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Modeling of Phosphorus Nutrition to Obtain Maximum Yield, High P Use Efficiency and Low P-Loss Risk for Wheat Grown in Sandy Calcareous Soils

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Abstract: Fertilization with high levels of phosphorus increases the risk of environmental pollution. Identification of critical values of P in soil (SOP) and in plant tissues (PiP) is essential for achieving the maximum wheat yield without P loss. The critical value is the value of P which gives the optimum yield; the response of crop yield to P fertilization above this value is not predictable or nil. Here, a 4-year field experiment was conducted to identify the SOP and PiP for achieving maximum yield of bread wheat using 11 rates of P fertilization (0, 15, 30, 45, 60, 75, 90, 105, 120, 135, and 150 kg P_2O_5 ha^{-1}). The linear–linear and Mitscherlich exponential models were employed to estimate the PiP and SOP. The degree of phosphorus saturation (DPS) was used to assess the potential environmental risk; furthermore, phosphorus use efficiency (PUE) was also calculated under the studied fertilization levels. Phosphorus in soil and wheat plant was affected by the application rates and growing seasons. Increasing P fertilization rates led to gradual increases in soil and plant P. The SOP ranged between 21 and 32 mg kg^{-1}, while the PiP ranged between 6.40 and 7.49 g kg^{-1}. The critical values of P calculated from the Mitscherlich exponential models were 20% higher than those calculated from the linear–linear models. Adding levels of P fertilization $\geq$90 kg P_2O_5 ha^{-1} leads to higher potentials of P runoff and leaching, in addition, PUE decreased sharply under high P fertilization levels. The response of wheat yield to P fertilization in sandy calcareous soil is predictable below Olsen P values of 21 mg kg^{-1}. Identification of critical P values for wheat production is of great importance to help policy makers improve P use efficiency and attain optimum wheat yield under eco-friendly environmental conditions by eliminating the accumulation of excess P fertilizers in soil and water.

Keywords: critical value of P in soil and plant; Olsen-P; P fertilization; degree of phosphorus saturation; bread wheat; PUE

1. Introduction

Wheat is the one of the most strategic cereal crops for ensuring global food security and is a major source for human food and livestock feed [1]. High growth and yield of wheat depend mainly on suitable agriculture management, especially soil fertility [2]. Expansion of wheat cultivation in newly reclaimed soils, which are widespread in arid and semiarid regions, is necessary to meet the rapid increase in human population. However, these are mostly calcareous sandy soils of low quality due to high calcium carbonate content and low nutrient availability due to high pH and unfavorable soil characteristics [1–5]. Moreover, since the dominant soil particles are sand, the water-holding capacity of the upper soil surface is low to medium [6]. Poor soil properties, scarcity of irrigation water resources, and high daily evapotranspiration are the most troublesome issues facing any agricultural project proposed for such areas [1,5]. In order to maximize economic revenues from the degraded calcareous sandy soils, there is an urgent need to identify and adopt effective fertilization management strategies.

Phosphorus (P), a nonrenewable resource, is an essential plant nutrient in agricultural production and should be applied to the soil as inorganic and/or organic P to sustain cropping systems [4,7–9]. Therefore, the species of labile P influence the levels of soil P availability, which is affected by several soil characteristics, i.e., soil organic matter (SOM), pH, $CaCO_3$, and Al, Fe, and Mn oxides [10–13]. Availability of P in calcareous soils is low due to chemical surface-precipitation and adsorption; nevertheless, distinguishing between the two mechanisms is not easy [1,10]. The fertilizers of P applied to soil react with the soil components to produce less soluble P forms [1,10]. Dicalcium or octacalcium phosphate is the main form of precipitated P in calcareous soils [10,11,13,14]. Under P deficient conditions, the application of P fertilizers is required to increase the availability of P to target levels, depending on soil properties [1,10]. During the last century, the rates of P application have been increased to raise the availability of P in soil, but raising availability of P in soils also increases the loss of P through run off, leaching, and erosion, causing water eutrophication [15,16]. Besides, the amount of rock phosphate for P manufacturing is limited, thus, management of P fertilization in a careful manner is mandatory [17–19]. Phosphorus fertilization practices need ideal management to reduce the loss of this non-renewable resource and minimize pollution of water, but current methods for measuring availability of soil P and plant P requirements are not adequately accurate to achieve this goal [20].

The critical value of soil P for potential yield of crop plants, which varies according to soil type, crop species, and environmental factors, is defined as the content of P in the soil above which an increase in potential yield is not expected [12,21,22]. To attain potential yields, farmers tend to apply excess amounts of P fertilizers beyond recommended doses leading to accumulation of P in the topsoil of farmlands and the formation of a large P pool [15,16]. The minimum level of available soil P for maximum crop production is referred to as the agronomically critical value of the available soil P which is the available soil P content used by researchers as a criterion for P fertilizing [12,21,23]. Phosphorus fertilization of wheat and soil testing calibrations for P fertilizer recommendations continue to be important topics [24–26]. However, since soil tests typically analyze the top 15 cm of the soil surface, which might not reflect the actual available soil P for plant uptake, these tests alone are a poor prediction tool for fertilization requirement. These difficulties have challenged agronomists and soil scientists to develop alternative tools to better judge soil fertility and identify where P fertilization is required for sustainably high crop production. Therefore, a combination of plant tissue analysis and soil tests may be a more powerful diagnostic tool for nutrient requirement prediction [26–28]. Nutrient concentrations in plant tissues have been widely reported to vary greatly, not only according to soil fertility but also according to growth stage of the plant, crop species and variety, the sampled plant organ, and environmental conditions [25–28]. Therefore, tissue analysis should be done with a wide range of genotypes and environmental conditions, and tissue tests results must clearly specify the sampled plant organs and the growth stage [24,25]. Plant-tissue analyses, which directly evaluate effects of nutrient management practices, help understanding the physiological roles of nutrients in plants, guide comprehensive fertilization recommendations for crops, and suggest additional diagnostic approaches [26,28,29].

Continuous additions of P fertilizer to supply the plant with its nutrient requirements may lead to environmental pollution because the plant is not able to absorb the excess quantities of the applied fertilizer [20]. Besides, the application of excess fertilizer does not increase the potential yield, but rather reduce profits [1,23]. Therefore, the critical threshold of the nutrient that yields the maximum crop yield under different environmental conditions must be determined to provide information to fertilizer policy makers. Tissue analysis in combination with soil testing, based on a 4-year field experiment, was investigated in the current study to assess the critical P value for maximum yield of wheat (*Triticum aestivum* L.) grown in sandy calcareous soils.

2. Material and Methods

2.1. Field Experiment

The present experiment was carried out in sandy calcareous soils located at Elharga Belquran village, Sohag, Egypt. The soil of the experimental site was classified as Calcisols [30], and Table 1 shows the physical and chemical properties. Table 2 shows the climatic conditions of the experimental site.

Table 1. Some physical and chemical soil properties (0–20 cm) of the studied soil.

Properties	0–20 cm
Sand (%)	86
Silt (%)	10
Clay (%)	4
Texture	Sandy
Field capacity (v%)	16
Witling point (v%)	10
$CaCO_3$ (%)	18
pH (1:2 suspension)	8.1
ECe (dS m^{-1})	3.5
Organic matter (g kg^{-1})	4.0
Total N (mg kg^{-1})	200
Available N (mg kg^{-1})	20
Available Olsen P (mg kg^{-1})	5.0
Available K (mg kg^{-1})	200

Each value represents a mean of three replicates. EC_e: Electric Conductivity of the saturated soil extract.

Table 2. Average monthly maximum (T_{max}) and minimum (T_{min}) temperature, relative humidity (RH), wind speed (WS), and reference evapotranspiration (ET_o) during the 2016–2019 growing seasons.

Month	T_{max}	T_{min}	RH (%)	WS (km h^{-1})	ET_o (mm)
December	19	7	40	3.8	2.9
January	17	6	45	5.2	3.2
February	21	7	50	6.6	4.0
March	26	14	40	5.0	5.5
April	30	18	45	4.4	7.0

Data were obtained from Central Laboratory for Agricultural Climate, Egypt.

Wheat grains (*Triticum aestivum vulgar*, cv Solala 6) at rates of 150 kg ha^{-1} were sown by broadcasting on the first of December in the 2017–2020 growing seasons.

The experiment contained 11 rates of P fertilization i.e., 0, 15, 30, 45, 60, 75, 90, 105, 120, 135, and 150 kg P_2O_5 ha^{-1} per year. Phosphorus in the form of super phosphate (15.5%P_2O_5) was added directly to the soil in one dose before planting and mixing with the tillage layer. P fertilizer was added again once every year in November. The treatments were arranged in a randomized complete block design with four replicates each comprising an experimental unit of 20 m^2.

All the agriculture practices were applied according to the recommendations of the Ministry of Agriculture and Land Reclamation (Egypt). Potassium fertilizer in the form of potassium sulphate (50% K_2O) at a rate of 120 kg ha^{-1} was added in two equal portions (at cultivation and 30 days later). Nitrogen at the dose of 120 kg ha^{-1} was added as urea (46%N) in 5 equal doses, at the start and at 20, 50, 70, and 100 days after sowing. The rates and methods of fertilizer application followed the guidelines of the Ministry of Agriculture in Egypt. Wheat plants were harvested in May in all the studied growing seasons, and the grain, stover, and total yield were recorded.

2.2. Collection and Analysis of Soil Plant Samples

Soil and plant samples were collected after 60 days following sowing. Composite plant samples each representing 1/2 m^2 of wheat plant from each experimental unit were taken from each experimental unit. The collected samples were used to determine the P concentrations. The plant samples were cleaned, washed with tap and distilled water, air dried, oven-dried at 70 °C until constant weight, ground, and stored for chemical analysis. Plant samples were digested with a mixture of 350 mL H_2O_2, 0.42 g Se powder, 14 g $LiSO_4 \cdot H_2O$, and 420 mL concentrated H_2SO_4 [31]. P concentrations in the digest solution of each sample were determined by spectrophotometer as described by Burt [32]. Composite soil samples were collected by augur from 0–20 cm from each experimental unit. The collected soil samples were air-dried, crushed, and passed through a 2 mm sieve. This type of soil sample was used to determine soil Olsen P and other parameters.

Some physical and chemical properties of the soil were determined according to Burt [32]. The soil pH was measured in 1:2.5 soil to water suspension using a digital pH meter. Electrical conductivity (EC) was estimated using the salt bridge method [32]. Available soil nitrogen was extracted with 2 M potassium chloride and then the nitrogen in the extract was determined using the micro-Kjeldahl method [31]. The available soil P was extracted with 0.5 M sodium bicarbonate solution at pH 8.5 according to Olsen et al. [33] as described in Burt [31] and P was determined by spectrophotometer. Extraction of P using the Olsen method is recommended for these high pH soils [34,35]. The available potassium was extracted using ammonium acetate and was measured by flame photometry [31].

Phosphorus use efficiency was calculated using the following equation:

$$\mathrm{PUE} = (\mathrm{Yp} - \mathrm{Yo})/\mathrm{P})$$

where PUE is P use efficiency, Yp is the yield under a particular P level (kg), Yo is the yield of the control (kg), and P is the fertilization rate [35]. The degree of P saturation (DPS) was calculated for predicting P loss risk from the studied soil. The DPS was measured by the method of Jalali and Jalali [36] and calculated using the following equation:

$$\mathrm{DPS}\ (\%) = \frac{\mathrm{Pox}}{\mathrm{Al} + \mathrm{Fe}} \times 100$$

where Pox is the P extracted from soil with ammonium oxalate (pH = 3), and Al and Fe is aluminum and iron in the same extract. DPS is in %, while Al and Fe values are in mmol kg^{-1} of soil. Al and Fe in the oxalate extraction were measured using the ICP−OES thermo iCAP 6000 analyzer. The critical value of DPS is considered to be 25%, above which P loss risk is expected [36].

2.3. Data Analysis

The maximum yield which was used to calculate the critical P, was considered to be 90% of the maximum yield [12,37]. Relative yield (RY) was designed to avoid the seasonal variation in the wheat yield and was calculated using the following equation:

$$\mathrm{RY} = \mathrm{Yf}/\mathrm{Ym}$$

where RY is the relative yield, Yf is the yield of a treatment (kg ha^{-1}), and Ym is the maximum yield for each year (kg ha^{-1}). The critical level of P in soil and plant tissue was calculated with linear and exponential models as described in the following equations:

$$\mathrm{RY} = \mathrm{a} + \mathrm{bX}.$$

$$\mathrm{RY} = \mathrm{a} \times 10^{-1} \mathrm{e}^{\mathrm{bX}}.$$

where RY is the relative yield, X is the critical level of P, a and b are the constants of the equation. The critical soil P for degree of P saturation (DPS) was calculated by the same methods.

$$\mathrm{DPS} = \mathrm{a} + \mathrm{bX}.$$

$$\mathrm{DPS} = \mathrm{a} \times 10^{-1} \mathrm{e}^{\mathrm{bX}}.$$

where DPS degree of P saturation, X is the critical level of P, a and b are the constants of the equation.

Analysis of Variance (ANOVA) and LSD tests at 5% level of probability were used to test significant difference between the treatments. Statistical analyses were performed using SPSS software, version 15 (SPSS, Chicago, IL, USA). The linear–linear and Mitscherlich exponential models were performed using SigmaPlot 14 Software (Systat Software, San Jose, CA, USA). The data that were processed in the mathematical models were the data from all seasons, replications, and P rates (n = 176, 4 years, 11 P rates, and 4 replicates).

3. Results

3.1. Effect of P Fertilization Rates on P in Soil and Plant

Increasing P fertilization rate increased P concentration in soil and plants. Olsen soil P concentrations as well as P in wheat shoot are shown in Table 3. The application of P fertilizer to the sandy calcareous soil caused remarkable changes in the availability of P in soil. Available Olsen P varied from 3.75 to 44.50 mg kg^{-1}. The maximum Olsen P values were obtained from the soil fertilized with the highest P rate (150 kg P_2O_5 ha^{-1}), while the lowest ones were recorded in the unfertilized soil. P in wheat tissue ranged from 3.18 to 9.49 g kg^{-1} dry weight. The highest significant P values in wheat tissue were recorded in wheat plants fertilized with 150 kg P_2O_5 ha^{-1}, while the lowest ones were found in the control.

Table 3. Average values of soil Olsen P, P in plant, grain yield, and straw yield of wheat in the four growing seasons (2017–2020).

Season	P Rate (kg ha^{-1})	Soil Olsen P (mg kg^{-1})	P in Plant (g kg^{-1})	Grain Yield (kg ha^{-1})	Straw Yield (kg ha^{-1})
2017	0	5.00 ± 1.41^{G}	3.37 ± 0.07^{I}	3842 ± 247^{C}	5175 ± 354^{A}
	15	8.75 ± 3.65^{G}	4.08 ± 0.46^{H}	4427 ± 126^{B}	5750 ± 233^{B}
	30	13.50 ± 5.09^{GF}	4.55 ± 0.42^{GH}	5025 ± 483^{B}	6300 ± 460^{AB}
	45	17.75 ± 6.69^{F}	5.16 ± 0.31^{FG}	5480 ± 656^{A}	6425 ± 183^{AB}
	60	21.00 ± 7.36^{EF}	5.63 ± 0.20^{F}	5505 ± 678^{A}	6150 ± 489^{AB}
	75	25.50 ± 8.54^{ED}	6.40 ± 0.29^{E}	5475 ± 779^{A}	6525 ± 672^{A}
	90	27.25 ± 8.84^{D}	7.20 ± 0.53^{DE}	5485 ± 741^{A}	6650 ± 638^{A}
	105	32.50 ± 11.91^{CD}	7.94 ± 0.20^{CD}	5335 ± 736^{A}	6275 ± 720^{A}
	120	35.25 ± 10.76^{BC}	8.48 ± 0.15^{BC}	5547 ± 622^{A}	6400 ± 820^{A}
	135	38.50 ± 14.33^{B}	8.99 ± 0.18^{AB}	5545 ± 758^{A}	6150 ± 845^{AB}
	150	44.50 ± 15.77^{A}	9.49 ± 0.16^{A}	5632 ± 659^{A}	6550 ± 620^{A}
2018	0	4.25 ± 0.50^{H}	3.38 ± 0.12^{G}	3875 ± 126^{D}	4300 ± 141^{DE}
	15	9.25 ± 0.96^{G}	4.03 ± 0.26^{FG}	4400 ± 141^{C}	4625 ± 236^{D}
	30	14.25 ± 1.26^{F}	4.29 ± 0.08^{F}	4963 ± 281^{B}	5375 ± 519^{C}
	45	18.00 ± 0.82^{E}	5.08 ± 0.21^{EF}	5385 ± 87^{A}	6250 ± 289^{AB}
	60	24.25 ± 4.57^{D}	5.87 ± 0.09^{E}	5498 ± 87^{A}	6100 ± 115^{B}
	75	27.25 ± 2.06^{D}	6.48 ± 0.38^{DE}	5592 ± 82^{A}	6500 ± 141^{AB}
	90	27.50 ± 0.58^{D}	7.10 ± 0.71^{D}	5558 ± 128^{A}	6375 ± 222^{AB}
	105	33.25 ± 2.87^{C}	7.97 ± 0.70^{BC}	5605 ± 110^{A}	6675 ± 189^{AB}
	120	36.00 ± 1.83^{C}	8.69 ± 0.18^{AB}	5558 ± 51^{A}	6600 ± 183^{AB}
	135	39.75 ± 4.50^{B}	9.10 ± 0.09^{A}	5610 ± 66^{A}	6725 ± 206^{A}
	150	44.00 ± 2.83^{A}	9.39 ± 0.09^{A}	5573 ± 152^{A}	6800 ± 141^{A}

Table 3. *Cont.*

Season	P Rate (kg ha^{-1})	Soil Olsen P (mg kg^{-1})	P in Plant (g kg^{-1})	Grain Yield (kg ha^{-1})	Straw Yield (kg ha^{-1})
2019	0	4.00 ± 1.15^{I}	3.18 ± 0.24^{F}	3175 ± 236^{D}	3900 ± 115^{E}
	15	10.00 ± 1.63^{H}	4.05 ± 0.74^{E}	4250 ± 191^{C}	5075 ± 96^{D}
	30	15.00 ± 2.94^{G}	4.15 ± 0.66^{E}	4950 ± 100^{B}	5225 ± 330^{D}
	45	16.00 ± 3.77^{G}	4.77 ± 0.94^{E}	5533 ± 238^{A}	5800 ± 50^{BC}
	60	18.75 ± 3.51^{F}	5.34 ± 0.66^{DE}	5308 ± 216^{B}	5775 ± 100^{BC}
	75	24.75 ± 1.89^{E}	5.75 ± 0.96^{CD}	5475 ± 96^{A}	5725 ± 50^{BC}
	90	31.25 ± 1.50^{D}	7.35 ± 0.93^{B}	5485 ± 60^{A}	5475 ± 320^{BD}
	105	33.00 ± 2.16^{CD}	7.53 ± 0.22^{B}	5300 ± 115^{A}	6225 ± 171^{AC}
	120	35.25 ± 1.71^{BC}	8.23 ± 0.26^{AB}	5450 ± 208^{A}	6525 ± 310^{AC}
	135	38.75 ± 1.50^{B}	8.55 ± 1.05^{A}	5575 ± 96^{A}	6400 ± 245^{A}
	150	43.25 ± 1.50^{A}	8.90 ± 0.81^{A}	5500 ± 141^{A}	6500 ± 377^{A}
2020	0	3.75 ± 0.96^{H}	3.20 ± 0.24^{E}	3000 ± 141^{E}	3325 ± 236^{E}
	15	10.50 ± 3.70^{G}	4.35 ± 0.70^{D}	4025 ± 330^{D}	4450 ± 412^{D}
	30	13.00 ± 2.58^{F}	4.43 ± 0.81^{D}	4425 ± 386^{C}	5350 ± 443^{D}
	45	18.50 ± 3.11^{E}	4.88 ± 0.63^{D}	5275 ± 411^{A}	6175 ± 418^{C}
	60	24.75 ± 3.77^{D}	5.38 ± 0.67^{CD}	5475 ± 206^{A}	6425 ± 386^{C}
	75	26.00 ± 4.08^{D}	5.88 ± 0.81^{C}	5000 ± 141^{B}	5975 ± 314^{C}
	90	32.75 ± 2.06^{C}	7.50 ± 0.71^{B}	5475 ± 222^{A}	6350 ± 243^{A}
	105	34.00 ± 1.41^{C}	7.83 ± 0.17^{B}	5450 ± 208^{A}	6825 ± 126^{A}
	120	38.00 ± 3.56^{B}	8.33 ± 0.41^{AB}	5425 ± 310^{A}	6250 ± 289^{B}
	135	41.25 ± 3.40^{AB}	8.60 ± 1.43^{AB}	5575 ± 96^{A}	6825 ± 356^{A}
	150	42.25 ± 8.58^{A}	8.95 ± 0.74^{A}	5575 ± 386^{A}	6850 ± 243^{A}

Means denoted by different letters indicate significant difference according to Duncan's test at $p < 0.05$.

The rates of P fertilizer significantly ($p < 0.05$) affected P availability and uptake (Table 4).

Table 4. Results of the statistical analysis of the obtained data.

Source of Variance	*p*-Value (Significance Level)					
	Soil Olsen P	P in Plant	Grain Yield	Straw Yield	PUE	DPS
Year	*	*	*	**	**	**
P rate	**	**	**	**	**	**

PUE = Phosphorus use efficiency, DPS = Degree of phosphorus saturation. * = $p < 0.05$, ** = $p < 0.01$, and ns = non-significant differences ($p \geq 0.05$).

3.2. Effect of P Fertilizer Rates on Yield of Wheat and P Use Efficiency

The data in Table 3 show the effect of P fertilizer rates on wheat yield through the four growing seasons. The grain yield ranged from 3000 to 5632 kg ha^{-1}, while the straw yield ranged from 3325 to 6850 kg ha^{-1}. The highest grain and straw yield values were found in wheat plant fertilized with 150 kg P_2O_5 ha^{-1}, while the lowest ones were found in the control. The grain and straw yield of wheat responded significantly to the application of P rates. The application of 15, 30, 45, 60, 75, 90, 105, 120, 135, and 150 kg P_2O_5 ha^{-1} caused increases in the grain yield by 22, 39, 56, 57, 55, 58, 56, 58, 61, and 60%, respectively, over the unfertilized soil, while in the case of straw yield these increases were 19, 33, 48, 46, 48, 49, 56, 54, 56, and 60%, respectively. Straw and grain yield of wheat were affected significantly by years (Table 4). The addition of P significantly affected the PUE through the four growing seasons (Figure 1). The maximum PUE was obtained under the low P rates, while increasing the P rates significantly reduced the value of PUE.

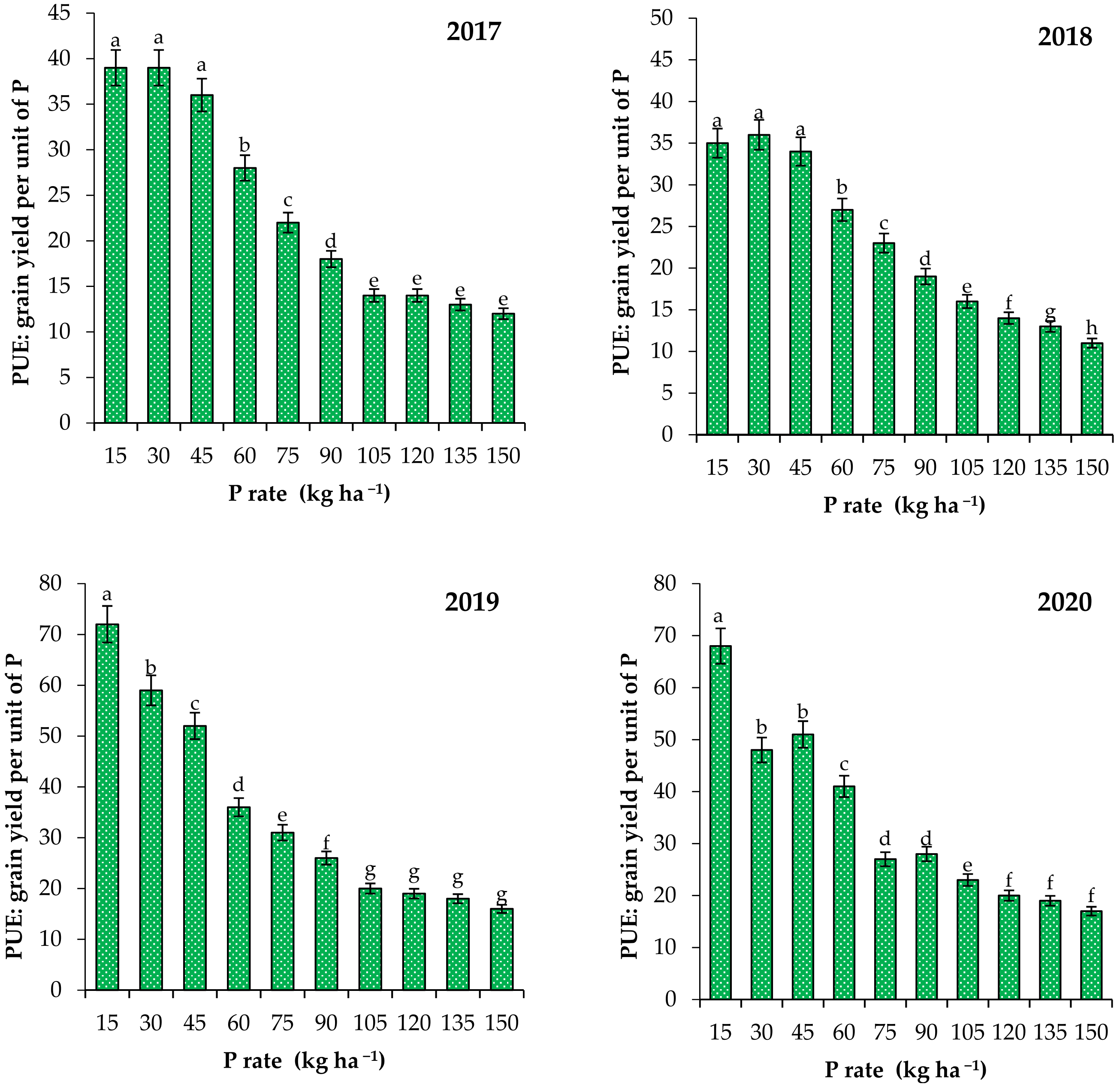

Figure 1. P use efficiency (PUE) as affected by fertilization rates during the four growing seasons (2017–2020). Means denoted by different letters indicate significant difference according to Duncan's test at $p < 0.05$.

3.3. Critical P in Soil and Plant and P Loss Risk

The critical P in plant (PiP) and soil (SOP) was calculated based on the linear–linear and Mitscherlich exponential models and the data are shown in Table 5. The critical value of SOP ranged between 21.11–31.60 mg kg^{-1}, while the critical value of PiP ranged between 6.40–7.49 g kg^{-1}. The critical values of P calculated from the Mitscherlich exponential models were higher than that calculated from the linear–linear models. The critical SOP values from the Mitscherlich exponential models were higher by 18.6% and 22.9% than the linear–linear model in the case of grain and straw yield. The critical plant P (PiP) values calculated from the Mitscherlich exponential models were slightly higher than the linear–linear equations in the case of grain and straw yield. The critical P in plant (PiP) and soil (SOP) calculated from the linear–linear equation for straw yield were higher by 21.8% and 15.0%, respectively than grain yield. The critical P in plant (PiP) and soil (SOP) calculated from the Mitscherlich exponential models for straw yield were higher by 26.2% and 18.6%, respectively, than grain yield.

The degree of phosphorus saturation (DPS) was measured as an indicator to predict the occurrence of P run-off or leaching, and the results are presented in Figure 2. The values of DPS were affected significantly by the P rates and years. Increasing the P rates significantly increased DPS. DPS increased slightly with increasing years at P rates $\geq$45 kg P_2O_5 ha^{-1}. The relationships between soil Olsen P and DPS were evaluated by linear–linear and Mitscherlich exponential models and the data are shown in Table 5. The two models adequately described the relationship between available soil P and DPS (R = 0.86 and 0.73 for the linear–linear and exponential models, respectively). The critical level of available soil P for P loss risk is 29.11 and 36.00 mg kg^{-1} according to the linear–linear and exponential models, respectively.

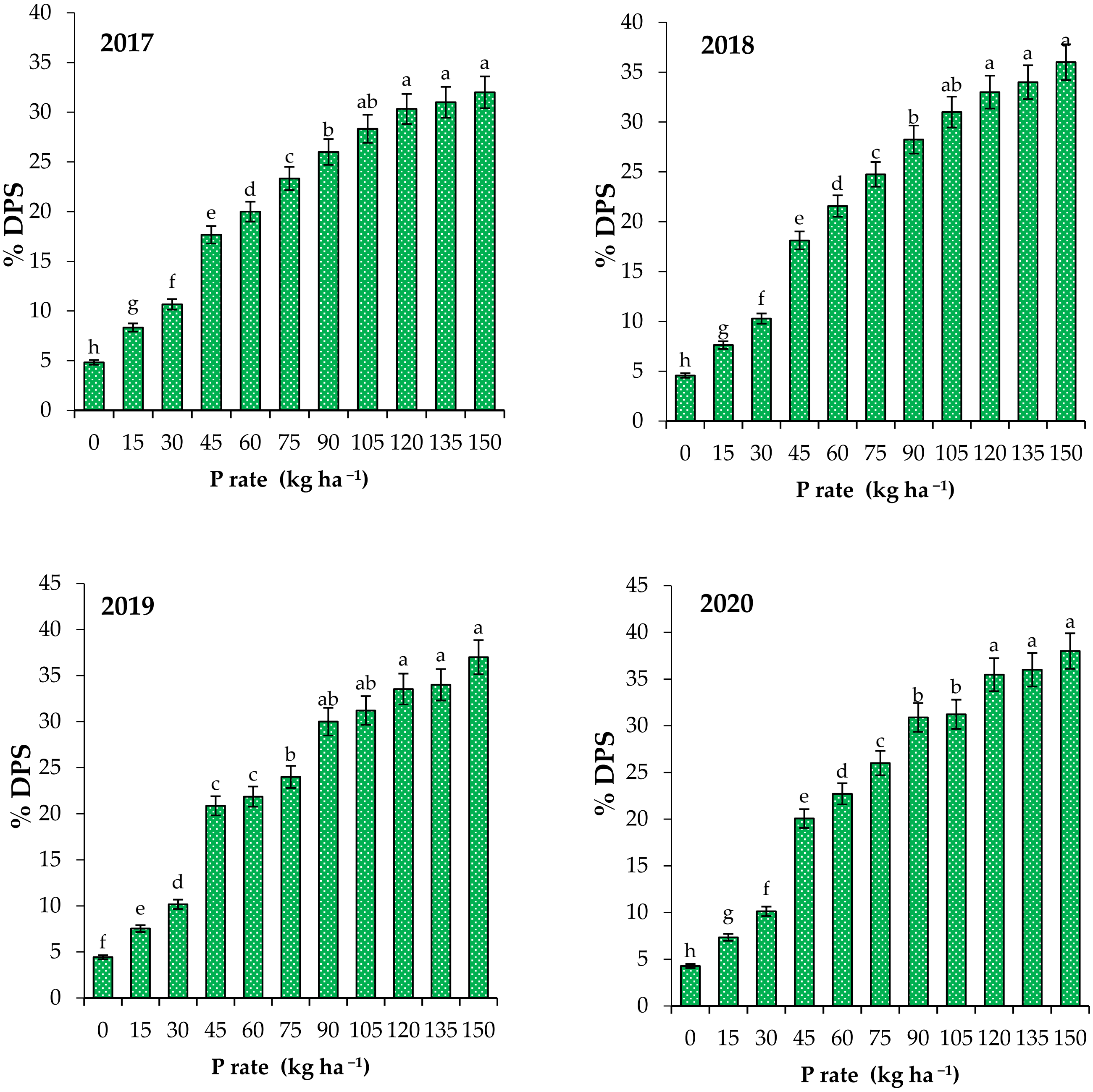

Figure 2. The degree of phosphorus saturation (DPS) as affected by fertilization rates during the four growing seasons (2017–2020). Means denoted by different letters indicate significant difference according to Duncan's test at $p < 0.05$.

Table 5. Critical P values in soil (SOP) and plant tissue (PiP) calculated for grain (RGY) and straw (RSY) yields and degree of phosphorus saturation (DPS) fitted by the linear–linear (LL) and exponential models (Exp) under the four growing seasons (*n* = 176). R^2 correlates X (critical P value) and Y (relative yield). Critical P values are in mg kg^{-1} for soil and g kg^{-1} in plant.

Model	Parameters	Formulas	R^2	Critical P Value
LL	SOP—RGY	$y = 0.009X + 0.710$	0.84	21.11
	SOP—RSY	$y = 0.007X + 0.720$	0.76	25.71
	PiP—RGY	$y = 0.041X + 0.637$	0.71	6.40
	PiP—RSY	$y = 0.042X + 0.591$	0.69	7.36
	SOP—DPS	$DPS = 0.823X + 1.0396$	0.86	29.11
sExp	SOP—RGY	$y = 0.7327e^{8.213\times10^{-3}x}$	0.59	25.04
	SOP—RSY	$y = 0.694e^{8.213\times10^{-3}x}$	0.57	31.60
	PiP—RGY	$y = 0.6818e^{4.315\times10^{-2}x}$	0.62	6.45
	PiP—RSY	$y = 0.638e^{4.592\times10^{-2}x}$	0.60	7.49
	SOP—DPS	$DPS = 16.312e^{11.859\times10^{-3}x}$	0.73	36.00

4. Discussion

The current study was carried out to identify the critical P concentrations either in the soil or plant tissue to maximize the potential grain and straw yield of wheat based on long-term field experiments. Phosphorus is a pivotal nutrient in wheat production playing a key role in plant physiological processes such as nutrients movement, nucleic acid synthesis, photosynthesis, energy transformation, structural development, and various metabolic processes; therefore, its deficiency adversely affects potential yield [38–44]. The obtained results revealed that wheat grown in sandy calcareous soils responded significantly ($p < 0.05$.) to the application of P fertilizer. The application of 15, 30, 45, 60, 75, 90, 105, 120, 135, and 150 kg P_2O_5 ha^{-1} increased the potential grain yield of wheat up to 22, 39, 56, 57, 55, 58, 56, 58, 61, and 60%, and the straw yield by 19, 33, 48, 46, 48, 49, 56, 54, 56, and 60%, respectively, compared to the non-fertilized treatment which is in accordance with the previous results observed by Agegnehu et al. [45] and Deng et al. [46]. All the treatments of P rates received the same amount of N (120 kg N ha^{-1}) so it is not a limiting factor.

Critical soil P is the value of available P which gives the optimum yield; the response of crop yield to P fertilization above this value is not predictable or nil [22]. Determination of the critical value of available P in soil is crucial for fitting P fertilizing requirements [21]. If the soil-available P exceeds the critical value, further P application would not be justifiable and could increase the accumulation of P in soil and thereby increase the risk of environmental pollution with P [47,48]. The critical available P value is also dramatically influenced by soil type and structure, soil pH, sampling depth, and soil organic carbon content [49,50]. Based on Jordan-Meille et al. [51], the critical available P value was shown to range between 10 and 40 mg kg^{-1}, depending on country, crop type, and soil type. Although there are great variations in the available P measurement procedures between investigated countries, critical P status calibration and estimation of recommended P doses there is little theoretical support for such wide ranges of P values. [52]. In our study, the critical available soil P values (21–32 mg kg^{-1}) were within and/or similar to the reported range of 7–28 mg kg^{-1} reported in the literature for wheat production, the data of which are greatly affected by soil type, environmental conditions, and crop rotation [21,33,50–53]. Plant tissue analysis directly assesses the nutrient status in plants [26,28]. The results in our study reveal that critical P values in wheat tissue (PiP) ranged from 6.40 to 7.49 g kg^{-1}, which are within the previously reported range of P in wheat plants (2 to 8.8 g kg^{-1}) [27,54–58].

Several models have been employed to measure the critical available P values including the linear–linear, linear–plateau, the two linear split, exponential Mitscherlich, and quadratic polynomial models resulting in variations in the estimates [7,50,52,59,60]. Variations in critical P values calculation using different models indicate that employing the linear–linear model is more risky for farmers [33]. In the current study, the critical P values estimated from the exponential Mitscherlich model were higher than those estimated using the linear–linear model as also found in other reported results [21,50,53,61]. The estimated critical values from the linear–linear model are lower possibly due to these having a sharp discontinuance at the critical point of P value along with the linear component [21,50,53].

The risk of P loss from soil by leaching or run-off depends on the degree of P saturation (DPS) in soil [36,58]. When the soil is saturated with P, any additions above this level will lead to an increase in the environmental risks of P pollution [62,63]. Previous studies indicate that the critical DPS value is 25% and above this value, the P loss to surface and ground waters increases significantly [36,58–64]. The addition of P rates above 75 kg P_2O_5 ha^{-1} results in a DPS value above 25%. Based on the relationship between the available soil P and the DPS values the safe limit of soil Olsen P value must be below 29–36 mg kg^{-1}; increasing the levels of Olsen P above this point leads to increased risk of P losses. Wang et al. [65] studied the P loss risk from agriculture soils and reported that the soil with Olsen P > 30 mg kg^{-1} leads to increase the risk of P leaching and run-off.

5. Conclusions

Identification of critical values of soil and plant P is essential for achieving the yield potential in crop plants. A powerful approach combined both plant tissue and soil analyses, employing both the linear–linear and the exponential Mitscherlich models. This was successfully implemented to identify the critical values of P in spring bread wheat grown in sandy calcareous soils. Mitscherlich exponential models gave higher critical P values than the linear–linear models. Based on a 4-year field experiment, the critical P value for maximum wheat yield ranged from 21 to 32 mg kg^{-1}, while in wheat tissue it ranged from 6.40 to 7.49 g kg^{-1}. Adding levels of P fertilization $\geq$90 kg P_2O_5 ha^{-1} leads to potential environmental risks and significantly reduces the P use efficiency. Identification of critical P values is of great importance to policy makers to improve the application efficiency of P fertilizers, maximize the yield potential of crop plants, reduce the inputs and the excess accumulation of P fertilizers in soil, and minimize the potential risks of water contamination.

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