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Effects of elevated carbon dioxide on plant physiology, nutritional quality and plant biotic factors: A review

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Abstract

Carbon dioxide, methane, and nitrous oxide are some of the important greenhouse gases among which CO_2 ranks first in percent contribution to promote global warming. CO_2 may can contribute to the global warming but it is also a very important gas for plants to carry out photosynthesis. Furthermore, how a plant reacts to Increased CO_2 levels assist to determine future breeding strategies. Increased CO_2 concentrations are expected to boost plant physiological responses in general. A thorough perusal of current literatures on the effects of increasing CO_2 on crops has helped in understanding that an increased CO_2 levels can have both positive and negative impacts on the plant system. Elevated CO_2 conditions not only affect metabolic activities like photosynthesis, quality of protein produced in plants but also influence defense mechanism in plants against biotic (pest and plant pathogen) and abiotic stress; interaction of plant roots with soil microbes.

Keywords: Global warming, carbon dioxide, metabolic activities, biotic and abiotic stress

Introduction

Climate change has emerged as a significant hazard to the natural environment. The fundamental cause of climate change is a rise in carbon dioxide levels in the atmosphere. Prior to industrialization, the atmospheric CO_2 level was 260 ppm, but it has now surpassed 400 ppm (May 2021). It is anticipated to reach 550 parts per million within the next decade (IPCC 2013) [15]. The increase in atmospheric carbon dioxide levels has a substantial impact on plant growth and development. The effects of elevated CO_2 levels on plants and trees can be examined in confined environments such as greenhouse chambers and controlled environment chambers (CECs), where the experimental conditions can be closely monitored. It can also be evaluated in open top chambers (OTCs) and free air CO_2 enrichment facilities (FACE) which promote natural field conditions without altering the microclimate or biotic interactions. However, Screen Aided CO_2 Control Systems are being offered as a medium ground between OTC and FACE facilities, as OTC does not guarantee appropriate microclimate and FACE is expensive due to the high amount of CO_2 required, rising costs (Leadley *et al.*, 1997; Machacova 2010). In this review, we have discussed about effects of elevated carbon dioxide on various parameters like plant physiology, nutritional quality and biotic factors.

Effect of eCO_2 on plant physiological responses

Elevated CO_2 has beneficial effects on plant productivity, biomass, and yield (Reddy *et al.*, 2010, Tausz Posch *et al.*, 2020) [37, 44]. It helps in increasing photosynthetic rates (Drake *et al.*, 1997) [8] decreasing stomatal conductance (Drake *et al.*, 1997, Ainsworth and Rogers 2007, Lee *et al.*, 2020) [8, 1, 24], thereby improves water uptake and nutrient uptake efficiency (Drake *et al.*, 1997, Leakey *et al.*, 2009, Kant *et al.*, 2012) [8, 23]. In contrast to the previously stated general notion, several research have shown that increasing eCO_2 enhances stomatal conductance in stress conditions such as dry and warm drought occur (Purcell *et al.*, 2018, Konrad *et al.*, 2008, Medlyn *et al.*, 2013) [36, 21, 32]. Photosynthesis, the fundamental determinant of plant biomass and production, is regulated by a variety of factors, the most important of which is atmospheric carbon dioxide concentration. The increase in net photosynthetic rate caused by eCO_2 is principally attributable to a decrease in photorespiration and an increase in RuBisCO carboxylation activity. However, this rise in photosynthetic rate does not correspond to a continuous increase in eCO_2. Plants exhibit photosynthetic acclimation after extended eCO_2 exposure, resulting in a decrease in photosynthetic activity (Drake *et al.*, 1997, Kirschbaum 2010) [8, 20] due to a limitation of maximum carboxylation rate (V_{cmax}) by decreasing RuBisco activity (Leakey *et al.*, 2009) [23], limited regeneration of RuBP

(Tausz *et al.*, 2013) [43]. This downregulation of photosynthetic potential is well described in an experiment performed at the Poplar Free Air CO_2 Enrichment (PopFACE) facility, where there is an initial increase in the rate of photosynthesis under eCO_2 (38 percent increase in A_{sat}) that later decreases due to the concurrent decrease in maximum capacity for carboxylation (V_{cmax}) and maximum rates of electron transport (J_{max}), which is related to the activity of RuBisCO and regeneration of RuBP (Long, 2003) [27]. Similarly, Zheng *et al.* 2019 [53] observed a decrease in photosynthesis in a soybean crop cultivated under eCO_2 circumstances, which is corroborated by a decrease in net photosynthetic rate (A_n). The reduction in maximum carboxylation rate (V_{cmax}) at 600 ppm and maximum electron transport rate (J_{max}) at 400 ppm of eCO_2 was linked to the downregulation of photosynthetic rate. Other factors that contribute to the decrease in A_n include changes in stomatal conductance (G_s), stomatal density, stomatal area, and stomatal distribution, reduced mesophyll tissue, and lower nitrogen availability (Zheng *et al.*, 2019) [53]. Kirschbaum *et al.* (2010) [20] observed that increasing photosynthesis (+30%) increased the relative growth rate by up to 10%, which can translate into an increase in absolute growth during the plant's exponential development phase. A meta-analytic review by Zhang *et al.* (2021) [52] has shown increased photosynthetic rates upto 28.6% under elevated carbon dioxide conditions (+670ppm) along with improved water use effiency upto 58.6%. C3 plants were shown to be more responsive than C4 plants, as C3 plants do not exhibit a saturation effect for carbon fixation under ambient circumstances. eCO_2 conditions improve overall net photosynthetic rate in *Brassica juncea* by 50% (Ruhil *et al.*, 2014) [38], while decreasing stomatal conductance and transpiration rate, hence improving photosynthetic water use efficiency. As a result of the increased leaf area index, it also resulted in more biomass and seed output. Higher carbon uptake by plants under eCO_2 conditions is ascribed to increased biomass and yield. A favorable association occurs between increased biomass, yields, and photosynthetic rate in CO_2 enrichment experiments (Ghini *et al.*, 2015, Kellner *et al.*, 2019, Tausz Posch *et al.*, 2020) [10, 19, 44, 43]. Pandey *et al.* (2017) [34] revealed that eCO_2 wheat crop had a good effect on belowground biomass (+24%) and aboveground biomass (+15%), as well as an increase in grain production (+35%), inflorescence weight (+27%), and harvest index (+11.4%). Similarly, under eCO_2 there was an increase in belowground biomass of up to 22 to 38 percent in poplar trees, and overall biomass increase was greater than under ambient conditions (Calfapietra *et al.*, 2003) [5]. Ainsworth and Long (2020) [2] observed an 18% increase in yield of 18 C3 crop species in the presence of adequate water and nutrients in a meta-analytic review. Ghini *et al.* (2015) [10] investigated the effects of eCO_2 on two cultivated coffee varieties, Catuaí and Obatã, and observed an increase in growth metrics such as plant height and stem girth. It was also found that the fertilising impact of eCO_2 increased crop yields by up to 14.6 percent for Catuaí and 12 percent for Obatã.

Effect of eCO_2 on nutritional quality

In general, increased CO_2 has a detrimental impact on plant nutritional quality since it leads to a decrease in nitrogen, protein, and mineral content (Lee *et al.*, 2020, Loladze 2014) [24, 26]. The mechanisms responsible for reduced nitrogen and protein content could be the diluting impact of eCO_2 caused by carbohydrate buildup or the limited plant uptake of minerals (Taub *et al.*, 2008) [42]. Other factors that may be responsible for the decrease in nutritional quality include a restriction in transpirational flow in xylem vessels or an altered distribution of nutrients in plant tissues (McGrath and Lobell 2013) [31]. Reduced nitrogen assimilation as a result of carbon dioxide acclimatization results in the depletion of organic N compounds such as proteins, which eventually impacts food quality (Bloom *et al.*, 2010) [3]. The increase in the C:N ratio caused by increased carbon assimilation under eCO_2 resulted in a 39.7 percent decrease in nitrogen concentration, whereas magnesium, phosphorous, and chlorophyll content were negatively affected (Lee *et al.*, 2020) [24]. Reductions in zinc and iron content have been found in C3 and legume crops, with C3 crops showing a higher reduction than legume crops and C4 plants showing only a loss in iron content. Reduction of protein content is less influenced in leguminous crops due to increased nitrogen (N_2) fixation, whereas non-leguminous C3 crops are severely affected due to lower N_2 fixation (Myers *et al.*, 2014). Leguminous crops do not show significant protein reduction owing to their increased nodulation activity (Ainsworth and Long 2020) [2]. Similarly, Loladze (2014) [26] observed that eCO_2 had a detrimental influence on plant mineral content up to 8%, with a considerable drop in key minerals such as Ca, K, Zn, and Fe, as well as an increase in carbohydrate to minerals ratio. Zhu *et al.* (2018) [54] investigated the effects of eCO_2 on grain quality in 18 cultivated rice lines and observed a significant decrease in proteins, minerals such as Fe and Zn, vitamin B (B1, B2, B5, and B9), but a rise in vitamin E content. Broberg *et al.* (2017) [4] reported a decrease in mineral concentrations such as N, Fe, S, Zn, and Mg in a meta-analysis report. In contrast, eCO_2 has favourable benefits such as improved strawberry flavour due to an increase in glucose, fructose, sucrose, and other total sugars content (Wang *et al.*, 2004) [45]. Almuhyawi *et al.* (2020) investigated the effects of eCO_2 on three broccoli sprout cultivars and observed an increase, not only in biomass and photosynthesis but also in amino acid derived glucosinolates and other nutritional aspects, which improved the anti-cancer and anti-inflammatory properties of the broccoli sprout cultivars. Jing *et al.* (2020) observed an improved taste of rice as well as improvements in grain characteristics such as grain length and width under eCO_2. The oil content of soyabean seed increased with an increase in oleic acid content, but protein and amino acid content decreased (Li *et al.*, 2018). Strawberries cultivated with eCO_2 showed higher amounts of polyphenols, flavonoids, and anthocyanins, which improved the overall appearance, aroma, and nutritional quality of the fruits (Wang & Bunce., 2004) [45].

Effects of eCO_2 on plant biotic factors

Pests

The performance of insect herbivores is influenced by eCO_2 as it affects the growth and development of insect herbivores and their feeding habits, fecundity, reproduction, survival rate and mortality. (Senthil-Nathan., 2021) [40]. The consumption rate of insects increases as the plant nutrient quality declines owing to the dilution effect caused by eCO_2 on proteins, nutrients, increased C:N ratio and secondary metabolites (Chen *et al.*, 2005) [6]. When exposed to eCO_2 conditions plant-pest interactions are influenced by the changes in C:N ratio, production of primary and secondary metabolites which plays a key role in plant defense mechanisms (Zavala *et al.*, 2016) [50]. Plants grown under eCO_2 had higher carbohydrate content and lower nitrogen content due to improved photosynthetic rate (Reddy *et al.*, 2010, Xu *et al.*, 2019) [37]. In order to compensate for nutritional requirements, insects feed more in plants exposed to eCO_2 (Ainsworth and Rogers 2020) [2], extending their time of growth and development (Xu *et al.*, 2019). Plant defence mechanisms against insects are controlled by phytohormonal pathways such as Jasmonic acid (JA), salicylic acid (SA), and ethylene signalling (Wu *et al.*, 2010). Johnson *et al.* (2020) found that eCO_2 suppressed the jasmonic acid pathway in *Medicago sativa*, while simultaneously increasing the relative growth rate in *Helicoverpa armigera* by up to 66 percent when they feed on plants exposed to eCO_2. Xu *et al.* (2019) investigated the effects of eCO_2 on maize and found an increase in defensive chemicals such as jasmonic acid content and total phenolics content, as well as an increase in defensive enzyme activity of peroxidase, polyphenol oxidase, phenyl alanine ammonia lyase, and proteinase inhibitors, which confers resistance to the chewing insect *Ostrinia furnacali*. Plant vulnerability to biotic agents changes as eCO_2 alters the generation of biotic stress-induced defence hormones including jasmonic acid (JA), which confers resistance to *Spodoptera litura* in tobacco but not in melon (Zhang *et al.*, 2020) [51]. Guo *et al.* (2012) [12] observed that tomato plants grown in eCO_2 conditions have reduced resistance to *Helicoverpa armigera* due to decreased levels of JA and JA-induced defensive enzymes. Ghini *et al.* (2015) [10] found a considerable reduction in the incidence of leaf miners in two Coffee cultivars throughout the critical time of pest occurrence under eCO_2.

Diseases

Many studies have revealed that eCO_2 has an impact on plant pathogen interactions (Luck *et al.*, 2011, Itagaki *et al.*, 2015) [28, 16]. Phytohormones such as salicylic acid (SA), jasmonic acid (JA), and ethylene affect plant defence systems (Gimenez- Ibanez and Solano 2013) [11]. SA controls systemic acquired resistance (SAR) against biotrophic infections in plants, whereas JA controls induced systemic resistance (ISR) against necrotrophic pathogens and herbivores (Pieterse *et al.*, 2012) [35]. Plants exposed to increased CO_2 levels have varying effects on SA and JA concentrations, activating plant defence mechanisms via increased transcript expression of pathogenesis related proteins (Eastburn *et al.*, 2011, Sun *et al.*, 2013) [9, 41], as seen in mustard crop grown in eCO_2 conditions, where the transcript levels of PR-1, PR-2, and NPR-1 were higher due to the increased SA levels. Despite increasing JA levels under eCO_2, NPR-1 inhibition of PR-12 and PR-13 lowered transcript levels of JA-induced pathogenesis associated genes (PR-12 and PR-13). The increased PAL activity is responsible for the considerable increase in SA concentrations in non-infected plants cultivated under eCO_2. However, after *Alternaria brassicae* pathogen infection in mustard crop, SA concentrations reduced dramatically while JA concentrations increased in eCO_2 conditions. The combination of these phytohormonal alterations and induced PAL activity reduced the disease severity of alternaria blight in mustard by up to 29.57 percent (Mathur *et al.*, 2017). Due to increased total phenol concentrations, higher PAL activity, and high epicuticular wax, Mathur *et al.* (2013) [29] observed that mustard plants cultivated in eCO_2 exhibited a decreased incidence and severity of Alternaria blight produced by *Alternaria brassicae* and Downy mildew induced by *Hyaloperonospora brassicae*. However, white rust caused by *Albugo candida* increased in mustard cultivated in eCO_2, possibly due to increased sugar availability (Mathur *et al.*, 2013) [29].

Soil microbes

C3 crops cultivated in high CO_2 conditions have significantly higher levels of non-structural carbohydrates, resulting in carbohydrate-rich soil exudates that promote crop-microbe symbiosis (Ainsworth and Long 2020) [2]. Microbe activity is limited due to a lack of labile C and energy (Schimel and Weintraub 2003) [39]. Microbial activity in the rhizosphere can be boosted by the emission of carbon-rich soil exudates (Kuzyakov and Blagodatskaya, 2015) [22]. He *et al.* (2013) studied the impact of eCO_2 on soil microbial activity in a soyabean crop and observed an increase in functional genes involved in C fixation, C degradation, and other nitrogen cycling processes. The enhanced availability of C aided in efficient nitrification under eCO_2 circumstances, enhancing the Novosphingobium genera microbial activity and nitrogen fixing capabilities (He *et al.*, 2013). Similarly, eCO_2 circumstances increased the microbial communities of Bacilli and Betaproteobacteria (Da Costa *et al.*, 2018) [7]. The rhizosphere of *Robinia pseudoacacia* was negatively impacted by heavy metal toxicity produced by Cd and Pb, leading in a decrease in microbial abundance and activity. However, eCO_2 increased soil fertility and rhizospheric conditions, resulting in an increase in organic compounds as well as an improvement in microbial abundance, biomass, and activity (Huang *et al.*, 2017) [17]. Williams *et al.* (2018) [46] studied the effects of eCO_2 in Arabidopsis, resulting in higher rhizosphere colonization of *Pseudomonas simia* WCS417 due to better rhizosphere deposits. eCO_2 circumstances had no significant effect on soil microbial populations or the rhizosphere of *Bothriochloa ischaemum*, according to Xiao *et al.* (2017) [48].

Conclusion

Carbon dioxide emissions have risen to over 400ppm, up from 250ppm as predicted in the 1960s, and it may can rise to atmospheric 550ppm in the coming decade (IPCC 2013) [15]. The rise in CO_2 levels has become a major driving force with long-term effects on plant physiology, nutrition, and pathogen interactions. A thorough study on works of elevated CO_2 on plant system suggested that genes governing photosynthesis, carbohydrate metabolism, plant defence pathways, and secondary metabolite production have been upregulated (Eastburn *et al.*, 2011) [9]. eCO_2 conditions influence photosynthetic rate and water use efficiency to boost plant productivity. Plant defence system against biotic or abiotic stress has been found to be stimulated by eCO_2 conditions by manipulating phytohormone concentrations, as well as phytohormonal crosstalk. Consequently, we can say that a thorough understanding of the underlying mechanisms by which eCO_2 affects plant defence pathways will aid in the development of crops that are resistant to adverse conditions. However, the nutritional aspects of plants grown in eCO_2 must be emphasised in order to improve crop quality in the face of adversely changing climate scenarios. Integrating genomics, transcriptomics, proteomics, and metabolomics with eCO_2 analysis over plant ecosystems would aid in understanding morphological, biochemical, and physiological changes in plants as well as evaluating crop responses to climate change.

References

1. Ainsworth EA, Rogers A. The response of photosynthesis and stomatal conductance to rising [CO_2]: mechanisms and environmental interactions. Plant, cell and environment. 2007;30(3):258–270. doi.org/10.1111/j.1365-3040.2007.01641.x
2. Ainsworth E, Long S. 30 years of free-air carbon dioxide enrichment (FACE): What have we learned about future crop productivity and its potential for adaptation? Global Change Biology. 2020;27(1):27-49. doi: 10.1111/gcb.15375
3. Bloom A, Burger M, Asensio J, Cousins A. Carbon Dioxide Enrichment Inhibits Nitrate Assimilation in Wheat and Arabidopsis. Science. 2010;328(5980):899-903. doi: 10.1126/science.1186440
4. Broberg M, Högy P, Pleijel H. CO_2-Induced Changes in Wheat Grain Composition: Meta-Analysis and Response Functions. Agronomy. 2017;7(2):32. doi: 10.3390/agronomy7020032
5. Calfapietra C, Gielen B, Galema AN, Lukac M, De Angelis P, Moscatelli MC. Free-air CO_2 enrichment (FACE) enhances biomass production in a short-rotation poplar plantation. Tree physiology. 2003;23(12):805-814. https://doi.org/10.1093/treephys/23.12.805
6. Chen F, Wu G, Ge F, Parajulee M, Shrestha R. Effects of elevated CO_2 and transgenic Bt cotton on plant chemistry, performance, and feeding of an insect herbivore, the cotton bollworm. Entomologia Experimentalis Et Applicata. 2005;115(2):341-350. doi: 10.1111/j.1570-7458.2005.00258.x
7. da Costa D, Dias A, Cotta S, Vilela D, de Andrade P, Pellizari V. Changes of bacterial communities in the rhizosphere of sugarcane under elevated concentration of atmospheric CO_2 GCB Bioenergy. 2017;10(2):137-145. doi: 10.1111/gcbb.12476
8. Drake BG, Gonzalez-Meler MA, Long SP. More efficient plants: A Consequence of Rising Atmospheric CO_2? Annual review of plant physiology and plant molecular biology. 1997;48:609-639. https://doi.org/10.1146/annurev.arplant.48.1.609
9. Eastburn D, McElrone A, Bilgin D. Influence of atmospheric and climatic change on plant-pathogen interactions. Plant Pathology. 2011;60(1):54-69. doi: 10.1111/j.1365-3059.2010.02402.x
10. Ghini R, Torre-Neto A, Dentzien A, Guerreiro-Filho O, Iost R, Patrício F. *et al.*, Coffee growth, pest and yield responses to free-air CO_2 enrichment. Climatic Change. 2015;132(2):307-320. doi: 10.1007/s10584-015-1422-2
11. Gimenez-Ibanez S, Solano R. Nuclear jasmonate and salicylate signaling and crosstalk in defense against pathogens. Frontiers In Plant Science, 2013, 4. doi: 10.3389/fpls.2013.00072
12. Guo H, Sun Y, Ren Q, Zhu-Salzman K, Kang L, Wang C. *et al.*, Elevated CO_2 Reduces the Resistance and Tolerance of Tomato Plants to Helicoverpa armigera by Suppressing the JA Signaling Pathway. Plos ONE. 2012;7(7):e41426. doi: 10.1371/journal.pone.0041426
13. He Z, Xiong J, Kent A, Deng Y, Xue K, Wang G, *et al.*, Distinct responses of soil microbial communities to elevated CO_2 and O3 in a soybean agro-ecosystem. The ISME Journal. 2013;8(3):714-726. doi: 10.1038/ismej.2013.177
14. Huang S, Jia X, Zhao Y, Bai B, Chang Y. Elevated CO_2 benefits the soil microenvironment in the rhizosphere of *Robinia pseudoacacia* L. seedlings in Cd- and Pb-contaminated soils. Chemosphere. 2017;168:606-616. doi: 10.1016/j.chemosphere.2016.11.017
15. IPCC. Climate change 2013: the physical science basis. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge. 2013, 1535.
16. Itagaki K, Shibuya T, Tojo M, Endo R, Kitaya Y. Development of Powdery Mildew Fungus on Cucumber Leaves Acclimatized to Different CO_2 Concentrations. Hortscience. 2015;50(11):1662-1665. doi: 10.21273/hortsci.50.11.1662
17. Johnson SN, Waterman JM, Hall CR. Increased insect herbivore performance under elevated CO_2 is associated with lower plant defence signalling and minimal declines in nutritional quality. Scientific reports. 2020;10(1):14553. https://doi.org/10.1038/s41598-020-70823-3
18. Leakey A, Ainsworth E, Bernacchi C, Rogers A, Long S, Ort D. Elevated CO2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. Journal Of Experimental Botany. 2009;60(10):2859-2876. doi: 10.1093/jxb/erp096
19. Kellner J, Houska T, Manderscheid R, Weigel H, Breuer, L, Kraft P. Response of maize biomass and soil water fluxes on elevated CO_2 and drought—From field experiments to process-based simulations. Global Change Biology. 2019;25(9):2947-2957. doi: 10.1111/gcb.14723
20. Kirschbaum M. Does Enhanced Photosynthesis Enhance Growth? Lessons Learned from CO_2 Enrichment Studies. Plant Physiology. 2010;155(1):117-124. doi: 10.1104/pp.110.166819
21. Konrad W, Roth-Nebelsick A, Grein M. Modelling of stomatal density response to atmospheric. Journal Of Theoretical Biology. 2008;253(4):638-658. doi: 10.1016/j.jtbi.2008.03.032
22. Kuzyakov Y, Blagodatskaya E. Microbial hotspots and hot moments in soil: Concept and review. Soil Biology And Biochemistry. 2015;83:184-199. doi: 10.1016/j.soilbio.2015.01.025
23. Leakey AD, Ainsworth EA, Bernacchi CJ, Rogers A, Long SP, Ort DR. Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. 2009.
24. Lee YH, Sang WG, Baek JK, Kim JH, Shin P, Seo MC. The effect of concurrent elevation in CO_2 and temperature on the growth, photosynthesis, and yield of potato crops. PloS one. 2020;15(10):e0241081. https://doi.org/10.1371/journal.pone.0241081
25. Lee Y, Sang W, Baek J, Kim J, Shin P, Seo M, Cho J. The effect of concurrent elevation in CO_2 and temperature on the growth, photosynthesis, and yield of potato crops. PLOS ONE. 2020;15(10):e0241081. doi: 10.1371/journal.pone.0241081

26. Loladze I. Hidden shift of the ionome of plants exposed to elevated CO_2 depletes minerals at the base of human nutrition. Elife, 2014, 3. doi: 10.7554/elife.02245
27. Long S. Gas exchange measurements, what can they tell us about the underlying limitations to photosynthesis? Procedures and sources of error. Journal Of Experimental Botany. 2003;54(392):2393-2401. doi: 10.1093/jxb/erg262
28. Luck J, Spackman M, Freeman A, Trębicki P, Griffiths W, Finlay K. Climate change and diseases of food crops. Plant Pathology. 2011;60(1):113-121. doi: 10.1111/j.1365-3059.2010.02414.x
29. Mathur P, Sharma E, Singh SD, Bhatnagar AK, Singh VP, Kapoor R. Effect of elevated co_2 on infection of three foliar diseases in oilseed *Brassica juncea*. Journal of Plant Pathology. 2013;95(1):135–144. http://www.jstor.org/stable/23721745
30. Mathur P, Singh V, Kapoor R. Interactive effects of CO_2 concentrations and Alternaria brassicae (Berk.) Sacc. infection on defense signalling in Brassica juncea (L.) Czern. & Coss. European Journal Of Plant Pathology. 2017;151(2):413-425. doi: 10.1007/s10658-017-1382-7
31. McGrath JM, Lobell DB. Reduction of transpiration and altered nutrient allocation contribute to nutrient decline of crops grown in elevated CO_2 concentrations. Plant, cell & environment. 2013;36(3):697–705. https://doi.org/10.1111/pce.12007
32. Medlyn BE, Duursma RA, De Kauwe MG, Prentice IC. The optimal stomatal response to atmospheric CO_2 concentration: Alternative solutions, alternative interpretations. Agricultural and Forest Meteorology. 2013, 182-183, 200-203. https://doi.org/10.1016/j.agrformet.2013.04.019
33. Myers SS, Zanobetti A, Kloog I, Huybers P, Leakey AD, Bloom AJ. Increasing CO_2 threatens human nutrition. Nature. 2014;510(7503):139-142. https://doi.org/10.1038/nature13179
34. Pandey V, Sharma M, Deeba F, Maurya V, Gupta S, Singh S. *et al.*, Impact of Elevated CO_2 on Wheat Growth and Yield under Free Air CO_2 Enrichment. American Journal Of Climate Change. 2017;06(04):573-596. doi: 10.4236/ajcc.2017.64029
35. Pieterse CM, Van der Does D, Zamioudis C, Leon-Reyes A, Van Wees SC. Hormonal modulation of plant immunity. Annual review of cell and developmental biology. 2012;28:489–521. https://doi.org/10.1146/annurev-cellbio-092910-154055
36. Purcell C, Batke S, Yiotis C, Caballero R, Soh W, Murray M. Increasing stomatal conductance in response to rising atmospheric CO_2. Annals Of Botany. 2018;121(6):1137-1149. doi: 10.1093/aob/mcx208
37. Reddy AR, Rasineni GK, Raghavendra AS. The impact of global elevated CO_2 concentration on photosynthesis and plant productivity. Current Science 2010;99(1):46-57. http://www.jstor.org/stable/24108349
38. Ruhil K, Sheeba Ahmad A, Iqbal M, Tripathy BC. Photosynthesis and growth responses of mustard (Brassica juncea L. cv Pusa Bold) plants to free air carbon dioxide enrichment (FACE). Protoplasma, 2015;252(4):935–946. https://doi.org/10.1007/s00709-014-0723-z
39. Schimel J. The implications of exoenzyme activity on microbial carbon and nitrogen limitation in soil: a theoretical model. Soil Biology And Biochemistry. 2003;35(4):549-563. doi: 10.1016/s0038-0717(03)00015-4
40. Senthil-Nathan, S. (2021). Effects of elevated CO_2 on resistant and susceptible rice cultivar and its primary host, brown planthopper (BPH), Nilaparvata lugens (Stål). Scientific Reports, 11(1). doi: 10.1038/s41598-021-87992-4
41. Sun Y, Guo H, Zhu-Salzman K, Ge F. Elevated CO_2 increases the abundance of the peach aphid on Arabidopsis by reducing jasmonic acid defenses. Plant Science. 2013;210:128-140. doi: 10.1016/j.plantsci.2013.05.014
42. Taub D, Miller B, Allen H. Effects of elevated CO_2 on the protein concentration of food crops: a meta-analysis. Global Change Biology. 2007;14(3):565-575. doi: 10.1111/j.1365-2486.2007.01511.x
43. Tausz M, Tausz-Posch S, Norton R, Fitzgerald G, Nicolas M, Seneweera S. Understanding crop physiology to select breeding targets and improve crop management under increasing atmospheric CO_2 concentrations. Environmental And Experimental Botany. 2013;88:71-80. doi: 10.1016/j.envexpbot.2011.12.005
44. Tausz-Posch S, Tausz M, Bourgault M. Elevated $[CO_2]$ effects on crops: Advances in understanding acclimation, nitrogen dynamics and interactions with drought and other organisms. Plant biology (Stuttgart, Germany), 2020;22Suppl1:38–51. https://doi.org/10.1111/plb.12994
45. Wang S, Bunce J. Elevated carbon dioxide affects fruit flavor in field-grown strawberries (Fragaria×ananassa Duch). Journal Of The Science Of Food And Agriculture. 2004;84(12):1464-1468. doi: 10.1002/jsfa.1824
46. Williams A, Pétriacq P, Beerling DJ, Cotton T, Ton J. Impacts of Atmospheric CO_2 and Soil Nutritional Value on Plant Responses to Rhizosphere Colonization by Soil Bacteria. Frontiers in plant science. 2018;9:1493. https://doi.org/10.3389/fpls.2018.01493
47. Wu J, Baldwin IT. New insights into plant responses to the attack from insect herbivores. Annual review of genetics. 2010;44:1-24. https://doi.org/10.1146/annurev-genet-102209-163500
48. Xiao L, Liu G, Li P, Xue S. Elevated CO_2 and nitrogen addition have minimal influence on the rhizospheric effects of Bothriochloa ischaemum. Scientific reports. 2017;7(1):6527. https://doi.org/10.1038/s41598-017-06994-3
49. Xu H, Xie H, Wu S, Wang Z, He K. Effects of Elevated CO_2 and Increased N Fertilization on Plant Secondary Metabolites and Chewing Insect Fitness. Frontiers in plant science. 2019;10:739. https://doi.org/10.3389/fpls.2019.00739
50. Zavala J, Gog L, Giacometti R. Anthropogenic increase in carbon dioxide modifies plant-insect interactions. Annals Of Applied Biology. 2016;170(1):68-77. doi: 10.1111/aab.12319
51. Zhang J, Deng L, Jiang H, Peng C, Huang C, Zhang M. The effects of elevated CO_2, elevated O3, elevated temperature, and drought on plant leaf gas exchanges: a global meta-analysis of experimental studies. Environmental Science And Pollution Research. 2020;28(12):15274-15289. doi: 10.1007/s11356-020-11728-6

52. Zhang Q, Dai, W., Wang X, Li J. Elevated CO_2 concentration affects the defense of tobacco and melon against lepidopteran larvae through the jasmonic acid signaling pathway. Scientific Reports. 2020, 10(1). doi: 10.1038/s41598-020-60749-1
53. Zheng Y, Li F, Hao L, Yu J, Guo L, Zhou H. Elevated CO_2 concentration induces photosynthetic down-regulation with changes in leaf structure, non-structural carbohydrates and nitrogen content of soybean. BMC plant biology. 2019;19(1):255. https://doi.org/10.1186/s12870-019-1788-9
54. Zhu C, Kobayashi K, Loladze I, Zhu J, Jiang Q, Xu X. *et al.*, Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. Science Advances. 2018, 4(5). doi: 10.1126/sciadv.aaq1012