

Influence of Mineral Phosphorus Fertilization on Assimilation and Selected Physiological Parameters in Soybean in the Transylvanian Plain

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Abstract. Mineral phosphorus fertilization is an effective method for correcting nutrient deficiencies and enhancing the controlled uptake of nutrients by plants, including their translocation from leaves to seeds. In an experiment conducted at SCDA Turda in 2023, the effect of phosphorus fertilization on net CO₂ assimilation rate (A , $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), stomatal conductance (g_s , $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$), leaf transpiration rate (E , $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$), and leaf vapor pressure deficit (VPD, kPa) in soybean was evaluated during the beginning of seed filling (R5 growth stage). The experiment included four phosphorus fertilization levels (b_2 – 40 kg/ha, b_3 – 80 kg/ha, b_4 – 120 kg/ha, b_5 – 160 kg/ha) and an unfertilized control (b_1), under variable temperature conditions grouped into three intervals (22–24°C, 25–27°C, and 28–30°C). Results showed that phosphorus fertilization significantly improved net CO₂ assimilation rate and leaf transpiration rate, enhancing key physiological processes such as photosynthesis and stomatal regulation. In the moderate temperature range (22–27°C), fertilization contributed to a reduction in leaf vapor pressure deficit and promoted more efficient use of water and nutrients. At higher temperatures (28–30°C), high phosphorus doses (160 kg/ha) led to a decrease in photosynthetic efficiency (VPD) and stomatal activity (g_s), indicating greater water stress. These findings highlight the importance of phosphorus fertilization and environmental management practices, which are crucial for optimizing plant physiological processes—particularly in the context of climate change, where efficient water and nutrient management becomes a priority.

Keywords: net CO₂ assimilation, stomatal conductance, transpiration, leaf vapor pressure deficit, soybean

INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) is a valuable crop due to its high protein and oil content, playing an essential role in both human and animal nutrition (Leamy et al., 2017). Climatic conditions and applied agronomic technologies significantly influence these processes. The genetic and physiological factors of soybean, such as photosynthesis, net CO₂ assimilation, and root system development, affect the overall growth and performance of the crop (Szostak et al., 2020).

Often referred to as the “golden plant” or the “plant of the future,” soybean plays a crucial role in providing plant-based protein and oil at a global scale (Muntean et al., 2019; Soria-Hernández et al., 2020; Parrini et al., 2023). Investigating the physiological processes that govern its growth is essential for optimizing vegetative growth and biomass accumulation (Zhu et al., 2008; Nair et al., 2023), as well as for improving crop quality and productivity (Xu et al., 2022; Kulig et al., 2023; Urdă et al., 2024).

Mineral fertilization plays a key role in optimizing nutrition for this crop, significantly impacting yield and quality (Kubar et al., 2021; Negrea et al., 2022; Ceclan et al., 2023). Nitrogen, derived both from fertilizers and symbiotic fixation, contributes to plant development and protein accumulation (Pratap et al., 2011; Patil et al., 2017; Chețan et al., 2021), while potassium regulates the osmotic potential of cells and reduces abiotic stress (Cotrim et al., 2023). Studies on the Felix variety indicate that phosphorus fertilization strengthens plant immunity (Popa et al., 2023) and, together with nitrogen and potassium, improves photosynthetic processes (Bărdaș et al., 2023), supporting soybean growth and productivity (Urdă et al., 2021). Photosynthesis in soybean follows a seasonal dynamic, with three periods of high activity: leaf formation, flowering, and accumulation of storage compounds (Woodward and Rawson, 1976). Maximum photosynthetic intensity is reached when leaves attain full size and maturity, while stems and pods exhibit lower respiratory activity (Huber et al., 1986; Burzo et al., 1999; Delian, 2013).

Phosphorus (P) is an essential element for plant metabolism (King et al., 2013), involved in photosynthesis, cellular respiration, and protein synthesis, thus supporting growth and development (Singh et al., 2018; Kayoumu et al., 2023). As part of ATP, phosphorus provides energy for cellular biochemical processes (Khan et al., 2023), and as a component of nucleic acids (DNA and RNA), it plays a fundamental role in genetic information transfer and metabolic regulation (Kolodiazhnyi, 2021). Adequate phosphorus supply stimulates the development of a strong root system, facilitating efficient uptake of water and nutrients and supporting overall plant growth (Hanson et al., 2000; Rusu, 2023). Phosphorus directly influences flower and seed formation and development, having a significant impact on crop productivity and quality (Suciu et al., 2022; Negrea et al., 2023).

Climatic fluctuations can affect phosphorus uptake and fertilization efficiency, leading to variations in crop performance (Şimon et al., 2022). Therefore, optimal fertilizer application is crucial for maintaining plant productivity (Johan et al., 2021).

Moreover, phosphorus enhances plant tolerance to biotic and abiotic stress, contributing to resistance against diseases, pests, drought, and extreme temperatures (Ibrahim et al., 2022). Interest in soybean cultivation is expected to increase in the coming years, considering its importance as a major global source of protein and oil (Li et al., 2004; Ali, 2010; Lieberei and Reisdorff, 2012).

The aim of this study is to evaluate the impact of phosphorus fertilization and temperature on physiological processes in soybean, including net CO₂ assimilation, stomatal conductance, leaf transpiration rate, and leaf vapor pressure deficit, within the broader context of managing water, heat, light, and nutrient resources.

MATERIAL AND METHODS

The research was carried out at the Agricultural Research and Development Station (ARDS) Turda, using the soybean cultivar Felix, known for its high yield potential and resistance to lodging and pod shattering, with harvest occurring in the first half of September (Mureşanu et al., 2010).

Experiments were conducted under the specific climatic conditions of the Transylvanian Plain, on a Faeoziom soil type (RSST, 2012), equivalent to Phaeozem according to the World Reference Base (2015), with a neutral pH (6.8–7.2, determined potentiometrically in distilled water), clay texture (clay content ranging from 51.8–55.5%), and humus content between 2.20–3.00% (determined using the Walkley-Black method). Total nitrogen content ranged between 0.124–0.162% (Kjeldahl method), while the soil was moderately supplied with phosphorus (0.9–5 ppm) and well supplied with potassium (126–140 ppm), according to the Egner-Riehm–Domingo extraction method. Soil samples for chemical analyses were collected from a depth of 0–30 cm.

The experimental factors analyzed in this study were ambient temperature and mineral phosphorus fertilization. Factor A – ambient temperature – included three levels: a₁ (22–24°C), a₂ (25–27°C), and a₃ (28–30°C). Factor B – phosphorus fertilization – included five levels: b₁ (P₀ kg/ha), b₂ (P₄₀ kg/ha), b₃ (P₈₀ kg/ha), b₄ (P₁₂₀ kg/ha), and b₅ (P₁₆₀ kg/ha).

Physiological parameters were measured using non-destructive methods, without detaching leaves, based on the use of the CIRAS-3 portable gas analyzer (PP Systems, USA, 2014), which simultaneously records multiple physiological and environmental indicators. Measurements were conducted according to the Fehr and Cavin scale during the R₅ phenophase (beginning of seed filling) in the first decade of August. Fifteen readings were taken on five plants per variant, with three replications for each variant. The measurement duration was determined by the time required for tissue adaptation inside the measurement chamber. The analyzed parameters included net CO₂ assimilation rate (A, µmol CO₂ m⁻² s⁻¹), stomatal conductance (g_s, mmol H₂O m⁻² s⁻¹), leaf transpiration rate (E, mmol H₂O m⁻² s⁻¹), and vapor pressure deficit (VPD, kPa), under semi-controlled conditions with CO₂ at 390 µmol mol⁻¹ and variable photosynthetically active radiation (PAR, 0–2000 µmol m⁻² s⁻¹).

Statistical analysis was performed using analysis of variance (ANOVA) with the Polyfact Soft program, version 4, using the least significant difference (LSD) at 5%, 1%, and 0.1% levels. Correlations between physiological parameters and experimental observations were evaluated through post-hoc multiple comparison tests.

During the growing season, thermal conditions played a crucial role in soybean cultivation. The year 2023 was characterized by a warm thermal regime, with pronounced warming during the summer months (July and August). Spring started with below-average temperatures (March–April), resulting in delayed sowing until the last decade of April. Low temperatures slowed biological activity, and plants required approximately 24 days to emerge, affecting early developmental stages and nutrient uptake.

From May onwards, temperatures rose above the multi-annual average, with a deviation of +1.0°C in June, stimulating basic biological processes, including photosynthesis and biomass accumulation, allowing recovery from spring delays. However, high daytime temperatures (35°C) during flowering negatively affected plant development, with similar results reported by Gibson and Mullen (1996) and Radzka et al. (2023).

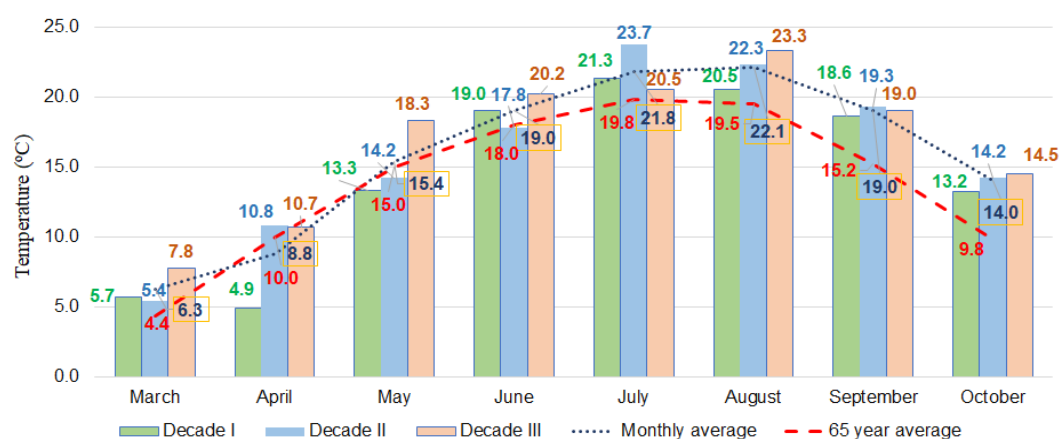


Figure 1. Monthly and ten-day period temperatures recorded from March 1 to October 31, 2023, at SCDA Turda

Summer months continued with elevated temperatures, exceeding the multi-annual average by 2.0°C in July and 2.6°C in August, favoring intense physiological activity and supporting growth and biomass accumulation, with an accelerated rate of essential nutrient uptake (Figure 1).

The rainfall regime during the 2023 growing season influenced soybean development, with spring precipitation below the multi-annual average, recording 10.8 mm in March (compared to 24.3 mm) and 30.5 mm in April (compared to 45.6 mm). These conditions slowed the growth rate and nutrient uptake during the early emergence and initial growth stages.

In May, precipitation was below the multi-annual average of 69.4 mm, but slightly improved soil water conditions, while in June, abundant rainfall of 144.5 mm, well above the average of 59.9 mm, stimulated biological activity and supported plant growth.

The rainfall regime was further improved by significant precipitation in June (second and third decades), contributing to enhanced phosphorus net CO₂ assimilation, which is essential for supporting flowering and pollination processes. In July, the first two decades were dry, but rainfall in the third decade (63.8 mm) partially restored soil moisture, stimulating generative processes.

In August and September, a significant increase in precipitation was recorded, with both months being excessively rainy, exceeding the multi-annual average by 42.4 mm and 73.7 mm, respectively. Occasionally, excess soil water can be equally detrimental, limiting crop performance potential (Santos and Carlesso, 1998; Lobato et al., 2008).

Adequate water supply during the growing season ensures optimal conditions for phosphorus transport and solubilization in the soil, facilitating its uptake, which is essential for cellular energy (ATP), nucleic acid synthesis, and root development, thus supporting soybean growth.

Characterization of the thermal and rainfall regime for soybean cultivation in 2023 was based on primary data recorded by the Turda Meteorological Station (long. 23°47', lat. 46°35', alt. 427 m) (Figures 1 and 2).

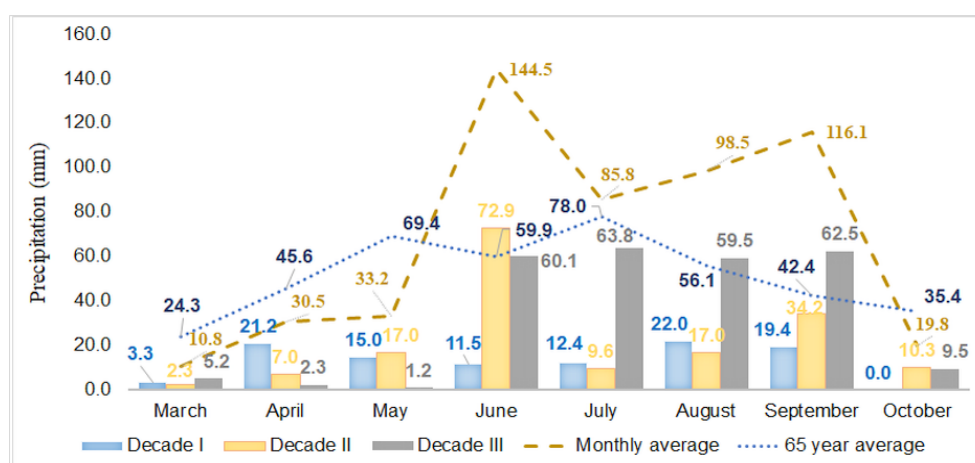


Figure 2. Monthly and ten-day period precipitation recorded from March 1 to October 31, 2023, at SCDA Turda

RESULTS AND DISCUSSIONS

Net CO₂ assimilation rate (A , $\mu\text{mol m}^{-2}\text{s}^{-1}$) showed a statistically significant positive increase ($p < 0.01$) in the temperature range of 22–24 °C, reaching a maximum value of 25.4 $\mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$ in variant b₄, where 120 kg/ha of phosphorus was applied. In variant b₅ (160 kg/ha phosphorus), net CO₂ assimilation rate slightly decreased, but values remained highly significantly positive compared to the unfertilized control ($p < 0.01$).

The same trend was observed in the temperature ranges of 25–27 °C and 28–30 °C, where net CO₂ assimilation rate initially increased up to variant b₃ (80 kg/ha phosphorus) and then slightly decreased in variant b₄. temperatures above 24 °C, excessive phosphorus doses may have a highly significant negative effect on compared to the unfertilized control.

Under phosphorus deficiency, net CO₂ assimilation rate values were the lowest across all analyzed temperature ranges. Therefore, it can be stated that phosphorus has a positive influence on net CO₂ assimilation, and its deficiency somewhat limits gas exchange, affecting the photosynthesis process (Chu et al., 2018), a phenomenon associated with CO₂ accumulation in the intercellular spaces (Qui et al., 1992). Tolerance of soybean varieties to phosphorus deficiency varies, with some varieties able to utilize smaller phosphorus amounts more efficiently, accumulating it in lower quantities (Foote and Howell, 1964).

Table 1. Influence of phosphorus and temperature on net CO₂ assimilation rate (A , $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), in soybean.

Temperature (°C)	P ₀	P ₄₀	P ₈₀	P ₁₂₀	P ₁₆₀
T 22-24°C	19.53	20.90	23.93	25.37	23.27
Difference	0.00	1.37	4.40	5.83	3.73
Significance	cv.	***	***	***	***
T 25-27°C	22.83	23.87	25.40	25.00	21.70
Difference	0.00	1.03	2.57	2.17	-1.13
Significance	cv.	***	***	***	000
T 28-30°C	21.27	23.87	24.83	22.80	19.93
Difference	0.00	2.60	3.57	1.53	-1.33
Significance	cv.	***	***	***	000
LSD (p 5%)-0.47; LSD (p 1%)-0.64; LSD (p 0.1%) – 0.86					

Notes: cv – control variant; - insignificant difference; * -significant positive difference; ** - very significant positive difference; *** - very significantly positive; 0 -significant negative; 00- significantly negative difference; 000 - very significantly negative; LSD - Least Significant Difference

In soybean, within the temperature range of 22–24°C, stomatal conductance (g_s) increased significantly in variants b₂ and b₃, showing statistically significant differences compared to the control. In contrast, in variants b₄ and b₅, where higher phosphorus doses were applied, g_s decreased, with a highly significant negative difference compared to the control.

In the temperature range of 25–27°C, stomatal conductance (g_s) increased significantly in variant b₂, while in variant b₃, a smaller but still significant increase was observed. In variants b₄ and b₅, where phosphorus doses exceeded 120–160 kg/ha, g_s decreased, with a highly significant negative difference ($p < 0.01$) compared to the control.

At temperatures of 28–30°C, g_s decreased significantly with increasing soil phosphorus concentration across all fertilized variants (b₂–b₅), the differences being highly significantly negative ($p < 0.01$) compared to the control. At high temperatures, the effect of phosphorus on g_s becomes predominantly negative, reducing gas exchange through the stomata.

The results obtained confirm the observations of Delian (2020) regarding the ability of stomata to respond to climatic variations. Thus, the interaction between phosphorus, temperature, and stomatal conductance highlights the importance of managing fertilization under the current conditions of climate change.

Table 2. The influence of phosphorus and temperature on stomatal conductance (g_s , $\text{mmol H}_2\text{O m}^{-2}\text{s}^{-1}$).

Temperature (°C)	P ₀	P ₄₀	P ₈₀	P ₁₂₀	P ₁₆₀
T 22-24°C	793.3	852.0	878.0	546.0	796.3
Difference	0.00	58.7	84.7	-247.3	3.0
Significance	cv.	***	***	000	-
T 25-27°C	432.3	605.3	450.3	350.0	310.0
Difference	0.00	173.0	18.0	-0.82	-122.3
Significance	cv.	***	*	000	000
T 28-30°C	532.0	293.0	300.7	195.0	344.3
Difference	0.00	-238.7	-231.0	-337.0	-187.7
Significance	cv.	000	000	000	000
LSD (p 5%) -16.7; LSD (p 1%) -22.8; LSD (p 0.1%) - 30.4.					

Notes: cv – control variant; - insignificant difference; * -significant positive difference; ** - very significant positive difference; *** - very significantly positive; 0 -significant negative; 00- significantly negative difference; 000 - very significantly negative; LSD - Least Significant Difference

The data analysis highlights a significant interaction between net CO₂ assimilation rate and stomatal conductance, depending on phosphorus fertilization, and shows a Gaussian-type distribution. Moderate phosphorus doses (40–80 kg/ha)

maximize these physiological processes, with a peak of 25.40 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ for net CO_2 assimilation rate and 878 $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ for stomatal conductance at 80 kg/ha, indicating an optimal physiological balance.

Higher phosphorus doses and elevated temperatures (120–160 kg/ha) cause both net CO_2 assimilation rate (A) and stomatal conductance (E) to decrease significantly. For example, the 160 kg/ha dose results in a net CO_2 assimilation rate of 19.90 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and stomatal conductance of 195 $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$, suggesting a negative effect of excessive fertilization on photosynthesis and stomatal regulation.

Observations indicate that, although stomatal conductance decreases, limiting gas exchange, the plant maintains net CO_2 assimilation rate through the activation of compensatory biochemical mechanisms, such as enhanced carboxylation and optimization of metabolic energy usage (ATP and NADPH). Phosphorus fertilization supports these physiological adaptations, facilitating efficient photosynthetic regulation under conditions of reduced CO_2 availability, as noted by Flex et al. (2004). Fertilization with 40–80 kg/ha phosphorus is optimal for maintaining balanced physiological activity, supporting efficient levels of net CO_2 assimilation rate and stomatal conductance (Figure 3).

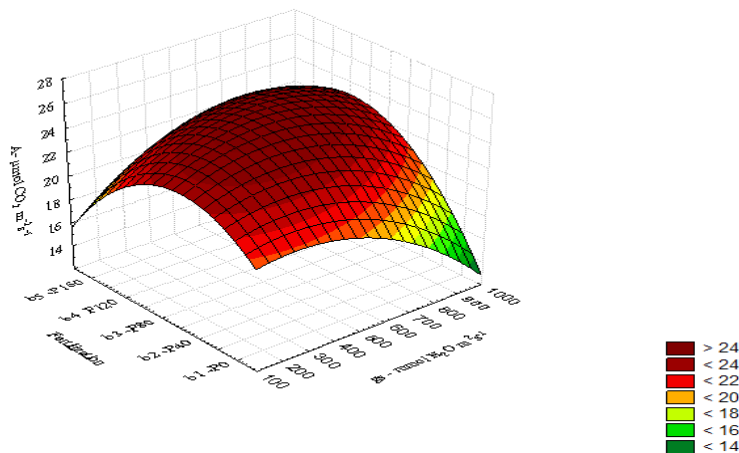


Figure 3. The influence of phosphorus fertilization on net CO_2 assimilation rate (A) and stomatal conductance (gs).

In soybean, within the temperature range of 22–24°C, there is a tendency for leaf transpiration to increase, exceeding 3.70 $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$, with rising soil phosphorus levels in variants b₂, b₃, and b₅, where significantly higher values were recorded. In contrast, in variant b₄, where 120 kg/ha phosphorus was applied, transpiration decreased, the statistical difference being highly significant and negative compared to the unfertilized control, where no mineral phosphorus was applied. This result indicates an initial positive relationship between phosphorus level and transpiration; however, excessive phosphorus application can lead to a reduction in transpiration.

In the temperature range of 25–27°C, transpiration exceeds 4.70 $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ with increasing phosphorus levels up to 80 kg/ha in variant b₃, the statistical difference being highly significant and positive compared to the control. Subsequently, values remain relatively constant or show a slight decrease compared to the control. As temperature rises, transpiration shows an upward trend even in variant b₁ (unfertilized); however, under conditions of high phosphorus concentration, it decreases, the difference being highly significant and negative compared to the control (Table 3).

Table 3. The influence of phosphorus and temperature on the leaf transpiration rate (E, $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$)

Temperature (°C)	P ₀	P ₄₀	P ₈₀	P ₁₂₀	P ₁₆₀
T 22-24°C	3.59	3.76	3.72	3.35	4.05
Difference	0.00	0.17	0.13	-0.24	0.46
Significance	cv.	**	*	000	***
T 25-27°C	3.89	4.76	4.31	3.81	3.85
Difference	0.00	0.87	0.42	-0.08	-0.04
Significance	cv.	***	***	-	-
T 28-30°C	5.36	4.24	4.26	3.50	3.90
Difference	0.00	-1.12	-1.10	-1.86	-1.45
Significance	cv.	000	000	000	000
LSD (p 5%) - 0.12; LSD (p 1%) - 0.16; LSD (p 0.1%) - 0.22.					
Notes: cv – control variant; - insignificant difference; * -significant positive difference; ** - very significant positive difference; *** - very significantly positive; 0 -insignificant negative; 00- significantly negative difference; 000 - very significantly negative; LSD - Least Significant Difference					

The interaction between net CO_2 assimilation rate (A) and leaf transpiration rate (E) is illustrated by a Gaussian-type curve, depending on the level of phosphorus fertilization. Moderate phosphorus doses, between 40 and 80 kg/ha, allow both net CO_2 assimilation rate and transpiration to reach maximum values, indicating an optimal physiological

system of the plant. Net CO₂ assimilation rate reaches 25.40 μmol CO₂ m⁻² s⁻¹ at 80 kg/ha, while transpiration attains 4.76 mmol H₂O m⁻² s⁻¹, reflecting a healthy and efficient physiological balance. These conditions are ideal for the performance of photosynthesis and transpiration, as plants benefit from a balanced use of water and nutrients.

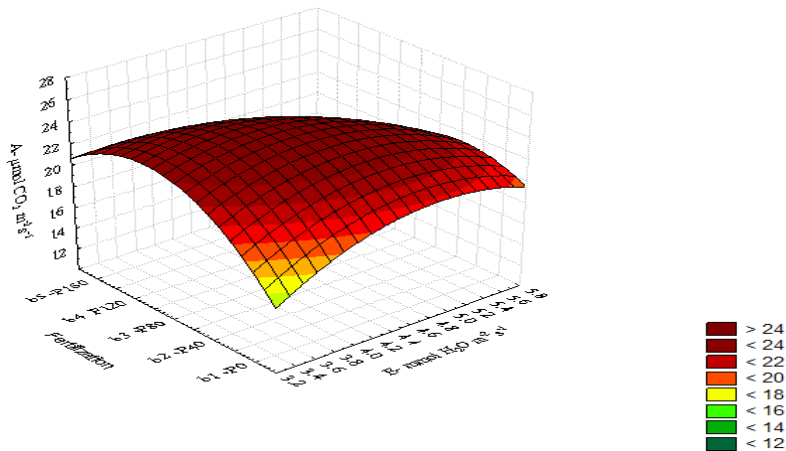


Figure 4. The influence of phosphorus fertilization on net CO₂ assimilation rate (A) and leaf transpiration rate (E)

In contrast, at high phosphorus doses (120 and 160 kg/ha), significant reductions in physiological performance are observed. At 160 kg/ha, net CO₂ assimilation rate decreases to 19.93 μmol CO₂ m⁻² s⁻¹, and transpiration drops to 3.90 mmol H₂O m⁻² s⁻¹, indicating that excess phosphorus disrupts the plant’s physiological balance, negatively affecting these processes (Figure 4).

These results demonstrate that high phosphorus doses have an inhibitory effect on plant physiological processes, reducing the efficiency of photosynthesis and transpiration. Moderate phosphorus fertilization, in the range of 40–80 kg/ha, is the most effective for optimizing these processes, contributing to the maintenance of a balanced physiological system.

In soybean, the leaf vapor pressure deficit (VPD) is influenced by temperature and soil phosphorus concentration. In the temperature range of 22–24°C, in the V2 (P40) and V3 (P80) treatments, VPD remained low (below 0.60 kPa), whereas in the V4 (P120) and V5 (P160) treatments, it increased significantly, reaching 0.71 kPa (V4), maintaining an adequate plant water balance. In the temperature range of 25–27°C, VPD progressively increased with the applied phosphorus dose, exceeding 1.20 kPa in the V4 (P120) and V5 (P160) treatments, with highly significant positive differences, indicating an intensification of transpiration (Table 4).

At 28–30°C, VPD in the V4 (P120) and V5 (P160) treatments exceeded 1.35 kPa, with highly significant positive differences, indicating pronounced water stress and reduced stomatal activity. Phosphorus deficiency in soybean reduced photosynthesis across all temperature ranges, as observed by Rao et al. (2002), who reported a 1.55-fold decrease under similar experimental conditions.

Temperature and increasing phosphorus doses influenced leaf VPD, reflecting improved air humidity around the leaves and a reduction in excessive water loss through transpiration, thereby directly affecting water use efficiency in photosynthesis and the plant's potential yield, a phenomenon also highlighted by Bunce (2016).

Table 4. Influence of phosphorus and temperature on vapor pressure deficit (VPD – kPa).

Temperature (°C)	P ₀	P ₄₀	P ₈₀	P ₁₂₀	P ₁₆₀
T 22-24°C	0.55	0.58	0.57	0.71	0.66
Difference	0.00	0.02	0.01	0.16	0.07
Significance	cv.	-	-	***	***
T 25-27°C	1.06	0.95	1.07	1.20	1.32
Difference	0.00	-0.11	0.02	0.14	0.27
Significance	cv.	000	-	***	***
T 28-30°C	1.18	1.46	1.54	1.76	1.34
Difference	0.00	0.29	0.36	0.58	0.16
Significance	cv.	***	***	***	***

LSD (p 5%)-05; LSD (p 1%)-0.07; LSD (p 0.1%) – 0.09.

Notes: cv – control variant; - insignificant difference; * -significant positive difference; ** - very significant positive difference; *** - very significantly positive; 0 -significant negative; 00- significantly negative difference; 000 - very significantly negative; LSD - Least Significant Difference

Net CO₂ assimilation rate and water deficit (VPD) exhibit an inversely proportional correlation, following a Gaussian-type curve. Under optimal phosphorus fertilization conditions (80 kg/ha), net CO₂ assimilation rate reaches a maximum

value of $25.4 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at a temperature of $25\text{--}27^\circ\text{C}$ while VPD remains at a minimal level of 1.07 kPa . This physiological configuration suggests a favorable balance between photosynthesis and transpiration, reflecting the efficiency of the plant's metabolic processes.

In contrast, extreme temperatures, above 30°C or below 18°C , significantly reduce the physiological efficiency of the plant. Phosphorus fertilization, recommended at doses of $40\text{--}80 \text{ kg/ha}$, influences these processes: at low temperatures, phosphorus stimulates net CO_2 assimilation rate, maintaining or slightly increasing the leaf vapor pressure deficit, while at high temperatures, both assimilation and transpiration decrease, and VPD rises.

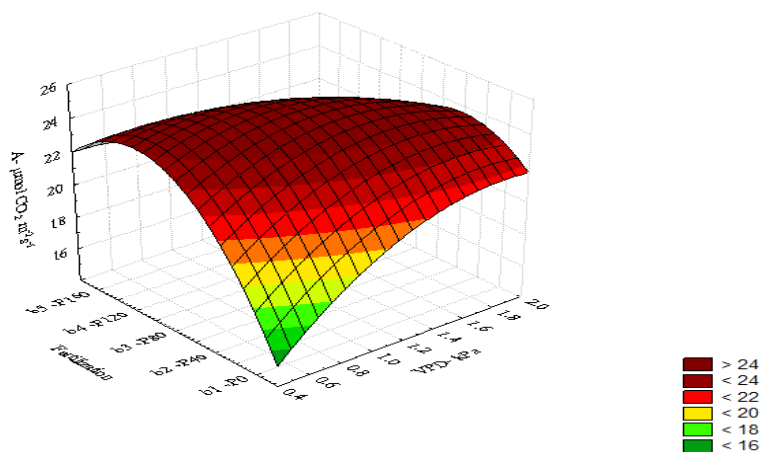


Figure 5. Influence of phosphorus fertilization on net CO_2 assimilation rate (A) and vapor pressure deficit (VPD).

The graph highlights that moderate temperatures are optimal for efficient photosynthesis, while significant deviations from this range negatively affect the plant's physiological functioning.

Higher phosphorus doses, such as 120 kg/ha and 160 kg/ha , cause a significant decrease in net CO_2 assimilation rate, accompanied by an increase in water deficit. At the highest phosphorus dose, 160 kg/ha , net CO_2 assimilation rate decreases to $19.93 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, with a vapor pressure deficit (VPD) of 1.54 kPa (Figure 5). These data indicate that moderate phosphorus fertilization (between 40 and 80 kg/ha) is optimal for maximizing net CO_2 assimilation rate while maintaining water deficit (VPD) at a low level, ensuring good physiological performance of the plant.

Net CO_2 assimilation rate and vapor pressure deficit (VPD) exhibit an inversely proportional correlation, described by a Gaussian-type curve. Under optimal phosphorus fertilization conditions (80 kg/ha), net CO_2 assimilation rate reaches a maximum value of $25.4 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at a temperature of $25\text{--}27^\circ\text{C}$, while VPD remains at a minimal level of 1.07 kPa . This physiological configuration indicates a favorable balance between photosynthesis and transpiration, reflecting the efficiency of the plant's metabolic processes.

CONCLUSIONS

Moderate phosphorus fertilization maximizes the physiological processes of soybean: The data indicate that moderate phosphorus fertilization (between 40 and 80 kg/ha) is optimal for maximizing net CO_2 assimilation, stomatal conductance (gs), and transpiration, while simultaneously reducing the water deficit (VPD). This fertilization range supports a healthy physiological balance, ensuring efficient photosynthesis and optimal water management, which contributes to high physiological performance in soybean.

Excess phosphorus disrupts plant physiological processes: At higher phosphorus doses (120 and 160 kg/ha), a significant decrease in net CO_2 assimilation, stomatal conductance (gs), and transpiration is observed. At the same time, the water deficit (VPD) increases, indicating a reduction in photosynthesis and transpiration efficiency. Excess phosphorus destabilizes physiological processes, limiting the overall performance of the plant.

Moderate temperatures ($22\text{--}27^\circ\text{C}$) favor physiological processes by maximizing net CO_2 assimilation, stomatal conductance (gs), and transpiration, while maintaining leaf vapor pressure deficit (VPD) at an optimal level. Deviations from this temperature range, either to lower or higher values, negatively affect physiological performance, reducing net CO_2 assimilation, stomatal conductance, and transpiration, while increasing VPD, resulting in more pronounced water stress.

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