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Original Research

Optimizing Maize Growth and Phosphorus Use Efficiency through Integrated P Application and Irrigation Strategies

Muhammad Afzal Khan[1], Atif Javed[1], Muhammad Shabaan[2], Muhammad Iqbal[1], Usman Zulfiqar[3*], Rehmat Kabir[4], Fasih Ullah Haider[5,6], Abd El-Zaher M.A. Mustafa[7], Humaira Rizwana[7], Mohamed S Elshikh[7]

[1]Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan
[2]Land Resources Research Institute, National Agricultural Research Centre, Islamabad, Pakistan
[3]Department of Agronomy, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur 63100, Pakistan
[4]Mountain Agricultural Research Centre MARC, Chilas, Pakistan Agricultural Research Council, Islamabad, Pakistan
[5]Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China
[6]University of Chinese Academy of Sciences, Beijing 100039, China
[7]Department of Botany and Microbiology, College of Science, King Saud University, Riyadh 11451, Saudi Arabia

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Abstract

Phosphorus (P) is crucial for plant functions like root growth, energy transfer, photosynthesis, and cell division. Yet, its soil efficiency is hindered by high fixation, low solubility, and immobility. Besides, its increased availability and subsequent plant uptake requires availability of sufficient moisture, as increased soil moisture contents higher dissolution of P occurs leading to increased root development, which, ultimately, increase nutrient uptake by plants. We performed a field experiment to check the effect of different P application levels along with different irrigation schemes in improving P uptake efficiency of maize and its related growth and yield attributes. In different treatments, irrigation was provided at recommended levels, skipped at milking and flowering stages to check the impacts of moisture contents on soil P availability. We observed that among different P levels, application of P at 90 kg ha^{-1} along with recommended irrigation level enhanced different maize traits, such as shoot length (13.4%), root length (51%), shoot fresh and dry weights (35 and 25%), root fresh and dry weights (37 and 42%), SPAD value (17%), chlorophyll 'a and b' (16 and 7%), P use efficiency (255%), harvest index (43%) and carotenoid contents (26%), as compared to control followed by P at 120 kg ha^{-1}. Furthermore, in terms of soil nutrient attributes, P at 90 kg ha^{-1} along with recommended irrigation level enhanced soil organic matter (17%), active carbon (22%), available P (122%) and extractable potassium

*e-mail: usman.zulfiqar@iub.edu.pk

(36%), as compared to control. A consecutive decline in all the measured attributes was pragmatic under skipped irrigation systems under all the P application levels. We concluded that P application at 90 kg ha-1 combined with recommended irrigation levels can significantly increase P use efficiency of maize along with increased soil P availability and related growth and yield attributes.

Keywords: Field experiment, maize, skip irrigation, Phosphorus, P-use efficiency

Introduction

Increasing global population and their subsequent dietary requirements have put a lot of onus on agriculture, whose output is significantly influenced by numerous factors i.e., land holdings, lack of proper mechanization and prevalence of various biotic and abiotic stresses [1-3]. Water stress causes significant setbacks to agricultural production every year [4, 5]. Water scarcity due to reduced rainfall and enhanced dry spells have given rise to drought stress, which is stimulated and prolonged for a relatively longer time period due to inadequate rainfall, and is not generally restricted to a specific region or time period [6, 7]. It is a multi-dimensional abiotic stress that chiefly occurs due to depreciated rainfall and long-term drying conditions [8]. About 33% population of human beings in developing countries are living in water deficit zones [9]. Pakistan also lies in the arid to semi-arid region, with low precipitation and high evapotranspiration, and as a result, more water is lost to the environment. Water is an essential factor for key plant physiological processes, such as photosynthesis, enzymatic activity, metabolism, protein synthesis and transpiration [10]. Water use efficiency (WUE) can be improved by the irrigation scheduling at different crop growth stages [11]. WUE decreases by over irrigation while deficit irrigation increases water use efficiency as well as crop production [12]. Kang et al. [13] revealed that the yield and WUE are strongly affected by the irrigation scheduling and soil water contents.

Maize (*Zea mays* L.) is the third most important feed and food cereal crop worldwide, after wheat and rice. It is an important cereal crop, which supplies diet to millions of people worldwide. Maize seeds contain ash (1.2%), protein (10.5%), fiber (2.8%), starch (80.8%), sugar (2%) and oil (2.7%) [14]. Maize is used as forage and feed for livestock and poultry and used as the raw material for almost 4000 products created by agro-based chemical industries. Its cultivated area in Pakistan is about 1.720 million hectares (Mha) that contributes to 0.7% in gross domestic product and 3.0% to value addition in agriculture [15]. Maize seeds are composed of 2%, 65% and 33%, amino acids, sugars and organic acids respectively [16]. Un-even spatiotemporal distribution and limited water resources have restricted its production as insufficient water halts the metabolic activities of maize and decreases its biomass production and metabolic photosynthetic rates by reducing the chlorophyll contents and subsequently, its yield [17]. Water stress to any stage of growth can decrease the maize yield due to the modification in the physiological processes of the plant [18].

Phosphorus (P) is an important primary macronutrient among all essential nutrients required by plants. It serves as a major element for improved root growth, energy carrier in the form of adenosine triphosphate (ATP), and in genetics owing to its role in the composition of deoxyribonucleic acid (DNA). Its application via different organic and inorganic sources is inevitable to proper crop growth, and that is why its deficiency cannot be ignored. The main function of the inorganic fertilizer is to enhance the crop production, but low use of P fertilizers is a major concern in obtaining the proven maximum crop yield, by comparison to nitrogen [19]. For maximum crop production, crop requires adequate supply of P during early stages of growth [20]. P is required by the crop in larger quantities after nitrogen (N), and application of phosphatic fertilizers is needed in order to maintain the fertility of soil. Agriculture sector depends largely upon phosphatic fertilizers, which are manufactured from rock phosphate, a non-renewable resource. It should be well managed to avoid its over exploitation. Availability of P depends upon the water contents in soil, where higher moisture contents results in higher mobility and P availability to the crop [21] and increased water contents also enhance the utilization efficiencies of P in plants by improving the root length as well as root shoot ratio, releasing organic acids and protons [22], and phosphatases [22].

Combined effect of P fertilizer and soil available water plays an essential role for growth and development of crops [23]. In order to increase the production, a suitable method of irrigation and application of fertilizer should be adopted. Malik and Khan, [24] suggested the recommended method of the application of P fertilizer is broadcasting in Pakistan, followed by incorporation in the soil, before crop sowing. This method resulted in the formation of insoluble P. Some studies have also revealed that split applications of N and P fertilizers by side -dressing or with irrigation can produce equal grain yield or sometimes more P uptake and higher grain yield [25, 26].

Hence, our hypothesis aimed to test whether applying P via chemical fertilizer, combined with an optimal irrigation scheme, could enhance P use efficiency, soil P availability, and consequently, improve maize growth and yield attributes. This field trial aimed to assess the influence of varying P levels (0, 90, 120, and

Table 1. Physio-chemical characteristics of soil used for study.

Characteristics		Unit	Value
Textural Class		Loam	
Bulk Density	0-15 cm	Mg m^{-3}	1.45
	15-30 cm		1.50
EC_e		dS m^{-1}	1.45
pH		_	7.5
Saturation percentage		(%)	35.5
Na^+		mmolc L^{-1}	3.58
K^+			0.67
$Ca^{2+} + Mg^{2+}$			10.15
CO_3^{2-}			0.72
HCO_3^-			8.2
Cl^-			4.80
SO_4^{2-}			0.78
Soil Organic Carbon	0-15 cm	mg kg^{-1}	5.0
	15-30 cm		4.5
Available Phosphorous	0-15 cm		6.45
	15-30 cm		4.58
Extractable Potassium	0-15 cm		124.6
	15-30 cm		105

150 kg ha^{-1}) on growth, yield, physiological aspects, and soil fertility under diverse irrigation management approaches.

Materials and Methods

A field trial was performed to study the effect of different levels of irrigation and phosphorus (P) on water and P use efficiency in maize at the research farm of Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad. The experimental site is situated at 31.25°N latitude, 73.04°E longitude, with an altitude of 184 meters, characterized by a semi-arid climate. The experiment was laid out in randomized complete block design (RCBD) with factorial arrangements. Composite samples of soil were randomly collected before the crop sowing from the field. Air dried soil samples were ground and homogenized by passing through 2 mm sieve, and analyzed for different soil properties (Table 1). Four different phosphorus levels (0, 90, 120 and 150 kg ha^{-1}) were used and three different irrigation levels (recommended, irrigation skipped at flowering stages and irrigation skipped at flowering and milking stages) were used for this purpose. Single super phosphate (SSP) was used as a source of P, and each treatment was replicated thrice. Maize (Syngenta-8611) was sown at 10 kg $acre^{-1}$ with a single row hand drill. At crop harvest, different soil physical parameters (bulk density and water contents at field capacity) were measured. Furthermore, different growth and yield attributes were noted upon harvest. At maturity, plant samples were collected and analyzed for P concentration. Soil samples were collected after harvesting of maize crop from 0-15 cm and 15-30 cm and were analyzed for available P and extractable K.

Harvest Index and Water Use Efficiency

Harvest index was calculated as the ratio between economic yield and biological yield multiplied by 100. Following formula was used in this regard.

$$\text{Harvest Index (HI)} = \frac{Economic\ yield}{Biological\ yield}$$

Where economic yield was measured in terms of grain yield and biological yield was reflected in terms of overall above-ground plant biomass.

Similarly, water use efficiency (WUE) in maize was recorded by dividing total plant yield (kg ha^{-1}) and total water applied (mm).

$$\text{Water use efficiency (WUE)} = \frac{Total\ yield\ (kg\ ha^{-1})}{Water\ applied\ (mm)}$$

Phosphorus Use Efficiency (PUE)

For calculating the PUE, a formula devised by Fageria and Baligar [27] was used. For this purpose, the following formula was used.

$$\text{PUE} = \frac{Total\ P\ uptake\ in\ fertilized\ plots - Total\ p\ uptake\ in\ control\ plots}{P\ doses\ applied\ (kg\ ha^{-1})} \times 100$$

Relative Water Contents (RWC)

Relative water contents in maize leaves were calculated by following the method of Barrs and Weatherly, [28]. The following formula was used for this purpose.

$$\text{RWC} = (Fresh\ leaf\ weight - Dry\ leaf\ weight\ ) / (Fully\ turgid\ leaf\ weight - dry\ leaf\ weight) \times 100$$

Chlorophyll Contents

For determining the chlorophyll contents in maize leaves, method of Arnon, [29] was used. During this process, 0.5 g of leaf sample was mixed with acetone (80%) followed by its homogenization and subsequent filtration. Three different wavelengths (480, 645 and 663 nm) were used to determine chlorophyll ‘a’, ‘b’ and carotenoid contents in maize leaves, and absorbance of the suspension was recorded. Following formula were used for relative estimation of chlorophyll contents.

$$\text{Chl 'a' (mg g}^{-1}\text{ FW)} = [12.7\ (\text{OD @ 663 nm}) - 2.69\ (\text{OD @ 645 nm}) \times \frac{sample\ vol.}{1000} \times \text{Wt. of fresh tissue}]$$

$$\text{Chl 'b' (mg g}^{-1}\text{ FW)} = [22.9\ (\text{OD @ 645 nm}) - 4.68\ (\text{OD @ 663 nm}) \times \frac{sample\ vol.}{1000} \times \text{Wt. of fresh tissue}]$$

$$\text{Carotenoid contents (mg g}^{-1}\text{ FW)} = \frac{Acar}{Em} \times 100$$

Where,

Em = 2500,

A^{car} = OD @ 480 + 0.114 (OD @ 663) – 0.638 (OD @ 645)

Statistical Analysis

Data obtained in all the treatments was analyzed by using computer based software 'Statistix 8.1' (Statistix, USA), where Tukey's test was used as a post-hoc test for comparing the difference between means at $P<0.05$ significance level. Graphs and error bars were computed in Microsoft Excel.

Results

Phosphorus is an essential plant nutrient, and is required for major plant functions ranging from root growth to biochemical and metabolic functions. However, its soil availability is limited on account of different factors, which lessen its plant use efficiency along with restriction of other important plant functions. Soil moisture contents offer a critical role in improving the soil P availability and are, therefore, of crucial importance in lieu of increased plant P availability and improved growth. We checked the impact of different P levels (0, 90, 120 and 150 kg ha^{-1}) in improving the P use efficiency in maize and its impact on improving maize growth and yield in association with different irrigation management schemes. Irrigation was provided at recommended levels, skipped at flowering and milking stages. Results of different plant attributes are given below.

Growth Attributes

In terms of different growth attributes (Fig. 1), we observed that application of P at 90 kg ha^{-1} in combination with recommended irrigation levels led to maximum significant improvement in plant growth attributes such as plant height (13%), shoot fresh weight (35%), root fresh weight (37%), shoot and root dry weights (25 and 42%) and root length (51%) as compared to control treatment followed by P at 120 kg ha^{-1}, which also increased these attributes significantly as compared to control treatment. In addition, P application at 90 kg ha^{-1} also increased plant height (11 and 8%), shoot fresh weight (13 and 36%), root fresh weight (72 and 94%), shoot dry weight (34 and 6%), root dry weights (68 and 75%) and root length (55 and 78%), when irrigation was skipped at flowering and flowering plus milking stages as compared to control treatment.

Yield Attributes

Data regarding different yield attributes (Fig. 2) disclosed that application of P at 90 kg ha^{-1} in association with recommended irrigation levels significantly improved plant yield attributes such as biological yield (28%), grain yield (29%), harvest index (43%), Cob length (35%), cob weight (18%) and 100 grain weight (32%) as compared to control treatment followed by P at 120 kg ha^{-1}, which also led to a significant increment in these attributes than control treatment. Furthermore, P application at 90 kg ha^{-1} also increased biological yield (42 and 62%), grain yield (71 and 76%), harvest index (48 and 65%), Cob length (71 and 79%), cob weight (23 and 43%) and 100 grain weight (30 and 57%) when irrigation was skipped at flowering and flowering plus milking stages as compared to control treatment.

Physiological Attributes

In terms of different maize physiological attributes (Fig. 3), joint application of P at 90 kg ha^{-1} with recommended irrigation level significantly uplifted plant physiological traits such as chlorophyll 'a' (16%), chlorophyll 'b' (8%), carotenoid contents (26%), relative water contents (18%), SPAD value (17%) and water use efficiency (31%) as compared to control treatment followed by P at 120 kg ha^{-1}, which also increased these above mentioned physiological traits significantly as compared to control. Moreover, P application at 90 kg ha^{-1} also significantly increased chlorophyll 'a' (30 and 33%), chlorophyll 'b' (14 and 28%), carotenoid contents (34 and 86%), relative water contents (56 and 51%), SPAD value (19 and 23%) and water use efficiency (58 and 86%), when irrigation was skipped at flowering and flowering plus milking stages as compared to control treatment.

Soil Fertility Attributes and Physical Attributes

Data in terms of different soil fertility attributes (Fig. 4) depicted that application of P at 90 kg ha^{-1} along with recommended irrigation levels significantly improved soil fertility status as evident in terms of different fertility related attributes such as soil organic matter contents (17%), soil active carbon (23%), soil available P (122%) and soil extractable K (37%) as compared to control treatment followed by P at 120 kg ha^{-1}, which also led to a significant increment in these attributes than control treatment. Furthermore, P application at 90 kg ha^{-1} also increased soil organic matter contents (47 and 49%), soil active carbon (46 and 55%),

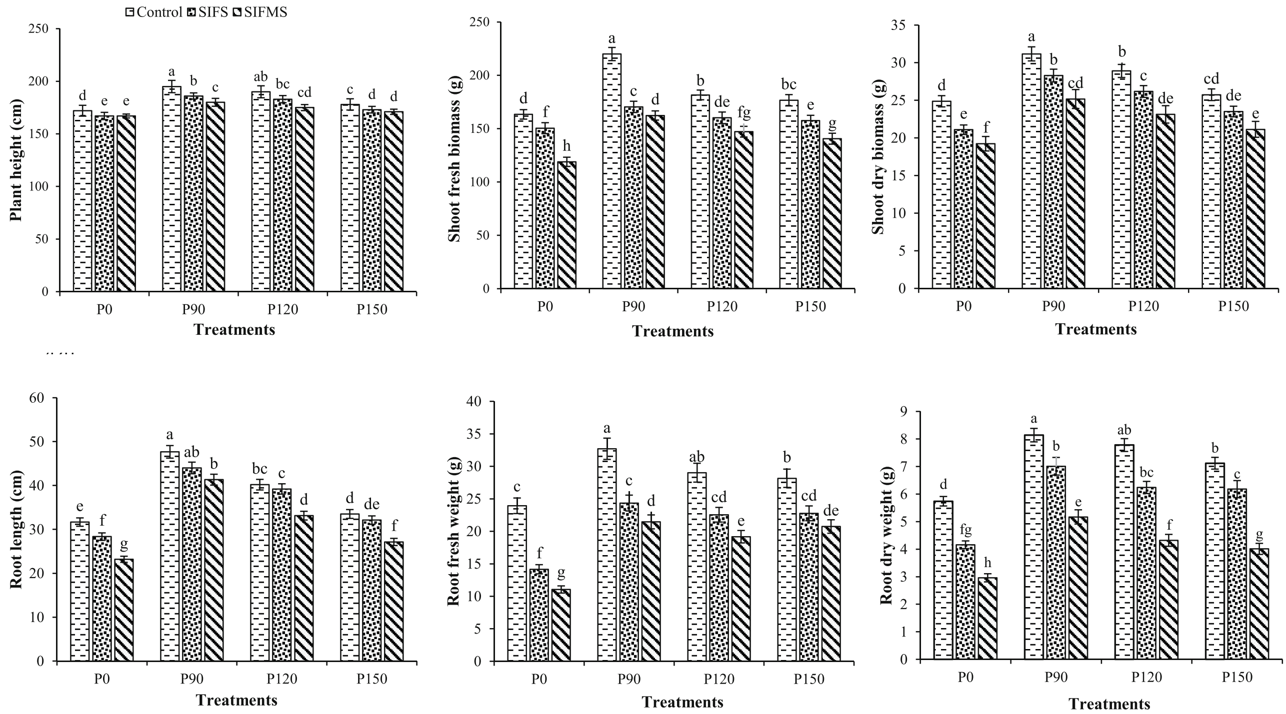

Fig. 1. Effect of different phosphorus levels and irrigation schemes on the growth attributes of maize under field conditions.

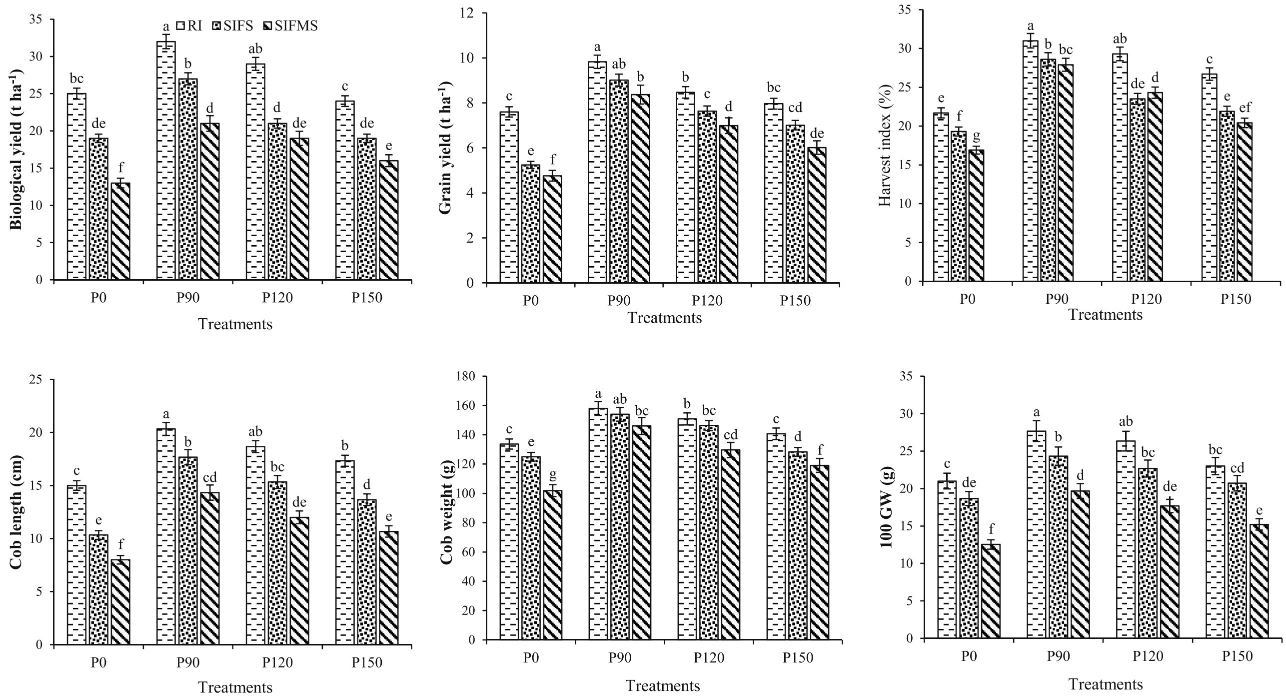

Fig. 2. Effect of different phosphorus levels and irrigation schemes on the yield attributes of maize under field conditions.

soil available P (279 and 248%) and soil extractable K (46 and 80%) when irrigation was skipped at flowering and flowering plus milking stages as compared to control treatment. Similarly, soil physical attributes (Fig. 5) as measured in terms of soil bulk density and P-use efficiency also explained the beneficial role of P application at 90 kg ha^{-1} at recommended irrigation levels.

We observed a non-significant impact of P application on the soil bulk density at all the irrigation management schemes at both depths. However, at 15-30 cm soil depth, more bulk density in all the treatments was observed as compared to 0-15 cm soil depth. In addition, results of P use efficiency again confirmed the advantageous role played by P against all the irrigation

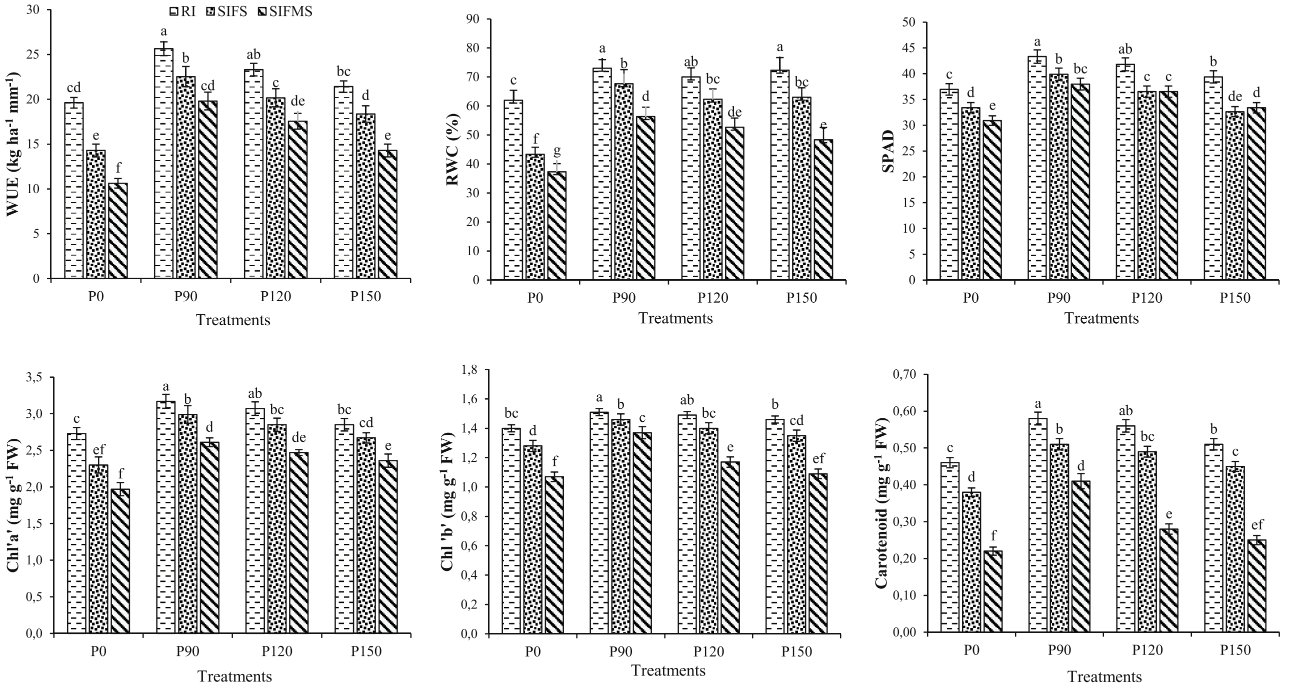

Fig. 3. Effect of different phosphorus levels and irrigation schemes on the physiological attributes of maize under field conditions.

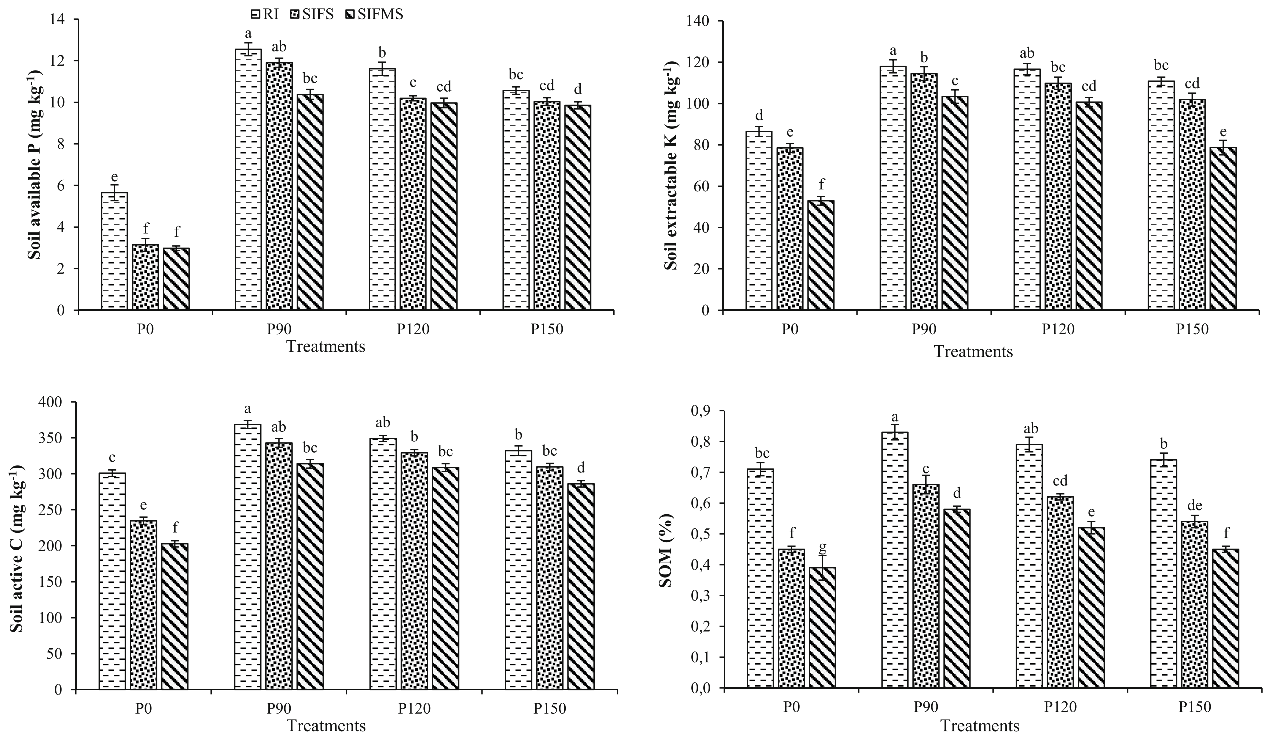

Fig. 4. Effect of different phosphorus levels and irrigation schemes on the soil nutrient contents in maize field.

schemes, where maximum outcomes were visible in P application at 90 kg ha^{-1} along with recommended irrigation levels. It was observed that application of P at 90 kg ha^{-1} enhanced the P use efficiency by 255, 531 and 887% respectively at recommended irrigation level, skipped irrigation at flowering and skipped irrigation at flowering plus milking stages respectively.

Discussion

Phosphorus (P) stands as an essential nutrient element, playing a pivotal role in carbohydrate metabolism and the energy transfer system within plants. It serves as a crucial component of DNA,

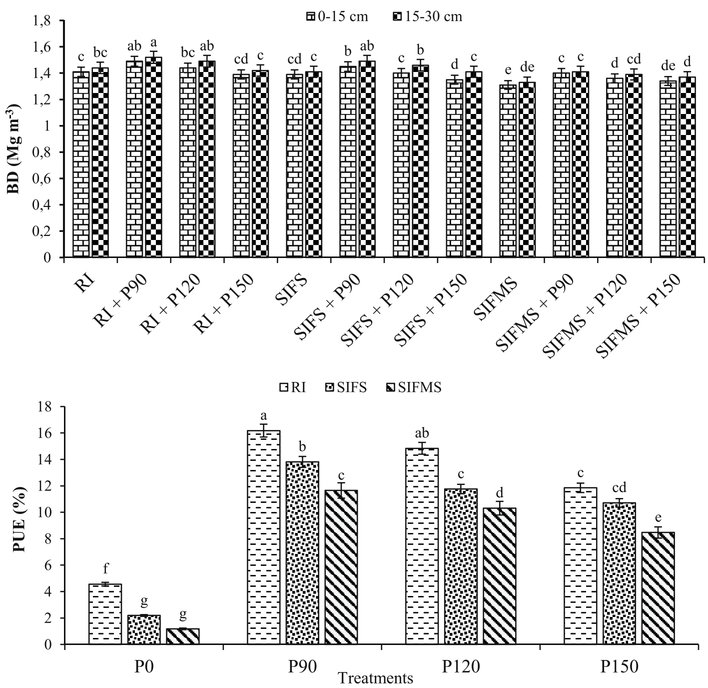

Fig. 5. Effect of different phosphorus levels and irrigation schemes on the soil bulk density and P use efficiency in maize field.

RNA, ATP, and phospholipids. Deficiency in P can significantly diminish various metabolic processes, affecting cell division, development, respiration, and photosynthesis [30]. Chemical fertilizers generally provided the plants P requirements. However, a large amount of P in fertilizers may become insoluble and lose their plant availability after entrance into the soil [31]. In calcareous soils developed under arid and semi-arid climates, the combination of factors such as the presence of calcium carbonate, high pH levels, limited organic matter, and soil dryness often results in insufficient available P for the optimal growth of most crops. Using chemical P fertilizers to address this deficiency is not notably effective in calcareous and alkaline soils, with the efficiency of P fertilizers in these conditions typically not exceeding 20% [32, 33]. We explored the individual and combined effects of P application and different irrigation management patterns in improving the P use efficiency of maize, soil P availability, maize growth and yield attributes. Based on the results, it was concluded that P application in combination with recommended irrigation level can significantly improve maize growth, yield and physiology along with improved soil fertility status.

In terms of growth attributes, P application at all the levels resulted in improved growth and yield attributes. This observed increment in plant growth and yield traits have been earlier reported by Zhang et al. [34] and Izhar Shafi et al. [35] Phosphorus offers a keen role in various plant functions such as energy transfer [36], respiration [37], photosynthesis [38] and root growth [39, 40]. In our current study, we noted a notable enhancement in photosynthetic and root attributes due to P application, illustrating the advantageous impact of P in augmenting plant growth and yield in our experiment. However, under water-stressed conditions, we observed a negative influence on all growth attributes, likely linked to reduced P uptake in lower moisture conditions. Similar findings were reported by Attarzadeh et al. [33], suggesting that heightened moisture stress diminishes P availability for plants, subsequently lowering uptake. Regarding maize yield attributes, P application across all irrigation schemes increased plant yield compared to their respective controls. Nonetheless, in cases where irrigation was withheld, diminished P uptake resulted in a significant decline in maize yield attributes. Similar outcomes were reported earlier by Zheng et al. [41], who observed that under alternative wetting and drying irrigation schemes, P uptake was reduced as compared to recommended irrigation continuous and recommended irrigation pattern, which caused a significant decrement in plant yield. In the current study, we also observed that P application at continuous and recommended irrigation level resulted in a considerable improvement in maize yield attributes; however, this increment was reduced at skipped irrigation systems, which not only decreased the P use efficiency, and hence, interfered with its functions and subsequently, decreased maize yield.

Results regarding the role of P application in improving plant physiological attributes revealed a significant correlation between P uptake, its used efficiency and plant physiology, which are also in line with the findings of Neocleous and Savvas, [42]. Phosphorus (P) is crucial for plant metabolic functions, notably in ATP formation, the body's primary energy carrier. In conditions with limited P, the efficiency of the photosynthetic apparatus is significantly impacted.

This limitation interferes with phosphorylation activities, Rubisco function, and Calvin cycle reactions, ultimately reducing carbon fixation and constraining photosynthetic processes. In our current study, the observed decrease in P uptake under skipped irrigation schemes resulted in reduced P use efficiency, leading to a decline in photosynthesis. This reduction in photosynthesis due to P deficiency has been documented in various crops like lettuce, wheat, maize, rice, and tomato by previous researchers [42-46].

Conclusion

Phosphorus stands as a vital macronutrient crucial for sustaining key plant functions. Its limited availability due to soil fixation restricts its accessibility for plants. The role of soil moisture content in enhancing soil P availability and subsequent plant uptake is evident. Our experiment explored the impact of various P application levels on maize growth, yield, physiology, and P use efficiency under diverse irrigation management schemes. We observed significant improvements across all measured maize attributes with the application of P at 90 kg ha^{-1} under recommended irrigation levels. Conversely, skipping irrigation at milking and flowering stages had detrimental effects, particularly evident in combined milking and flowering stage omissions. Furthermore, the combined application of P and recommended irrigation levels notably enhanced soil fertility status, augmenting available P and K contents along with organic matter levels. Looking ahead, this study opens avenues for further research. Future investigations could delve deeper into optimizing P application strategies under varying moisture and climatic and soil conditions to maximize crop productivity sustainably. Understanding these interactions can pave the way for more precise recommendations, fostering enhanced P use efficiency and overall plant growth and yield.

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