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Plant Growth and Development in Relation to Phosphorus: A review

Amin FATHI, Jaber MEHDINIYA AFRA*

Ayatollah Amoli Branch, Islamic Azad University, Amol, Iran
**Corresponding author: J. Mehdiniya Afra: afra.mahdiniya@gmail.com*

REVIEW

Abstract

Phosphorus (P) deficiency is a primal limiting factor for crop yields, particularly during the early developmental phase. This nutritious element plays a key role in several physiological mechanisms such as seed and fruit formation, respiration, photosynthesis, energy storage, and transfer, cell division, cell enlargement, and many other processes in the plant. Part of P applied to soil as fertilizer is could be into insoluble forms, rendering it unavailable to plants and causing environmental pollution. Therefore, increasing p absorption ability by plants appears to be critical for increasing agricultural productivity and decreasing pollution. Improving the crops P use efficiency (PUE) could be an effective method to increase P uptake. The maximum PUE is observed where nutrient supply via chemical fertilizer is the lowest level. This review discussed the significance of plant growth, yield quality, and PUE.

Keywords: phosphorus**,** respiration, photosynthesis, yield quality, physiological mechanisms

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INTRODUCTION

Phosphorus (P), as an essential macronutrient, is an essential component of key molecules such as RNA and DNA nucleotides and energy provision (Da Cunha Cruz et al., 2020; Heuer et al., 2017). The chemical phosphate fertilizers application has been increased more than four times in the past five decades that it is expected to reach 22–27 tons/year by 2050 (Mogollón et al., 2018). The doubling of global food production via agricultural systems up to the 1990s can be relatively explained by a 3.5-fold increase in P fertilization (Jiao et al. 2016; Tilman et al. 2002). Nevertheless, P is a non-renewable resource, and current global reserves may be exhausted over next century (Gao et al., 2019; Cordell et al., 2009). As well, excessive use of P fertilizer in agriculture can also cause eutrophication (Smil 2000). This makes improving P use efficiency an urgent need. Plants have evolved morphological and physiological adaptations to efficiently take up and utilize P (Hodge, 2004; Lambers, 2006; Shen, 2011). A mineral macronutrient, P, is found in soil mostly in insoluble forms and is crucial for various physiological processes in plants (Theodorou and Plaxton, 1993; Vance, 2001). P absorption capacity of the soil controls the concentration of dissolved P (Jalali and Kolahchi, 2005). Due to the high capacity of the soil to absorb P, its mobility in the soil is low compared to other food elements to absorb P (Jalali and Kolahchi, 2005). Therefore, all the P fertilizer consumed is not used by the plant at the time of consumption (Jalali and Kolahchi, 2005). The increase in agricultural productivity and decrease in pollution are both promoted by improving plant P uptake from the soil (Wang et al., 2015). There have been various adaptations for plants to access insoluble nutrientsthat including modifications to root morphology (George et al., 2002; Gilbert et al., 1999) and secretion of exudates, like phosphatase (Dong et al., 2004;

Ryan et al., 2001). A transgenic plant's roots can absorb nutrients from the soil matrix through the chelation of organic acids exuded into the rhizosphere (Wang et al., 2015). Due to slow diffusion and high soil fixation, P is a unique nutrient with a low availability. Growing plants can be limited by P (Shen et al., 2011). In the past decades, chemical fertilizers have improved soil P fertility and crop production, but damaged the environment (Shen et al., 2011). By integrating root morphological and physiological adaptation strategies, it is possible to maximize root efficiency by maintaining a proper P supply at the root zone (Shen et al., 2011). P concentrations in plants range between 0.05% and 0.5% of total plant dry weight. P concentrations in soil are 2000-fold greater than in plants, but because it is fixed in aluminum/iron or calcium/magnesium phosphates, it cannot be taken up by plants (Malhotra et al., 2018). In agricultural fields, plants often struggle with P deficiency. It has been estimated that 30–40% of the world's arable land has P deficiency, which reduces crop yields. The PUE in agricultural fields ranges from 15 to 20%, indicating that most of the P element fertilized in soil does not reach the plants and leaches into ground and surface waters, resulting in eutrophication (Correll 1998; Smith 2003; Malhotra et al., 2018). In this review, an attempt has been made to provide up-to-date information on the effects of P on plant growth and development.

PHOSPHORUS DEFICIENCY IN PLANTS

It is common for agricultural fields to suffer from P deficiency problems. Deficiency detection is difficult because crops usually do not show any visual symptoms in the early stages. Often, its deficiency is confused with N due to the red veins on young leaves (Malhotra et al., 2018). However, general chlorosis is not seen in P-deficient plants. The reduction of photosynthesis or energy investment is associated with P deficiency reducing plant growth. Due to its limitations, yield and product quality are negatively affected (Haji Boland, 2015; Malhotra et al., 2018). Young plants need more P than mature plants, so deficiency symptoms are more pronounced in the former. Plants appear with dark green foliage and reduced leaf area under low P conditions. Reduced cell division and enlargement result in reduced leaf expansion and smaller leaves (Malhotra et al., 2018). When P is limited, older leaves synthesize more anthocyanins, resulting in purple pigmentation. Curled and twisted leaves as well as internal brown spots are also symptoms (Peaslee 1977; Malhotra et al. 2018).

PHOSPHORUS AND PLANT GROWTH

A plant's root anatomy is related to its ability to absorb nutrients, which is the first organ to be exposed to nutrient availability (Da Cunha Cruz et al., 2020). A key aspect of P acquisition is the root's morphological response to localized P (Gao et al., 2019; Mehdiniya Afra et al., 2014). Rarely have root architecture changes been examined in response to P (Strieder et al., 2017). Under P deficiency, some plants can increase root growth (Dissanayaka et al., 2017). Conversely, sensitive plants such as Arabidopsis thaliana show decreased root growth under low P conditions (Strieder et al., 2017). P signaling is unclear as to how it stimulates root growth. There may also be similar responses on roots (Da Cunha Cruz et al., 2020; Corrêa et al., 2017) at lower concentrations of the element. Plants at higher nutrient levels developed lower aerenchymas due to excessive or poor P concentrations (Da Cunha Cruz et al., 2020). In some species, the development of this tissue is constrained by excess P (Coelho et al., 2006; Vejchasarn et al., 2016; Díaz et al., 2018). This may be due to poor P conditions (Coelho et al., 2006; Vejchasarn et al., 2016). Typha species use the aerenchyma to diffuse oxygen and air throughout the root (Corrêa et al., 2015). Under conditions of excess or limited P concentrations, there may be reduced aerenchyma development, thereby limiting T. domingensis metabolism and growth (Da Cunha Cruz et al., 2020). P fertilizer placement has been shown to affect root morphology and growth in the past (Hansel et al., 2017). Primary and secondary roots are initiated and extended by P (Hansel et al., 2017). Amin et al. (2017) show that P is an essential macronutrient (along with nitrogen and potassium) for plants to store and transfer energy, to divide cells, and to develop tissues. In addition to P's role in root and shoot growth, it is also essential for overcoming the effects of mineral deficiency in the soil to optimize water use (Amin et al., 2017). The development and yield of crops are negatively affected by P-deficient soils (Singh et al., 2013). As the plant develops, P contributes to the early blooming, the number of floral buds, the biomass production, and the final crop yield (Bronson et al. 2001; Usman et al. 2010; Amin et al. 2017). P deficiency in Salvia and Mentha reduced root and shoot lengths and dry weights (Kharazmi et al., 2021). Figure 1 depicts the contribution of P in plant growth and development.

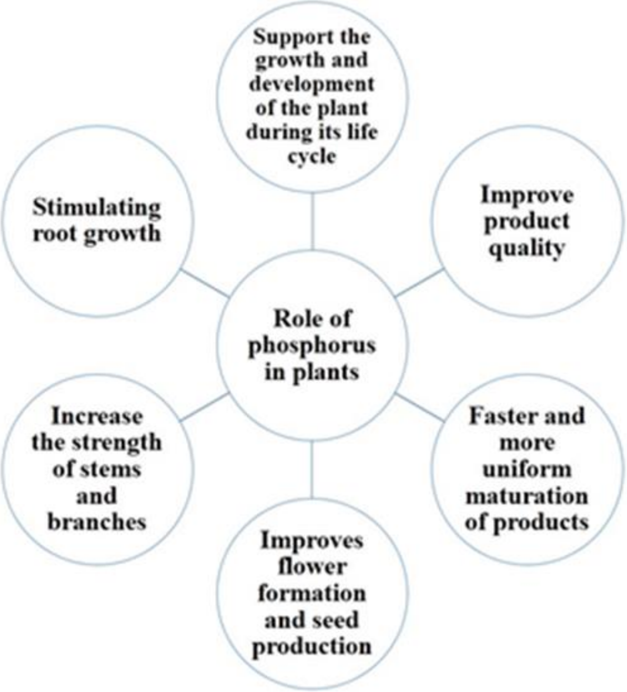

Figure 1: Contribution of P in plant growth and development

GRAIN QUALITY

Plant P uptake and utilization are crucial for crop yield (Afra and Mozafar, 2017). Among its many cellular functions, P maintains membrane structures, synthesizes biomolecules, and forms high-energy molecules (Malhotra et al., 2018). Moreover, it contributes to the division of cells, carbohydrate metabolism, enzyme activation and inactivation (Razaq et al., 2017). It promotes seed germination, root formation, stem and stalk strength, flower generation, seed formation, as well as crop yield and quality (Malhotra et al., 2018). In a nutrient deficient environment, plant growth is reduced due either to a decreased photosynthesis or an increased energy expenditure. Crop yield and quality are negatively affected by its limitations (Malhotra et al., 2018). Seeds and fruits contain significant amounts of P, which is assumed to be critical for seed formation and development (Malhotra et al., 2018). Rice and wheat seeds store most of the P taken up by plants. Consequently, a lack of P can reduce seed size, seed frequency, and viability (Malhotra et al., 2018). The soil provides plants with P. In acidic soils, P is fixed by calcium, while in alkaline soils, it is fixed by iron/aluminum (Ramtekey et al., 2021; Kochian et al., 2004). Therefore, farmers use excessive P fertilizers to ensure a high yield. In contrast, plants only utilize up to 30% of the applied P, with the remainder being fixed in the soil or contributing to eutrophication (Jez et al., 2016). According to researchers, nutrient concentration and plant growth are significantly affected by the application of P (Rafique et al., 2020). Wang et al. (2000) found that P treatment increased biomass and P accumulation in all organs, and root had the highest increase. In flowering, P supply increased root and leaf biomass and P partitioning, but it decreased stem partitioning. Seed biomass and P partitioning were facilitated by P at maturity. This increased the ratio of reproductive to vegetative cells, suggesting that it can improve nutrients' transport from vegetative to reproductive cells (Wang et al., 2021).

PHOTOSYNTHESIS

A sufficient amount of phosphorus is needed for preserving leaf photosynthesis, stomatal conductance, stimulating early root establishment, canopy development, and grain yield (Ali et al., 2010; Mohammadi et al., 2011). Numerous studies investigated the effect of P on fundamental physiological mechanisms such as growth, yield, photosynthesis, and nitrogen fixation of soybeans and other plant species (Sun et al., 1992; Raboy and Dickinson, 1993; Wang et al., 2018). The application of P increases photosynthesis, according to many reports. Specifically, Wang et al. (2018) found that the activity of the key enzyme of photosynthesis, Rubisco, and the protein content of leaves were greater in leaves treated with high P compared with low P treated leaves. Additionally, Singh and Reddy (2016) reported that RUBP regeneration, Rubisco activity, and maximum quantum yield were decreased under a P-deficient condition. Wang et al. (2021) reported that P supply enhanced the leaf area index and the photosynthetic rate during flowering. Therefore, the oil and seed yield of canola were both increased.

A study conducted by Carstensen et al. (2018) reported that NADPH levels increased under P deficiency, but ATP production remained limited, leading to a decrease in the fixation of CO2. As a result of lumen acidification, the non-photochemical quenching component gets activated, preventing overstimulation of photosystem II and leaf damage (Carstensen et al., 2018). P deficiency can affect plants for weeks without showing visible symptoms on their leaves. It seems that all the processes in the photosynthetic machinery are completely reversible under the influence of P deficiency. After resupplying orthophosphate to the leaf tissue, it can be repaired in less than 60 minutes (Carstensen et al., 2018).

PHOSPHORUS USE EFFICIENCY (PUE)

Plants with higher P uptake and utilization require increased P fertilizer efficiency. In addition to measuring the plants' ability to absorb P, PUE also measures the amount of biomass produced or the amount of yield produced (Van de Wiel et al., 2016). The PUE is an important trait that determines yield potential in several crops (Reddy et al., 2020). In comparison to crops with low PUE, crops with high PUE exhibit greater growth (Rengel and Marschner, 2005). The trait is, however, complex and quantitative (Heuer et al., 2017). PUE can be defined as the plant ability to produce more biomass per unit of P taken up by it (Hammond et al., 2009). In PUE, there are two vital mechanisms, namely P uptake efficiency (PUpE) and P utilization efficiency (PUtE) (Wang et al., 2010). PUE is therefore dependent on crop plants' capacity to take up P and utilize it in biomass production (Van de Wiel, van der Linden, and Scholten, 2016). Increase efficiency of both plant uptake and utilization through improvements in PUE (Weih et al., 2018). Generally, PUpE correlates positively with total P uptake, and P uptake also depends on plant dry matter yield. The basic method to increase the efficiency of P uptake under conditions of its limitation is to increase the total dry matter yield of the plant (Sandana, 2016).

CONCLUSIONS

The root system is critical to obtaining soil resources such as water and minerals from the soil, which are necessary for plant growth and development. The root system of plants can be altered significantly by nutrient deficiency, but they have also adapted root systems that allow them to survive and grow under nutrient-limited conditions. A plants root anatomy influences its ability to absorb nutrients, as nutrient availability is first senced in roots. One of the most important essential elements required by plants is P, which plays an important role in the growth and development of roots, strengthens and thickens stems, bulks the seeds, increases yield and early maturity, and is involved in the inoculation of flowers. P plays a main role in photosynthesis, respiration, energy storage, cell division, and cell enlargement in plants. In addition to contributing to environmental concerns, excessive P input into agricultural systems also contributes to eutrophication of water bodies. There is an urgent need to develop and adapt to innovative technologies to mitigate these negative environmental impacts so that the P fertilizer rate across different crop production systems can be optimized and PUE increased.

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