effect of improved root, shoot, and leaf growth under CO_2 enrichment.

Table 1. Effect of elevated CO_2 levels on total biomass (g plant^{-1}) of mungbean at 30 DAS and at maturity.

CO_2 Level	**Total biomass (g plant^{-1}) at 30 DAS**	**Total biomass (g plant^{-1}) at maturity**
Ambient CO_2	3.25	7.80
Elevated CO_2	5.40	11.20
SEm (±)	0.18	0.32
CD (P = 0.05)	0.52	0.94
CV (%)	7.6	8.3

Interpretation:

Elevated CO_2 significantly increased total biomass of mungbean at both growth stages. At 30 DAS, plants grown under elevated CO_2 recorded substantially higher biomass compared to ambient CO_2, indicating enhanced early vegetative growth. At physiological maturity, the cumulative effect of increased dry matter accumulation resulted in significantly greater total biomass under elevated CO_2

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conditions. The results demonstrate a strong stimulatory effect of CO_2 enrichment on overall biomass production in mungbean.

4.5 Effect on Root and Shoot Length

Root length and shoot length were significantly influenced by elevated CO_2 levels. Plants grown under elevated CO_2 exhibited longer roots and taller shoots compared to those under ambient CO_2 conditions at both growth stages. Enhanced root elongation under elevated CO_2 suggests improved soil exploration and nutrient acquisition capacity, while increased shoot length reflects vigorous above-ground growth.

The effect was more prominent at **30 DAS**, indicating that elevated CO_2 accelerates early plant development and establishes a stronger structural framework for subsequent growth.

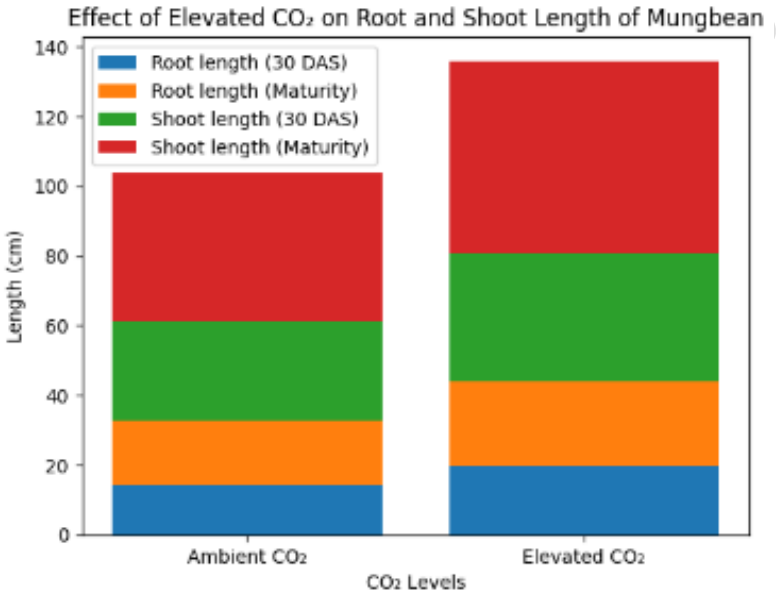


Figure 4. Effect of elevated CO_2 on root length and shoot length of mungbean.

4.6 Leaf Area Development

Leaf area per plant increased significantly under elevated CO_2 levels at both observation stages. At **30 DAS**, plants under elevated CO_2 exhibited rapid leaf expansion, resulting in significantly larger leaf area compared to ambient CO_2 treatments. Enhanced leaf area under CO_2 enrichment likely improved light interception and photosynthetic efficiency.

At maturity, elevated CO_2 maintained higher leaf area, which contributed to sustained photosynthetic activity and greater biomass accumulation.

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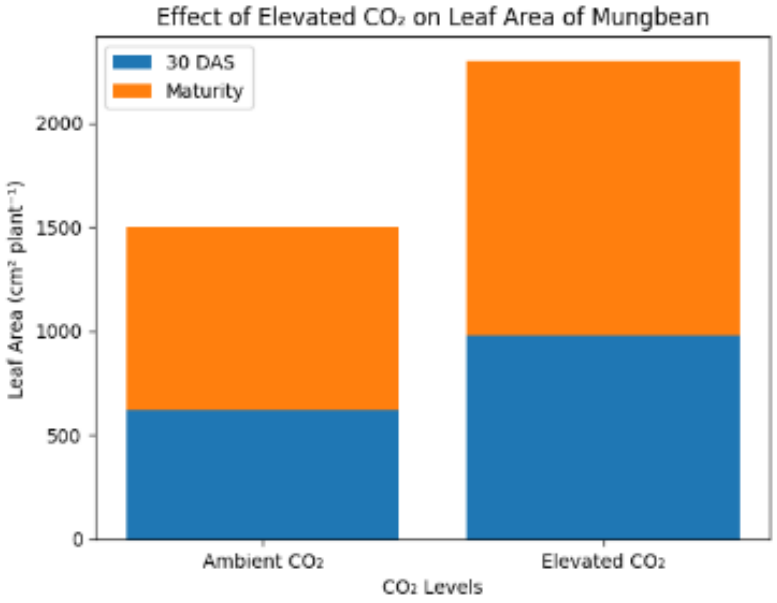


Figure 5. Effect of elevated CO_2 levels on leaf area (cm^2 $plant^{-1}$) of mungbean.

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4.7 Root:Shoot Ratio

Biomass partitioning in mungbean was significantly altered under elevated CO_2, as reflected by changes in the root:shoot ratio. At **30 DAS**, elevated CO_2 increased the root:shoot ratio, indicating preferential allocation of dry matter towards roots during early growth stages. This shift in biomass allocation suggests improved below-ground support for nutrient and water uptake.

At **maturity**, the root:shoot ratio slightly declined compared to early growth stages; however, it remained higher under elevated CO_2 than under ambient conditions, demonstrating a persistent influence of CO_2 enrichment on biomass partitioning.

Table 2. Root:shoot ratio of mungbean under ambient and elevated CO_2 conditions.

CO_2 Level	**Root:Shoot Ratio at 30 DAS**	**Root:Shoot Ratio at Maturity**
Ambient CO_2	0.24	0.21
Elevated CO_2	0.31	0.26
SEm (±)	0.01	0.01
CD (P = 0.05)	0.03	0.03
CV (%)	6.8	7.2

Interpretation

Elevated CO_2 significantly increased the root:shoot ratio of mungbean at both 30 DAS and at physiological maturity. The higher root:shoot ratio under elevated CO_2 at 30 DAS indicates preferential allocation of assimilates towards root growth during early vegetative stages. Although the

ratio declined at maturity, it remained significantly higher under elevated CO_2 compared to ambient CO_2, suggesting a sustained influence of CO_2 enrichment on biomass partitioning.

4.8 Summary of Growth Responses

Overall, elevated CO_2 levels significantly enhanced growth parameters, dry matter accumulation, and biomass allocation patterns in mungbean. The stimulatory effects of CO_2 enrichment were more pronounced during early vegetative growth, highlighting the sensitivity of mungbean to increased atmospheric CO_2 during initial developmental stages. These results clearly demonstrate that elevated atmospheric CO_2 can substantially improve growth performance and biomass production in mungbean, thereby indicating its potential adaptability under future climate change scenarios.

5. Discussion

The present study clearly demonstrates that elevated atmospheric CO_2 significantly enhances growth, dry matter accumulation, and biomass allocation in mungbean (*Vigna radiata* L.). The observed responses are consistent with the well-documented stimulatory effects of CO_2 enrichment on C_3 crops and provide important insights into the growth dynamics of mungbean under future climate change scenarios.

The significant increase in **root dry weight** under elevated CO_2, particularly at 30 DAS, indicates a preferential allocation of assimilated carbon towards below-ground biomass during early vegetative growth. Enhanced root growth under CO_2 enrichment has been widely reported in legumes and is often associated with improved nutrient and water uptake capacity. This early investment in root development likely supports sustained shoot growth and biomass accumulation at later growth stages. Similar increases in root biomass under elevated CO_2 have been reported in mungbean and other legumes, suggesting that enhanced sink strength below ground is a common adaptive response.

The observed increase in **shoot and leaf dry weight** under elevated CO_2 can be attributed to improved photosynthetic efficiency due to reduced photorespiration and increased carboxylation activity of Rubisco in C_3 plants. Enhanced leaf biomass and greater leaf area under CO_2 enrichment increase the photosynthetically active surface, thereby facilitating greater carbon assimilation. The more pronounced response at early growth stages suggests that mungbean is particularly sensitive to CO_2 enrichment during vegetative development, a finding that aligns with earlier studies reporting stronger CO_2 responses during initial growth phases.

Total biomass accumulation was significantly higher under elevated CO_2 at both observation stages, reflecting the cumulative effects of enhanced root, shoot, and leaf growth. The sustained increase in biomass up to maturity indicates that mungbean does not exhibit strong down-regulation of photosynthesis under the CO_2 levels used in this study, possibly due to adequate sink demand and efficient carbon utilization. This response is characteristic of legumes, which often maintain higher sink strength through continuous growth and symbiotic nitrogen fixation.

Changes in **biomass partitioning**, as reflected by the increased root:shoot ratio under elevated CO_2, further support the notion of altered carbon allocation patterns. The higher root:shoot ratio at 30 DAS

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suggests that elevated CO_2 promotes greater carbon investment in roots during early growth, which may enhance plant stability and resource acquisition. Although the root:shoot ratio declined at maturity, it remained higher under elevated CO_2 compared to ambient conditions, indicating a persistent influence of CO_2 enrichment on assimilate distribution.

The increase in **root and shoot length** under elevated CO_2 indicates accelerated morphological development and improved structural growth. Enhanced root elongation facilitates greater soil exploration, while increased shoot length contributes to improved canopy architecture. Similarly, the substantial increase in **leaf area** under elevated CO_2 enhances light interception and photosynthetic capacity, thereby reinforcing positive feedback between canopy development and biomass production.

Overall, the findings of this study corroborate earlier reports on the positive effects of elevated CO_2 on C_3 legumes and highlight mungbean's strong growth responsiveness to CO_2 enrichment. However, it is important to note that the beneficial effects of elevated CO_2 observed under controlled conditions may be influenced by other environmental factors such as nutrient availability, water stress, and temperature in real field situations. Therefore, while elevated CO_2 has the potential to enhance mungbean growth and biomass production, integrated crop management strategies will be essential to fully realize these benefits under future climate change conditions.

6. Conclusion

The present investigation clearly establishes that elevated atmospheric CO_2 levels exert a significant and positive influence on the growth, dry matter accumulation, and biomass allocation of mungbean (*Vigna radiata* L.). Exposure to CO_2-enriched conditions resulted in marked increases in root, shoot, and leaf dry weights, leading to a substantial enhancement in total plant biomass. The improvement in leaf area development under elevated CO_2 further contributed to greater photosynthetic surface and improved carbon assimilation efficiency. These responses were evident at both 30 days after sowing and at physiological maturity, with the magnitude of stimulation being more pronounced during the early vegetative growth phase. This indicates that mungbean is highly sensitive and responsive to CO_2 enrichment during its initial stages of development.

Elevated CO_2 significantly altered biomass partitioning patterns, as reflected by an increased root:shoot ratio, particularly at 30 DAS. Preferential allocation of assimilates towards root growth under CO_2-enriched conditions suggests improved below-ground structural development and enhanced capacity for nutrient and water uptake. This early investment in root biomass likely played a crucial role in supporting sustained shoot growth, greater leaf area expansion, and higher total biomass accumulation at later growth stages. In addition, enhanced root and shoot elongation observed under elevated CO_2 indicates improved morphological development and overall plant vigour.

The increase in leaf biomass and leaf area under elevated CO_2 underscores the role of CO_2 enrichment in accelerating canopy development and enhancing light interception, thereby reinforcing positive feedback between photosynthesis and biomass production. Such improvements in growth

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attributes are characteristic of C_3 crops and were particularly evident in mungbean, owing to its physiological efficiency and leguminous nature.

Overall, the findings of this study suggest that mungbean possesses a strong inherent capacity to benefit from rising atmospheric CO_2 concentrations. These positive growth and biomass responses highlight the potential of mungbean to maintain or even improve productivity under future climate change scenarios dominated by elevated CO_2 levels. However, the realization of these benefits under actual field conditions will depend on the availability of adequate nutrients and water, as CO_2-induced growth stimulation may increase crop demand for essential resources.

In conclusion, the results provide valuable insights into the adaptive potential of mungbean under changing atmospheric environments and underscore its importance in climate-resilient pulse production systems. The study also lays a foundation for future research aimed at evaluating interactive effects of elevated CO_2 with other climatic factors such as temperature, moisture stress, and nutrient availability, which will be critical for developing sustainable agricultural strategies in a changing climate.

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