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AN EMERGING CONCEPT OF PHOSPHORUS NUTRITION IN POTATO UNDER ELEVATED CARBON DIOXIDE [CO_2] CONDITION

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ABSTRACT: Potato (*Solanum tuberosum* L.) is a cheap source of carbohydrate and nutrition which is grown in different soil conditions. Phosphorus (P) is the crucial macronutrient that is involved in the metabolism in the plant such as glycolysis, respiration, formation of ATP and other catabolic and anabolic processes. Potato plant requires high P for optimum growth and development. However, under P deficiency the growth and yield of potatoes might lead to a significant reduction due to its disturbed metabolic activities. P deficiency might lead to a reduction in biomass and production, photoassimilates translocation, photosynthesis, flower formation, starch synthesis, source-sink activities and other physio-biochemical processes. The rising CO_2 due to anthropogenic intervention has significantly affected plant growth and development which has ultimately affected its yield and nutritional attributes. However, high CO_2 conditions might positively ameliorate the detrimental effect of P deficiency in potato plants. Improved root growth and increase in the total amount of nutrient uptake under elevated CO_2 conditions might also lead to enhancement in P use efficiency even when the P acquisition efficiency declines. Overall there is an array of the physiological, biochemical and molecular mechanism and interactions work under phosphorus stress with elevated CO_2 condition.

INTRODUCTION

Phosphorus (P) is a non-renewable source of plant fertilizer and an essential nutrient for all life forms on the earth and especially for plants that are the primary producers. The concentration of P in the soil ranges from 0.6 to 11 µM and is poorly mobile in soil. This P as fertilizer we mainly get from rock phosphate, which is excavated from mines. This non-renewable resource is projected to get depleted by 2050 from the major reservoirs (Vance *et al*., 2003). Most of the P in soil remains unavailable for plant uptake as it is fixed in soil colloids. P is primarily involved in the production of the energy currency of the cell, ATP for high energy bonds, biomolecules and membranes. It is an essential nutrient that intervenes in the cellular energy transfer, photosynthesis, respiration and component of nucleic acid-like DNA RNA and phospholipids (Chourasia *et al*., 2021; Kumar *et al*., 2021a; Lal *et al*., 2021d; Raigond *et al*., 2021; Tiwari *et al*., 2021b). This is also an integral component of metabolic pathways and signalling cascades (Cordell *et al*., 2009). It is, therefore, an extremely essential macronutrient that profoundly influences plant growth and development, ultimately affects the production and productivity of potatoes. The plant undergoes several adaptive mechanisms that help to cope up long term P starvation. The modifications by the plant to adapt certain kind of stress includes alteration in root system architecture, efflux of organic

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acid and hydrolysing enzymes like acid phosphatase and induction of high-affinity transporters (Raghothama and Karthikeyan, 2005; Changan *et al*., 2020; Raigond *et al*., 2020; Kumar *et al*., 2021b; Lal *et al*., 2021b). Mycorrhizal symbiosis increases P acquisition by enhancing the volume of soil explored by increasing the root surface area of plants. Phosphorus Solubilizing Bacteria (PSB) also play major role in availability to plants by realizing of some enzymes or acids so increase the available form of phosphorus to plant from the non-available form of P. The kinetic properties of phosphate transporters that enhance P uptake have little effect on its mobility in soil solution. Hence, attempts to select/engineer efficient genotypes for increased P acquisition must consider the properties of both plant and soil microorganisms

Global climate change is a major challenge of the present scenario and also for future agriculture. The climate change has affected the weather patterns, heat, drought, frequent snowfall and frost in high altitudes (Stocker *et al*., 2013). Global climate change and global warming is delivering a negative impact on plant growth, survival and crop yield. Atmospheric CO_2 concentration [CO_2] has increased from 280 ppm during pre-industrial times to almost 405 ppm at present (IPCC, 2013). Continued burning of fossil fuels and changing land-use patterns threaten to cause further increment in [CO_2]. The present atmospheric [CO_2] does not saturate photosynthesis in a majority of terrestrial plants. Hence elevated [CO_2] would have profound effects on plant growth like increased rate of carbohydrate synthesis and net photosynthesis coupled with inhibition of photorespiration, ultimately increasing biomass and yield. Climate scientists have projected that the current ambient CO_2 concentration of 400 will nearly double to 700 ppm by the end of the century (IPCC 2007), which is likely to be coupled with a rise in global atmospheric temperature by 0.3 to 4.8 (IPCC 2014). This predicted increase in air temperature will also increase the evapotranspiration water loss causing soil water limitation and agricultural drought in the field which affects the production and productivity of tuber crops (Vandegeer *et al*., 2013). High atmospheric [CO_2] will certainly increase the CGR (Crop growth rate) which in turn leads to increase in demand of nutrients from soil. This enhancement in the growth and development of the crop under high CO_2 will lead to nutrient deficiency. Such disparity is attributed to efficient nutrient utilization under elevated as compared to ambient CO_2 level. Elevated [CO_2] may increase acquisition efficiency and uptake patterns of essential nutrients such as P and S. Modern high yielding cultivars have higher nutrient requirement, which is expected to rise further with rising atmospheric [CO_2] (Lal and Pandey, 2015; Pandey *et al*., 2018; Lal *et al*., 2021d). Elevated [CO_2] enhances growth mainly through increased leaf area, photosynthesis and nutrient use efficiency, which are all compromised during P or S deficiencies as reported in soybean (Prior *et al*., 1998). Elevated [CO_2] in the atmosphere is beneficial to plants through its enhancement of crop growth, but detrimental to human life (Devi *et al*., 2021; Raigond *et al*., 2021; Tiwari *et al*., 2021c).

P deficiency reduces leaf area, photosynthesis, nitrogen (N) fixation, seed yield and quality in soybean plants (Cure *et al*., 1988). P deficiency decreased biomass, photosynthesis and stomatal conductance of soybean plants. Such negative influences on growth may be compensated for by elevated [CO_2] mainly by increasing nutrient use efficiency, leaf area and photosynthesis. High [CO_2] led to higher soybean yield, through its positive effects on number of pods and seeds, rather than seed size (Salvucci and Crafts-Brandner, 2004). Studies have shown that P deficiency coupled with elevated [CO_2] may alter nutrient dynamics and biomass partitioning in plant organs (Lal *et al*., 2021c; Tiwari *et al*., 2021a). Moreover, the positive influence of [CO_2] on plant growth may be beneficial even under nutrient deficiency owing to the increased carbohydrate synthesis and accumulation under high [CO_2] conditions.

Potato is the world's fourth important staple food after rice, wheat and maize which is an underground tuber crop (Kumar *et al*., 2020c, 2020b; Lal *et al*., 2020b, 2020c, 2020d; Thakur *et al*., 2020). It requires high P for its optimum growth and development for better production and productivity. Potato cultivation in the P deficient soil leads to a considerable loss in yield and production (Dechassa *et al*., 2003). Along with the deficiency of P, biomass reduction is also attributed with amount of PAR (photosynthetically active radiation) absorbed by the plant (Tiwari *et al*., 2020a, 2021b; Kumar *et al*., 2021b; Lal *et al*., 2021d, 2021a). The different traits have been affected under P deficiency along with interaction with high CO_2 are as follows. Under elevated CO_2 condition potato exhibit positive growth and development (Lal *et al*., 2020a, 2021a; Singh *et al*., 2020; Tiwari *et al*., 2020a, 2020b). However, this may influence the nutrient uptake and utilization. The combined interaction data of CO_2 and phosphorus stress in potato is very scarce, hence we tried an attempt to put forward all the parameter related to it in this article.

We must identify the best cultivation and practices under climate change in order to tackle both biotic and abiotic stresses like heat stress, drought, insect and pathogen. By taking these factors into consideration the newly developed cultivars of potato will best adapt the changing environment.

Effect on Photosynthesis

It was reported that Pi-regeneration capacity and not rubisco is involved in the acclimation of potato plants to elevated CO_2 (Sage, 1994). It was clear that acclimation of photosynthesis occurs in potato when the plant is exposed to elevated CO_2 for the long term. However, the analysis of A/Ci curves of potato leaves under high CO_2 shows inconsistent results. The symptoms of Pi deficiency can be visually observed by observing the plant which possesses reduce the growth of the plant, acute leaf angles, prolonged dormancy and a decrease in the size and number of flowers (Mengel *et al*., 2001). There was also the development of the dark green or blue-green foliage which shows the symptoms of Pi deficiency. Red, purple and brown pigment development along the veins is due to anthocyanin production along with the increased leaf sucrose concentrations (Kumar *et al*., 2017, 2020a; Lal and Tapas Ranjan Sahoo and Lopamudra Nayak, 2017; Sahoo *et al*., 2017; Pandey *et al*., 2018).

There was no change in the activation of Rubisco but a reduction in total protein content was observed in leaves grown in elevated CO_2 (Stitt & Schulze, 1994). Reduction in the stomatal conductance is another observation in response to elevated CO_2 due to partial stomatal closure. The reduction in the conductance for CO_2 diffusion into the leaf leads to the decrement of the photosynthetic rate. The photosynthetic rate was found to be decreased under elevated CO_2 (700 ppm) conditions and also in super-elevated conditions (1000 to 10,000 ppm).

Effect on pigment system

The P deficiency decreases the electron transport rate in the photosystem and chlorophyll fluorescence parameter. This deprivation of P inhibits photosynthesis by inhibiting rubisco activation and regeneration of ribulose-1, 5-bisphosphate (RuBP). The Rubisco content was found to be decreased under P deficient conditions (Pandey *et al.*, 2018).

Starch/Carbohydrate Content

The potato plant when exposed to elevated CO_2 for long-term there was an increase in the leaf starch contents. The high level of starch due to elevated CO_2 leads to accumulation of high starch in potato leaves which ultimately damage the chloroplasts. However, it was found that the concentration of soluble carbohydrates was unaffected under elevated CO_2 condition (Barnaby *et al.*, 2019). The affects the phosphate nutrition where ultimately the deficiency of P leads to accumulation of starch in the leave. The interactive effect of both P deficiency and elevated CO_2 leads to drastic increase in starch content in the leaves of plant (Lal *et al.*, 2019). This increase in leaf carbohydrate coincides with photosynthetic acclimation.

Effect on growth and development

The effect of elevated CO_2 on plant growth and development can also be observed. Under elevated CO_2 conditions there is an overall increase in the total biomass production. Leaf area of potato was found to be increased when CO_2 concentration was increased from 500 μmol mol^{-1} to 1000 μmol mol^{-1}. Leaf area index (LAI) was found to be increased under elevated CO_2 conditions in potato. However, the rate of decline of LAI was observed at the end of the growing season (Finnan *et al.*, 2005). Above-ground biomass and tuber dry weight was found to be increased in under elevated CO_2 and P deficient condition. This show that CO_2 ameliorate the deficiency of P stress in potato. In Changing climate and potential Impacts on Potato yield and quality project (CHIP) experiment it was also reported that above-ground biomass, tuber number and root biomass were found to be increased at an intermediate harvesting time (Craigon *et al.*, 2002). The biomass accumulation is also highly affected by P supply and light interception. P deficient potato plant possess poor root growth, haulm growth and delayed maturity as compared to well fertilized plant. During stressed situations, plants allocate more photosynthetic assimilates toward the growth of organs that have direct role in acquiring the limiting resource (Pandey *et al.*, 2015). Higher root-to-shoot ratio observed under nutrient deficiency and/or elevated [CO_2] aids in increasing nutrient uptake by providing more root surface (Pandey *et al.*, 2013). Soil exploration by enhanced root surface area is a preferred adaptation to changing climatic scenarios wherein elevated [CO_2] would increase carbon supply for the production of finer roots. In contrast, Maestre and Reynolds (2006) reported that root proliferation of a Brachypodium increased with nutrient availability and was not influenced by atmospheric [CO_2]. It was suggested that belowground biomass increased with elevated [CO_2] only when sufficient nutrient requirement of the plant was met.

Effects on crop yield

Earlier it was reported that tubers and root crops are identified as responsive crops to elevated CO_2. Moreover, it was also suggested that potato being the underground crop possess the large below the ground sink for carbon and along with the apoplastic mechanism of phloem loading it is the best crop that responded to elevated CO_2 condition under nutrient stress (Kimball *et al.*, 2002). Application of phosphorus fertilizer in potato crop shown to an increase in marketable tuber yield per hectare. Maximum tuber yield was recorded at a rate of 135 kg ha^{-1} with 98 % yield advantage over control treatment. Niguse *et al*., 2016 has conducted an experiment in Tigray, Ethiopia showed that the application of phosphorus at a rate of 89.50 kg ha^{-1} had the highest marketable and total tuber yield. (Misgina, 2016).

Effects on tuber quality

In the above section we concluded that the elevated atmospheric concentration of CO_2 increases the yield of tuber, but also improves the quality of tuber. Potato provides substantial amount of carbohydrates, protein, vitamin and other mineral. Any change in the quality parameter of potato will hamper the and will have an effect on human nutrition. Under elevated CO_2 there is a report of increase in the vitamin C content and reduction in nitrogen content. However, as the tuber yield is increased there is also an increase in the tuber starch and viscosity of the starch paste (Vorne *et al*., 2002). High dry matter content will benefit the potato processing industries like those involved in making potato chips and fries. Moreover. High dry matter content will prevent excessive fat absorption (Tiwari *et al*., 2020a). Major abiotic stress viz., high temperature, drought, salinity and nutrient stress like P stress will adversely affects the process of distribution of photo assimilate and substantially restrain the plant growth, development, tuberization, tuber bulking and finally the tuber yield and quality (Minhas, 2012). However, the magnitude of the yield increase will depend on agronomic practise, cultivar choice and growing conditions.

Interactive effects of CO_2 and P on nutrient concentration

Elevated [CO_2] leads to increased P acquisition to sustain growth under limited P supply to plants when the internal P is used judiciously for biomass production. Enhanced P uptake and utilization was reported in soybean plants exposed to elevated rather than ambient [CO_2] (Cure *et al*., 1988). In cereals, total P acquisition increased by 70% at sufficient P and elevated [CO_2], whereas 26% enhancement of P utilization efficiency was observed at low P. Improved root growth and increase in the total amount of nutrient uptake led to enhancement in P use efficiency even when the P acquisition efficiency declines. Elevated [CO_2] resulted in higher biomass and net photosynthesis owing to enhancement in P and N uptake per plant, which was closely associated with greater utilization efficiency. Similarly, elevated [CO_2] increased uptake of N, P and potassium in *Agrostis capillaris*, with no significant enhancement in biomass. Excessive P application reduces the micronutrient like zinc which ultimately leads to an increase in the rate of senescence in plants.

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