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Effects of Phosphate Application Rate on Grain Yield and Nutrition Use of Summer Maize under the Coastal Saline-Alkali Land

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Abstract: Saline-alkali soil is a major threat to global food security. Phosphorus (P) fertilizer is essential for crop growth and yield production. Nevertheless, the optimal phosphate fertilizer application rates for summer maize under coastal saline–alkali soil are still unclear. A field experiment with five phosphate application rates (0, 45, 90, 135, and 180 kg ha^{-1}, referred to as T1, T2, T3, T4, and T5, respectively) was conducted during the 2018–2020 summer maize seasons study the effects of phosphate rates on the grain yield, biomass, and nitrogen (N), P and potassium (K) accumulation, and N, P, and K physiological efficiency (denoted as NPE, PPE and KPE, respectively). Results showed that P application notably improved maize grain and biomass yield, the total uptake of N, P, K, and NPE and KPE across three seasons. As the P addition increased to 135 kg ha^{-1}, the grain yield achieved a maximum of 7168.4 kg ha^{-1}, with an average NPE of 2.15 kg kg^{-1}, PPE of 0.19 kg kg^{-1}, and KPE of 1.49 kg kg^{-1}. However, PPE continuously decreased with the input of phosphate. P application rates exceeding 135 kg ha^{-1} were not considered effective due to a decline in grain yield, nutrient uptake, and NPE. Furthermore, the effect of the planting season was significant on the total uptake of N and K, and the use efficiency of N, P, and K. TOPSIS revealed that a phosphate application rate of 90–135 kg ka^{-1} was the optimal pattern for maize production. These results may give a theoretical basis for the phosphate management of maize production in saline–alkali soil.

Keywords: summer maize; grain yield; biomass yield; fertilizer physiological efficiency; coastal saline–alkali land

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1. Introduction

Soil salinization is widely distributed worldwide, with a large area of approximately 0.8 billion hectares [1,2]. China, for instance, has approximately 9913 hectares of saline–alkali land, including more than 0.14 hectares of coastal saline–alkali land area, which accounts for 10.37% of the national cultivated land area [3]. Coastal saline–alkali soil has long been influenced by the ocean and continental interactions. In particular, the Yellow River Delta (YRD) in China is a typical coastal saline–alkali land. The salinity ranges from 0.2 to 4.6 g kg^{-1} in coastal saline–alkali soils in China, which is a serious menace to crop productivity and decreases grain yield by 10–90% [3,4]. This is largely because saline–alkali cultivated land has a poor soil pore structure and groundwater salinization [5,6]. In order to meet the challenges of global food security, improving the production capacity of saline–alkali land has become an urgent task [7,8].

Fertilizer application is considered to be one of the key essential and manageable methods in the reclamation of saline–alkali soils and the improvement in saline soil quality [9–11]. Phosphate fertilizer (P) is a critical component in many essential organic compounds in living organisms [12,13]. However, under coastal saline conditions, P uptake by crop roots is always restrained by competition of Na^+, Cl^-, and other salt ions, resulting in low P availability [14]. Additionally, low P availability, in turn, affects the uptake of other nutrients, such as nitrogen (N) and potassium (K), and restricts the growth and yield of crops in coastal alkaline soils [15–17]. To avoid P deficiency, farmers usually excessively input P fertilizer to achieve higher yields. MacDonald et al. [18] previously reported that the amount of P investment into cropland soils has exceeded the crop demand for P, leading to a global agronomic surplus of more than 13 kg P ha^{-1}. Evidence has shown that long-term over-fertilization of P leads to not only the degradation of soil quality [19] and the eutrophication of surface water [14] but also the achievement of sustainable agriculture [20,21]. Moreover, excessive P application tends to decrease the P-utilization efficiency (PUE) and other nutrient use efficiencies, including nitrogen (N) and potassium (K), eventually resulting in a decrease in crop yield [22–24]. In contrast, a suitable increase in P could improve crop yield quality as well as maintain the balance of soil nutrients [5,25–27]. Ullah et al. [28] reported that P input can balance soil N deficit and stimulate root formation, improving the storage capacity of inorganic P, thus determining crop tolerance to extreme environments. However, the rate of P addition on soil quality and plant yield is still controversial. For example, Xu et al. [21] reported that the optimal P rate was 90–135 kg P_2O_5 ha^{-1} to maximize yield and PUE. Whereas a Gaussian model analysis suggested that input rate ranging from 10 to 30 kg P_2O_5 ha^{-1} can decrease the mineralization and nutrient accumulation in soil and result in soil N, P, and K balance [29]. Recently, the technique for order preference by similarity to ideal solution (TOPSIS) has been used to comprehensively assess the performance of fertilizer application based on grain yield, resource use efficiency, and crop quality [30–33]. There were certain differences in various evaluation results for different treatments, which may be due to the algorithms and data utilization of analysis methods [30,33]. Li et al. [30] reported that TOPSIS performed best in assessing crop productivity and fruit quality under various water and nitrogen schedules relative to other approaches, thus using reasonable algorithms to make the evaluation of P application input in coastal saline–alkali soil more objective and scientific [33,34].

Maize (*Zea mays* L.), as an important crop, contributes one-third of grain production worldwide. Maize has been defined as a mild salt-tolerant crop and is widely grown in coastal saline–alkali land in summer. Most research on maize yield or fertilizer use efficiency in response to P rates is conducted in non-saline land, but few studies have been conducted on P rates in saline–alkali soils, especially in coastal saline–alkali areas. In fact, soil salinization had a certain inhibitory effect on the germination and growth of maize due to the soil salinity and poor structure [35]. Salt stress also hinders the development and growth of crop root systems, which seriously limits nutrient absorption and reduces phosphorus bioavailability. Therefore, more research is needed to explore the appropriate phosphate application management for summer maize production to meet the demands of future sustainable agriculture in coastal saline–alkali areas. The aim of this study was as follows: (1) Study the effect of different phosphorus rates on the grain and biomass yield of summer maize; N, P, and K uptake; and N, P, and K harvest index in coastal saline–alkali land. (2) Establish the optimum phosphorus fertilizer scheduling using the TOPSIS model for balancing yield and nutrition use. These results will provide the basis for phosphorus fertilizer scheduling management in summer maize fields under coastal saline–alkali land.

2. Materials and Methods

2.1. Experimental Site

A field experiment was performed over three summer maize growing seasons (2018, 2019, and 2020) at the Shuofeng family farm, Wudi County, Shandong Province, China (37.77° N, 117.63° E). Warm temperate continental monsoon climate prevails in the experimental area, with a 600 mm mean annual rainfall and a 13.6 °C mean air temperature. The effective rainfall during the maize-growing season in 2018, 2019, and 2020 was 447.4, 462.7, and 404.6 mm, respectively (Figure 1). Soil available N, P, and K in the 0–40 cm soil layer were 50.7 mg kg^{-1}, 10.4 mg kg^{-1}, and 152.0 mg kg^{-1}, respectively, and the soil organic matter was 1.0%.

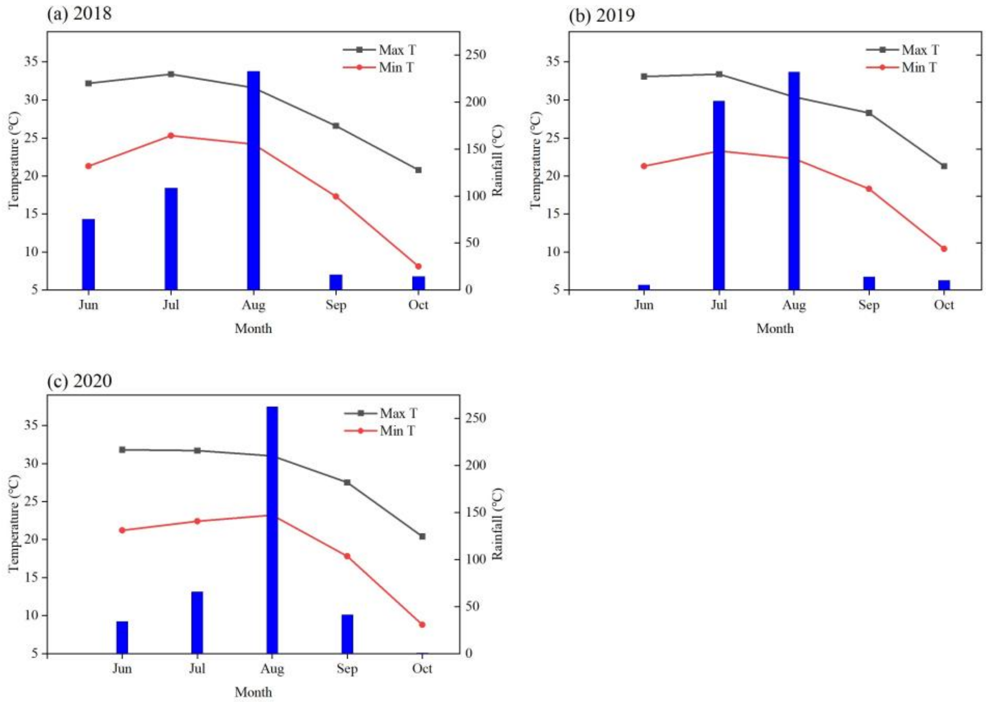

Figure 1. Maximum and minimum air temperature and monthly rainfall during the summer maize seasons in (**a**) 2018, (**b**) 2019, and (**c**) 2020.

2.2. Experimental Design and Data Collection

In this study, five phosphate fertilizer treatments were tested for maize production, i.e., 0, 45, 90, 135, and 180 kg P_2O_5 ha^{-1} (denoted as T1, T2, T3, T4, and T5, respectively). Each treatment was repeated three times and arranged within 15 plots. Each plot in the experimental area was 40 m^2 (5 m × 8 m). The summer maize cultivar was "Xinyan 156", which is widely cultivated in this region. The maize density was set at 50,000 plants per ha^{-1} (plant spacing 30 cm and row spacing 60 cm). All treatments received equal quantities of nitrogen, potassium, and calcium. The urea (46% N, 90 kg ha^{-1}), potassium sulfate (50% K_2O, 90 kg ha^{-1}), and calcium superphosphate (13% P_2O_5) were applied during seedbed preparation, and no fertilizer was applied for topdressing management hereafter. Farming chemicals, pendimethalin, and indoxacarb, were used in the farmland; thus, the experimental plot was kept free of diseases and weeds during the growing seasons. The sown date was 21 June 2018, 23 June 2019, and 18 June 2020.

At maturity, the grain yield and biomass yield were measured from three randomly chosen plants per plot from the soil surface in each growing season, totaling nine plants per treatment. All plants were cut from the soil surface. The crops were harvested on 10 October 2018, 24 October 2019, and 22 October 2020. Maize samples were collected and dissected into grains, cobs, stems, and leaves. Samples of each maize organ were dried in an oven at 105 °C for 30 min and then at 75 °C till constant weight. To measure nitrogen (N), phosphorus (P), and potassium (K) content, appropriate amounts (0.1–0.2 g, accurate to 0.0001 g) of the organs were weighted and then digested using H_2SO_4-H_2O_2 for sample chemical analysis. The organs' N concentration was measured using the Kjeldahl method [36]; P concentration was determined using the ammonium molybdate method; and K concentration was measured using an atomic absorption spectrophotometer [24].

2.3. Data Analysis

2.3.1. Total Nitrogen (N), Phosphorus (P), and Potassium (K) Uptake Content of Grain and Straw

The total N, P, and K uptake content of grain (denoted as TN_{grain}, TP_{grain}, and TK_{grain}, respectively) and straw (denoted as TN_{straw}, TP_{straw}, and TK_{straw}, respectively) were calculated by multiplying the dry weight of the organ and its N, P, K content.

2.3.2. Calculation of Nitrogen, Phosphorus, and Potassium Harvest Index

The nitrogen physiological efficiency (NPE), phosphorus physiological efficiency (PPE), and potassium physiological efficiency (KPE) were calculated using Equations (1)–(3):

$$\mathrm{NPE} = \frac{\mathrm{GY}}{\mathrm{TN_{grain}} + \mathrm{TN_{straw}}} \tag{1}$$

$$\mathrm{PPE} = \frac{\mathrm{GY}}{\mathrm{TP_{grain}} + \mathrm{TP_{straw}}} \tag{2}$$

$$\mathrm{KPE} = \frac{\mathrm{GY}}{\mathrm{TK_{grain}} + \mathrm{TK_{straw}}} \tag{3}$$

2.4. Determination of Optimum Phosphorus Management Using TOPSIS

To evaluate the optimal phosphorus rate that stabilizes the effects of grain yield and N/P/K use, the TOPSIS method was used. The steps were as follows:

(1) Construction of the evaluation indices' contribution matrix (GY, BY, TN, TP, TK, NPE, PPE and KPE)

$$\mathrm{X} = \left(\mathrm{X_{ij}}\right)_{\mathrm{n \times m}} \tag{4}$$

where n is the number of assessment objectives; m is the number of treatments; X_{ij} is contribution value of the ith treatment to the jth evaluation index.

(2) Normalization of the original matrix:

$$\overline{\mathrm{X}}_{\mathrm{ij}} = \frac{\mathrm{X_{ij}}}{\sqrt{\sum_{i=0}^{n} \mathrm{X_{ij}^2}}},\ \mathrm{i} = 1,2\ldots,\mathrm{n};\ \mathrm{j} = 1,2\ldots,\mathrm{m} \tag{5}$$

(3) Calculating the weighted normalized matrix:

$$\mathrm{V_{ij}} = \overline{\mathrm{X}}_{\mathrm{ij}} \times \mathrm{W_j} \tag{6}$$

Positive V_{ij} indicates the ideal best solution and negative V_{ij} indicates the ideal worst solution. W_j is the weight of the jth criterion; when the grain yield, NPK uptake, and fertilizer physiological efficiency were treated equally, W_j can be taken as 1.

(4) Calculating the Euclidean distance:

$$\begin{aligned} \mathrm{D_i^+} &= \sqrt{\textstyle\sum_{j=1}^{m} \left(\mathrm{V_{ij}} - \mathrm{V_j^+}\right)^2} \\ \mathrm{D_i^-} &= \sqrt{\textstyle\sum_{j=1}^{m} \left(\mathrm{V_{ij}} - \mathrm{V_j^-}\right)^2} \end{aligned} \tag{7}$$

(5) Calculating the treatments' performance scores:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (8)$$

When C_i is close to 1, the wheat has an optimal comprehensive advantage in terms of best balancing grain yield and fertilizer physiological efficiency.

Data processing was performed using SPSS (Version 21.0, IBM Corp., Armonk, NY, USA). The significant differences between the mean values were analyzed using one-way and two-way analysis of variance (ANOVA) according to Dennett's test at $p < 0.05$ and $p < 0.01$ level. All graphics were carried out in Origin 2020 software (Origin Lab, Northampton, MA, USA).

3. Results

3.1. Grain Yield and Biomass Yield

Two-way ANOVA showed that there was a significant effect of phosphate on grain yield (GY) and biomass yield (BY) in summer maize across three growing seasons (Figure 2, $p < 0.05$), with the increase in P application, GY and BY increased. The maximum GY and BY were obtained in T3 and T4, and the minimum GY and BY were obtained in T1. For example, the mean GY across the three growing seasons reached 6754.31 kg ha^{-1}, which was 40.21% higher than the T1 treatment. However, GY and BY were suppressed with the input of 180 kg P_2O_5 ha^{-1}. The planting season did not affect GY from the three seasons ($p > 0.05$), while it significantly affected the BY ($p < 0.05$).

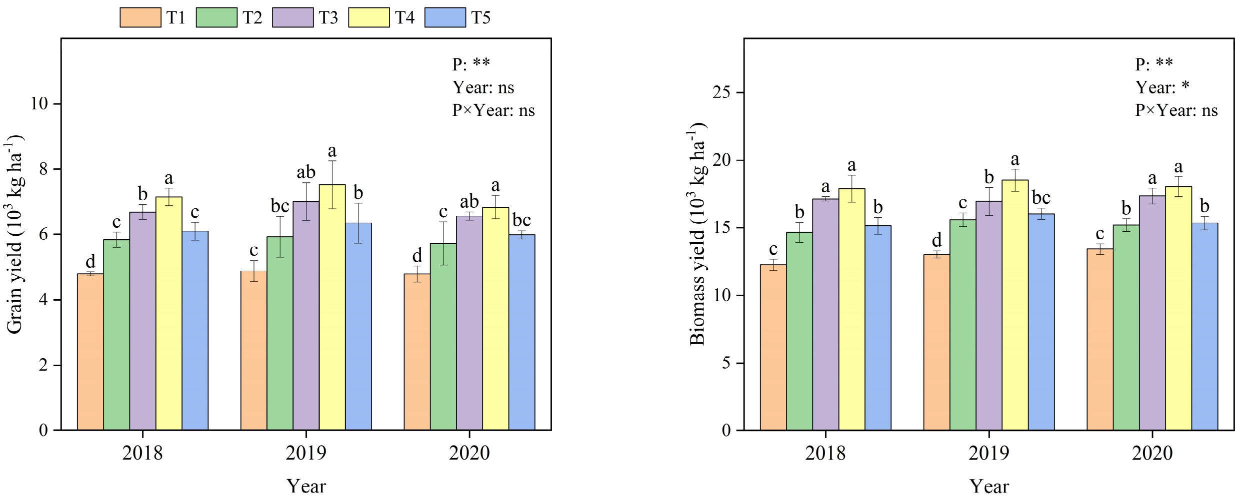

Figure 2. Influence of different phosphate fertilizer rates on grain yield and biomass yield in the 2018, 2019, and 2020 maize seasons. Different letters indicate a significant difference at * $p < 0.05$; ** $p < 0.01$; ns, not significant.

3.2. Nutrient Uptake Content and Partitioning

The total uptake content of N was significantly affected by P fertilizer application, season, and their interaction across 2018, 2019, and 2020 (Figure 3, $p < 0.05$). As P application increased, total nitrogen uptake increased and then decreased over the three seasons. T2, T3, T4, and T5 increased the total N uptake content by 8.2–19.6%, 21.5–58.1%, 37.6–56.4%, and 1.5–25.0%, respectively, relative to T1 over the three growing seasons. Similarly, the largest N uptake in grain was obtained with T4, being 88.4, 121.29, and 93.1 kg ha^{-1} in the 2018, 2019, and 2020 seasons, respectively. Additionally, the proportions of total N uptake in grain and straw over the three seasons were 47.1–61.2% and 38.8–52.9%, respectively, within all treatments. Furthermore, the total nitrogen uptake content in 2019 was obviously larger than those in 2018 and 2020 ($p < 0.05$). When the phosphate fertilizer supply was sufficient, the proportion of nitrogen uptake content in straw in 2019 was relatively high, while it was low in 2018 and 2020. Accordingly, a higher proportion of nitrogen uptake in grain under low P treatment in 2019 was obtained compared with sufficient P application, and the opposite results were found in the 2018 and 2020 seasons.

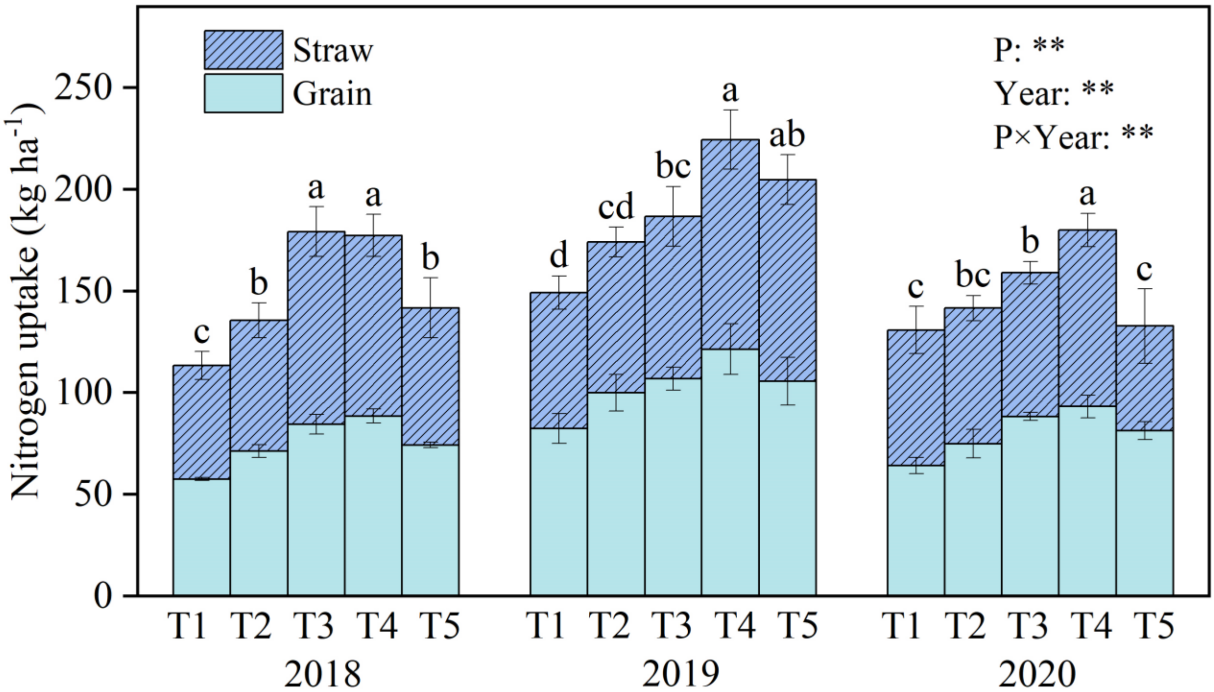

Figure 3. Influence of different phosphate fertilizer rates on nitrogen uptake content in the 2018, 2019, and 2020 maize seasons. Different letters indicate a significant difference at $p < 0.05$; ** $p < 0.01$.

The rate of P application significantly affected the changes in total P uptake (Figure 4). Total P uptake content increased as the P application increased from 0 to 135 kg P_2O_5 ha^{-1}, and then it decreased across the three seasons. Compared to T1, the total P content increased by 17.8–31.1%, 33.3–67.6%, 61.0–89.1%, and 32.8–45.7% in T2, T3, T4, and T5, respectively, over the three growing seasons. The grain P content was higher under the T4 treatment, being 16.9, 23.4, and 9.1 kg ha^{-1} in the 2018, 2019, and 2020 seasons, respectively. Additionally, the proportions of P uptake by grain and straw over the three seasons were 53.8–80.3% and 19.7–46.2%, respectively (Figure 4). Furthermore, the total P uptake content was significantly affected by the growing season ($p < 0.05$). Total P uptake in 2019 was significantly higher than in 2018 and 2020 ($p < 0.05$). When the phosphate fertilizer was not supplied in 2018 or 90 kg ha^{-1} in 2019 and 2020, the proportion of phosphorus uptake content in grain was higher than in the other treatments, and thus, it was relatively low for the proportions in straw.

P treatment, season, and their interaction among the two factors significantly affected the total potassium uptake (Figure 5). Similar to the N and P responses, total potassium uptake content increased and then decreased with an increase in phosphate fertilizer supply across the three seasons. Compared with no P application, P application increased total K content by −22.7–34.5%, 10.1–38.7%, 29.0–37.2%, and −0.07–30.1% in T2, T3, T4, and T5, respectively, within the three growing seasons. Furthermore, the largest potassium uptake in grain was obtained with T4, being 16.1, 21.7, and 24.2 kg ha^{-1} in 2018, 2019, and 2020, respectively. Interestingly, in 2019, there was no significant effect of P application on total K concentration. Additionally, the K uptake in grain was much lower than in straw within all treatments. For example, the proportion of K uptake by grain over the three seasons was 12.2–20.8% (Figure 5). To analyze the effect of season on K uptake, it was found that the total potassium uptake in 2020 was larger than in 2018 and 2019 ($p < 0.05$); the total K uptake content was 111.83–164.19 kg ha^{-1} in 2020, whereas it was 63.82–114.59 kg ha^{-1} in 2018 and 97.69–131.47 kg ha^{-1} in 2019.

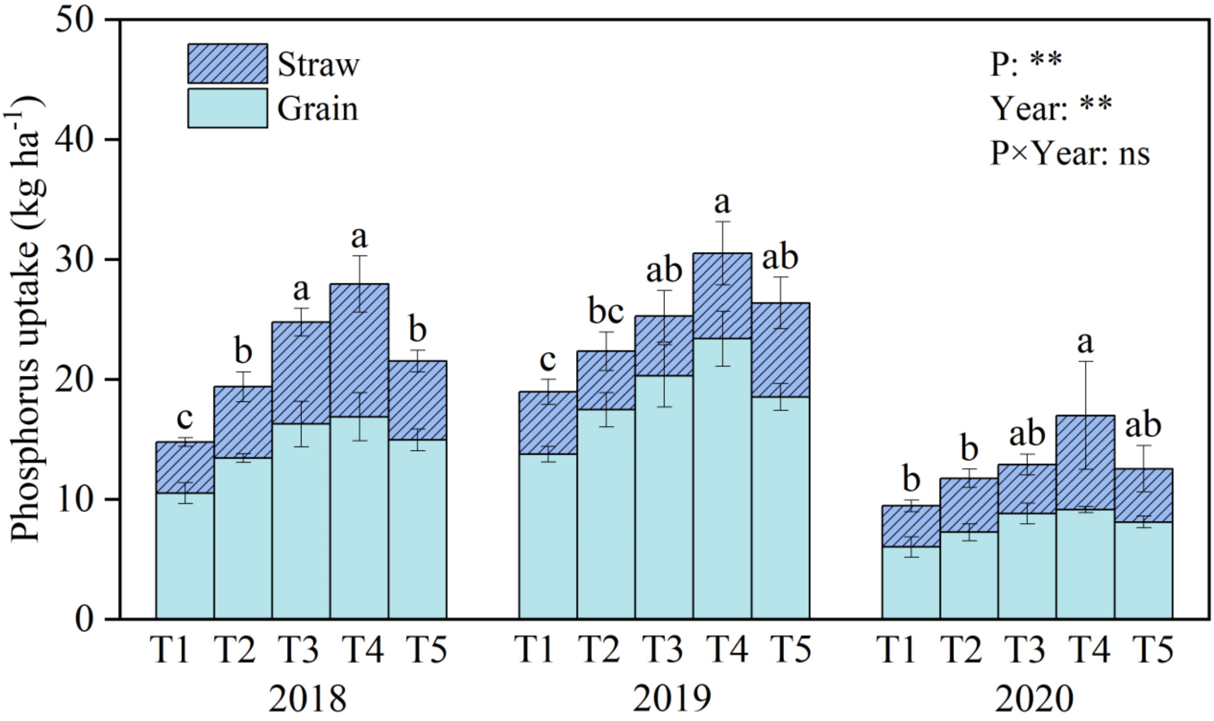

Figure 4. Influence of different phosphate fertilizer rates on phosphorus uptake content in the 2018, 2019, and 2020 maize seasons. Different letters indicate a significant difference at $p < 0.05$; ** $p < 0.01$; ns, not significant.

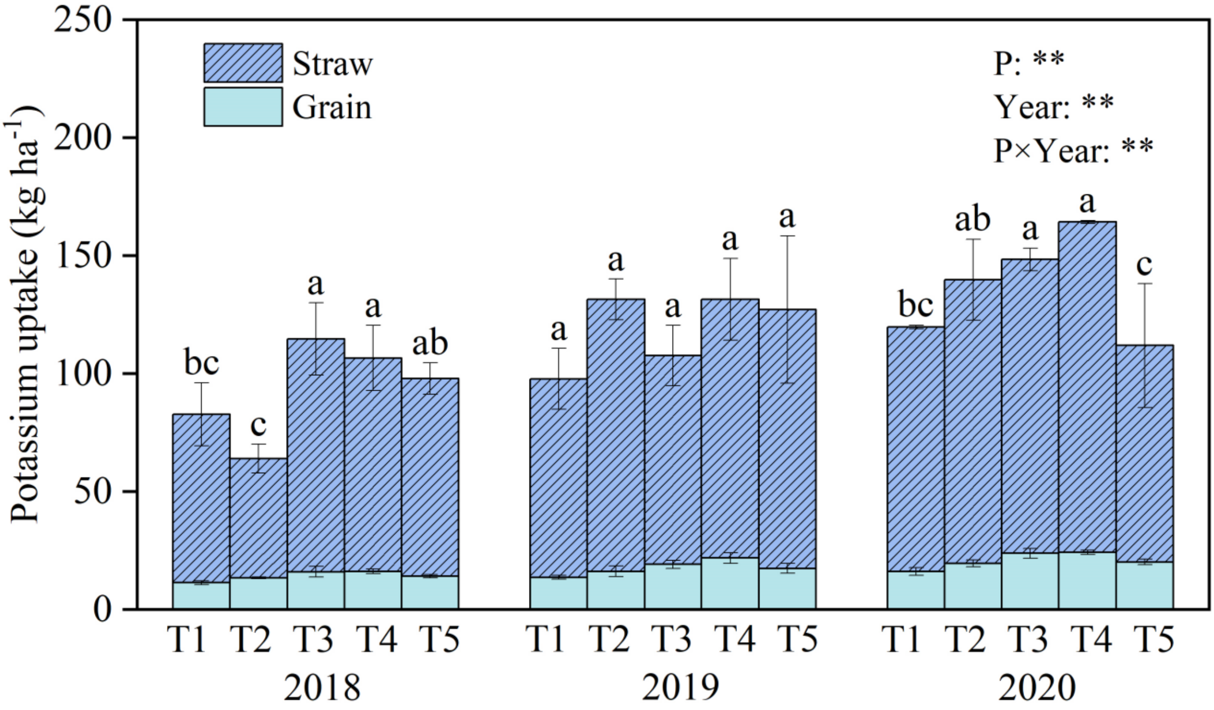

Figure 5. Influence of different phosphate fertilizer rates on potassium uptake content in the 2018, 2019, and 2020 maize seasons. Different letters indicate a significant difference at $p < 0.05$; ** $p < 0.01$.

3.3. Nitrogen (Phosphorus, Potassium) Physiological Efficiency (NPE, PPE, and KPE)

As shown in Figure 6, nitrogen physiological efficiency (NPE), phosphorus physiological efficiency (PPE), and potassium physiological efficiency (KPE) were significantly affected by the phosphate fertilizer rate, season, and their interaction ($p < 0.05$). The average of the NPE, PPE, and KPE across the three growing seasons ranged from 1.46 to 2.15, 0.11

to 0.40, and 1.11 to 1.49 kg kg^{-1}, respectively. For PPE, it decreased with the increasing phosphate fertilizer amount; T2, T3, and T4 increased by 253.7 kg kg^{-1}, 108.2 kg kg^{-1}, and 66.4 kg kg^{-1} relative to T5. Hence, the maximum PPE for P treatments was obtained in T2 within the three growing seasons. In contrast, the NPE and KPE changed differently from the PPE. T3 and T4 obtained maximum NPE and KPE, ranging from 1.94 to 2.15 and 1.37 to 1.49 kg kg^{-1}, respectively. Interestingly, the NPE in 2019 was significantly higher than in 2018 and 2020, and the PPE in 2018 and 2019 was higher than in 2020. However, the KPEs in 2019 and 2020 were much greater than in 2018 with T5 P treatments.

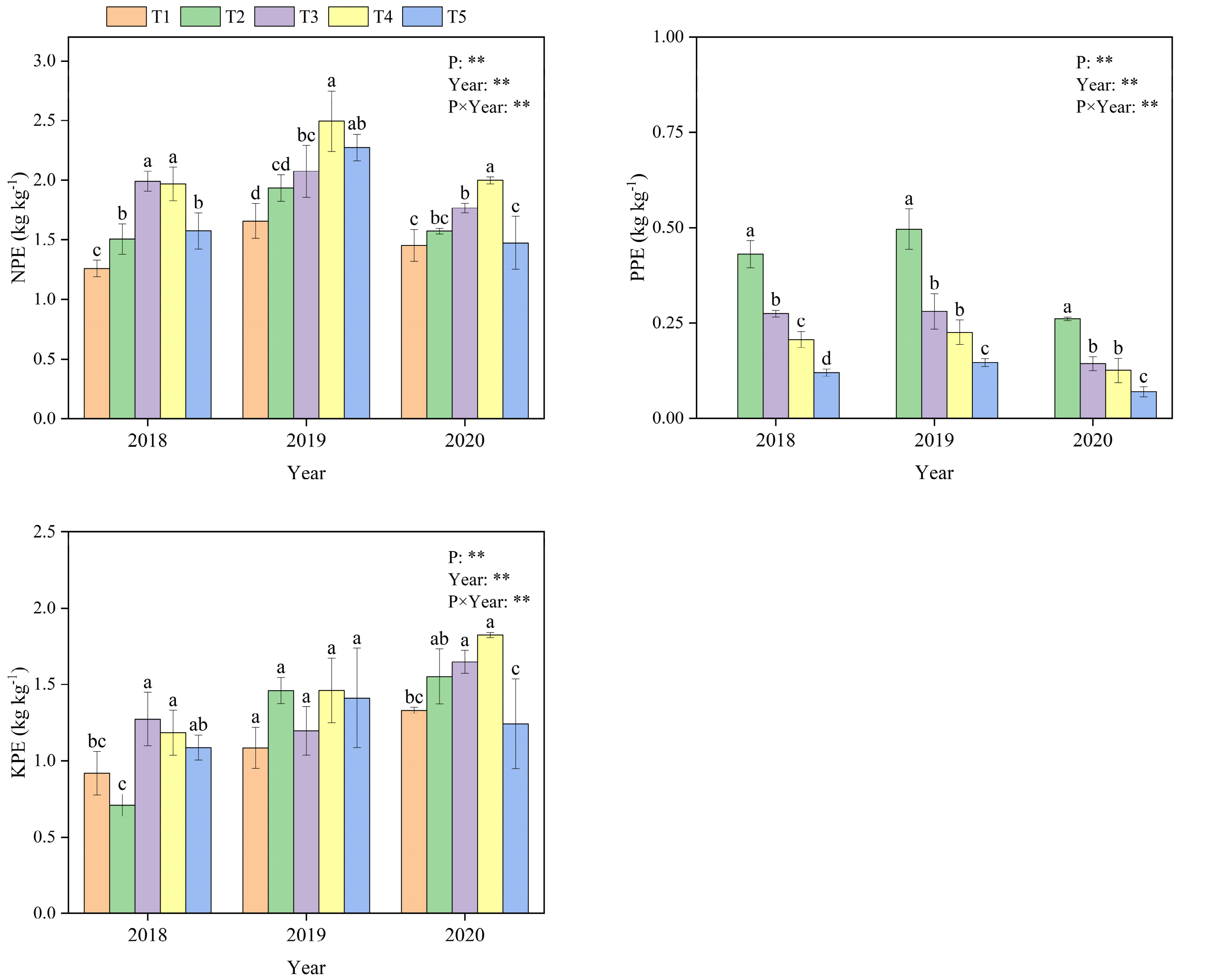

Figure 6. Influence of different phosphate fertilizer rates on nitrogen physiological efficiency (NPE), phosphorus physiological efficiency (PPE), and potassium physiological efficiency (KPE) in the 2018, 2019 and 2020 maize seasons. Different letters indicate a significant difference at $p < 0.05$; ** $p < 0.01$.

3.4. Comprehensive Evaluation of P Application Scheduling

As shown in Figure 7, the performance score, calculated by TOPSIS, followed the order of T3 > T4 > T2 > T5 > T1 in the 2018 season, but the order of T4 > T3 > T2 > T5 > T1 in the 2019 and 2020 seasons. The average ranking scores of T3 and T4 across the three years were 0.69 and 0.70, respectively, which was 11.7 times higher than T1. In addition, considering actual yield and fertilizer utilization, the normalized value radar chart further expressed the comprehensive performance under different phosphate fertilizer supplies. T3 and T4 performed well for GY, BY, TN, TP, TK, NPE, and KPE but poorly for PPE across the three seasons. These results indicated that T3 and T4 had good performance on grain and biomass yield, nutrition uptake, and fertilizer use efficiency.

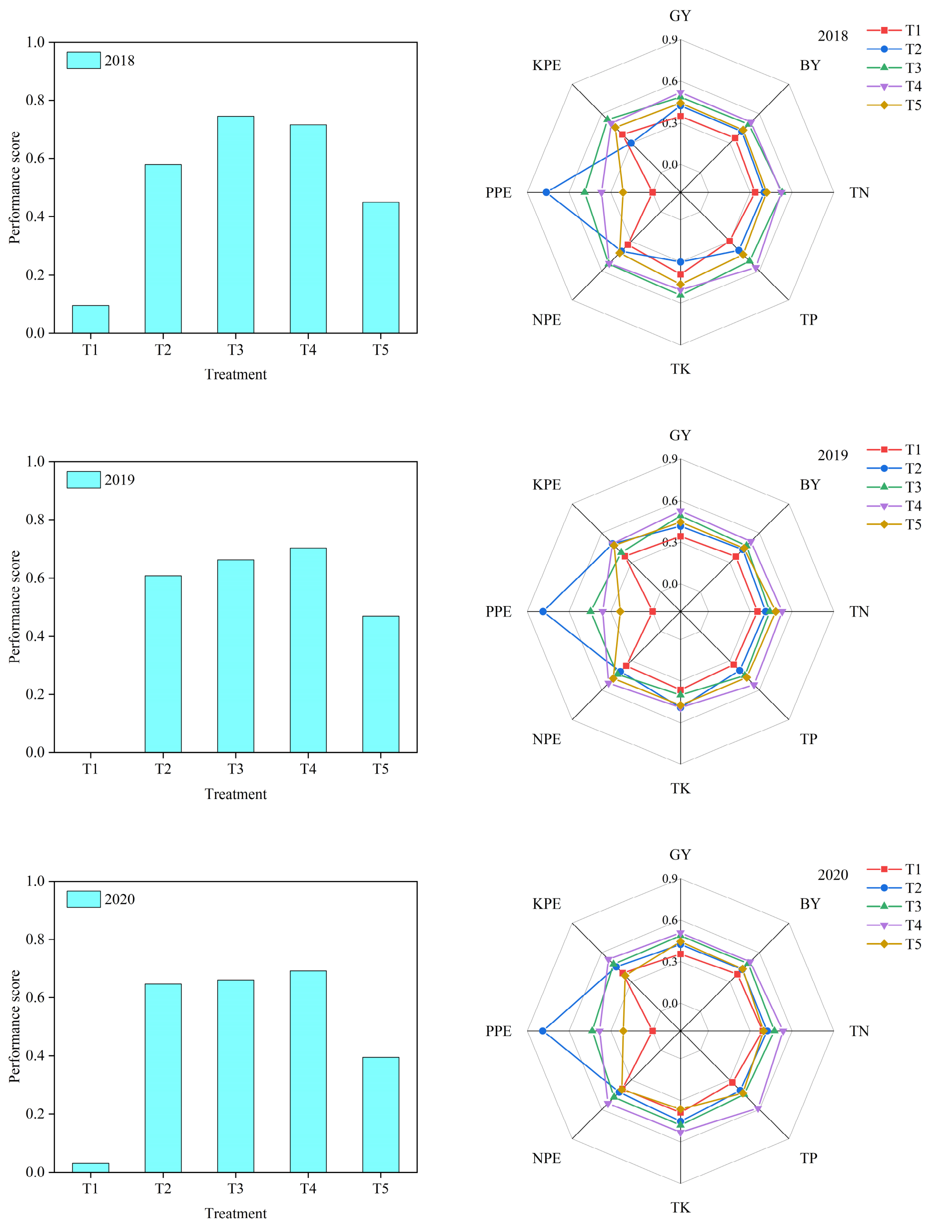

Figure 7. The TOPSIS score and normalized values of all indexes under different phosphate fertilizer rates in 2018, 2019, and 2020. Note: GY, grain yield; BY, biomass yield; TN, total nitrogen uptake; TP, total phosphorus uptake; TK, total potassium uptake; NPE, nitrogen physiological efficiency; PPE, phosphorus physiological efficiency; KPE, potassium physiological efficiency.

4. Discussion

Previous work has shown that the average maize yield potential for the non-saline land is 13,200 kg ha^{-1} under the North China Plain [20]. However, in this study, the average of grain in summer maize was 5992.89 kg ha^{-1} under coastal saline–alkali conditions, which was much lower than under non-salinity soil. This might be due to the stress of high soil salt seriously affecting the growth of underground crop roots and inhibiting the uptake of water and nutrients. Byrt et al. [37] reported that salt stress caused changes in the wall composition of specific root cells, and thus it hindered cell growth. Furthermore, this study showed that, compared with phosphorus supply treatments, the biomass yield and grain yield of summer maize with no P application were significantly lower across 2018, 2019, and 2020

(Figure 2). This result was in agreement with an earlier study conducted by Zribi et al. [38], who found that salt stress decreased whole plant growth and leaf water content, and P deficiency increased this impact. Furthermore, soil salinization also reduced the ability of leaf carbon fixation and thus impeded the formation of photosynthetic compounds in crops, with a more marked impact of P stress [39,40].

Supplementing phosphorus application is an important approach to enhance crop yield in response to salt stress [41,42]. Maize is a characteristically phosphorus-fertilizer-demanding crop. Earlier studies have reported that a deficiency in soil P significantly decreases yield and P absorption [43,44]. In the present study, the effects of P management on grain and biomass yield were significant. Maize yield significantly increased with increasing P application; for example, 135 kg P_2O_5 ha^{-1} application made the maize obtain maximum grain and biomass yield, which was consistent with Xu et al. [21], who conducted a 12-year field experiment with P fertilization rates on summer maize in North China. On the one hand, the reason may be that the P fertilizer supply regulates the biosynthesis of exogenous hormones, such as auxin, gibberellin, cytokinin, or abscisic acid, which are closely correlated with maize growth and grain yield [45]. On the other hand, the rising production of maize was likely associated with larger carbon fixation. Chenet al. [46] revealed that proper P management maximizes the leaf area index, net photosynthetic rate, and, therefore, biomass production for summer maize. However, yield markedly declined with a further supply of 180 kg P_2O_5 ha^{-1} under soil salt conditions, thus suggesting that excessive P application was unbeneficial to maize growth. Perhaps this is because the interactive action between salt stress and P over-fertilization results in an increase in osmotic pressure in root rhizospheres [47]. Thus, to avoid a soil P excess, it would be better if the application of P did not exceed 180 kg ha^{-1}.

Nutrient utilization of crops, including N, P, and K, is obviously related to the variety, fertilization, and soil environmental conditions [48,49]. Previous studies have reported that the prerequisite for high grain yield of crops is high biomass accumulation, and biomass accumulation and yield formation are dependent on nutrient absorption [29]. Xu et al. [21] showed that the total P uptake of crops treated with P_2O_5 was significantly higher than that without P_2O_5 application, and the P uptake increased with the increase in the P_2O_5 application rates. The study further reported that there was a significant difference in the total P uptake of crops when P_2O_5 application rates ranged from 90 to 225 kg ha^{-1}. Similarly, Yan et al. [48] showed that adequate fertilizer input was conducive to nutrient (N, P, and K) uptake by crops and improved N, P, or K transport from the stem or leaves to grain. In this study, the total N, P, and K uptake increased as the P_2O_5 application rate increased and then decreased (Figure 4). A P_2O_5 application rate of 135 kg ha^{-1} obtained the maximum nutrient uptake, which was in accordance with the results of grain and biomass yield. These results indicate that a moderate P_2O_5 application rate is conducive to NPK accumulation, which in turn also provides sufficient material for photosynthesis and improved biomass accumulation. Nevertheless, excessive P_2O_5 supply not only lowers N, P, and K accumulation but also decreases grain and biomass yield.

Further, nutrient use efficiency is usually considered by agricultural scientists to develop sustainable production [49–51]. Improving nutrient physiological efficiency is helpful for the rational utilization of agricultural resources. In our study, the P application rate dynamically affected the physiological efficiency of N, P, and K (Figure 6). The average NPE ranged from 1.26 to 2.49 kg kg^{-1}, while PPE ranged from 0.07 to 0.50 kg kg^{-1}, and KPE ranged from 0.71 to 1.82 kg kg^{-1}. In general, with P application rates of 90 and 135 kg ha^{-1}, the maximum NPEs were 1.94 and 2.15 kg kg^{-1}, respectively, which was 1.32–1.47 times higher than with no P application. Similar results were reported in maize [21], wheat [52], and cotton crops [14,53]. However, excessive P application with 180 kg ha^{-1} led to a decline in NPE because it exceeded the optimal demands of maize plants under salt conditions. P application has been shown to improve NPE, KPE, and crop yield, as well as reduce the PPE [54,55], which is consistent with our study. PPE decreased with the increase in P addition, reaching a maximum in the T1 treatment. An excessive P rate led to inefficient P utilization and, consequently, a high soil P retention [56]. Interestingly, our results showed that NPE, PPE, and KPE were also affected by planting seasons, alluding to the fact that precipitation and temperature might be important factors affecting the use of nutrient efficiency by regulating the soil moisture and salt movement. Further studies should focus on the comprehensive management of water and fertilizer application on maize production under saline–alkali conditions.

High grain yield is the goal of agricultural production, and high NPK utilization is required for efficient utilization of input production materials (e.g., fertilizer and water). In practice, it is difficult to achieve the highest yield, NPE, PPE, and KPE at the same time. In this study, the TOPSIS model was used to evaluate the maize yield and fertilizer use efficiency of five P treatments in saline–alkali soil. Previous studies have shown that TOPSIS can provide an effective solution for optimizing various traits and a comprehensive evaluation of multiple populations [30,33,57,58]. The TOPSIS model in this study showed that T3 ranked 1st and T4 ranked 2nd in the 2018 season. In 2019 and 2020, T4 ranked 1st, and T3 ranked 2nd. Therefore, the P application rate ranging from 90 to 135 kg ha^{-1} would be optimal for the management of maize production in saline–alkali land. The results provide a theoretical reference for producing a high grain yield while utilizing nutrients in saline–alkali land areas.

5. Conclusions

Supplementing phosphorus application significantly improved maize yield and N and K physiological efficiency, whereas P application rates exceeding 135 kg P_2O_5 ha^{-1} induced a decline in grain yield, nutrient uptake, and NPE. The P application rate ranging from 90 to 135 kg P_2O_5 ha^{-1} in saline–alkali land consistently resulted in a higher grain yield, total N, P, and K accumulation, and high NPE and KPE without much reduction in PPE in the three maize seasons. Furthermore, the TOPSIS model showed that 90 or 135 kg P_2O_5 ha^{-1} ranked 1st across the 2018, 2019 and 2020 seasons. Therefore, from the perspectives of efficient crop production and nutrient utilization, 90 to 135 kg P_2O_5 ha^{-1} is recommended as the most suitable P application management pattern for summer maize production in coastal saline–alkali land.

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