Novel value-added phosphorus-potassium-activator fertilizers improve phosphorus use efficiency and crop yields

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ABSTRACT
It is thus essential and critical to enhance phosphorus (P) fertilizer use efficiency of crops to improve agricultural and environmental sustainability. A pot experiment was conducted to examine the impact of different kinds of value-added P-potassium (K)-activator fertilizers (VPAFs) on soil nutrient bioavailability, growth and yield of wheat-maize crops. Compared with that of the control (NPK) treatment, the wheat yields of VPAF treatments increased from 6.59% to 18.61%, and the maize yields increased from −0.22% to 15.58%. In addition, the P fertilizer utilization rate of VPAF treatments increased by an average of 10.87% and 5.75% for wheat and maize, respectively. Therefore, VPAF application in agriculture can introduce multiple benefits including increasing crop yield, improving fertilizer utilization efficiency, enhancing nutrient bioavailability, and reducing pollution.

1. Introduction
Phosphorus (P) is a growth-limiting macronutrient element that plays an essential role in crop production [1]. P deficiency can severely hamper crop yield [2]. It has generally been noticed that the efficacy of P has been often low in most of the soils [3]. Generally, the P use efficiency of crop is only about 10 – 15% [4]. The insufficiency of P in the soil not only affects photosynthesis but also reduces the stress resistance and adaptability of crops [5]. Adequate P supply during crop growth ensures higher yields and better quality [6,7]. Although the application of P fertilizer can increase available P contents in the soil, excessive P has also caused many problems, such as waste of resources and environmental pollution [8,9]. Therefore, it is extremely important to improve P use efficiency.

Globally, for about 100 years, legacy P in agricultural soils has been instrumental in sustaining crop yields [10]. It has been suggested that more than 40% of the world’s cultivated crops are affected by P deficiency [11]. However, it doesn’t mean that there is very little P in the soil. When P fertilizers are applied to the soil, more than 80% of P accumulates in the soil through many processes and mechanisms, such as sorption, precipitation, microbial P mobilization and immobilization, and other processes [8,12]. Increase P use efficiency in the soil by the crops can reduce the waste of P resources and the risk of environmental pollution.

There are many factors that can influence the soil P and its availability. P availability changes with soil depth and pH [13,14]. Cropping system is another factor controlling P availability [15]. In addition, many studies have found fertilization is the key factor affecting P availability. Elrashidi et al. [16] found long-term fertilization causes P accumulation in soil surface or leaches P down to the groundwater layer. Long-term application of organic P fertilizer can increase the leaching depth of P in the soil, so that P accumulates in different soil depths [17]. Eghball et al. [18] found that long-term organic P application can increase soil P mobility compared to that of chemical P fertilizer.

In the present study, we mainly focus on the application of P activators to promote soil P availability and use efficiency. There are mainly three types of P activators for soils: (1) organic matter, such as humic acids, lignin, and biochar; (2) bio-fertilizers and bio-inoculants, such as P solubilizing microorganisms; (3) chemicals and other elements [10]. Previous studies have demonstrated that several P mobilizing sources (P activators) are helpful to improve the mobilization of unavailable P to available forms for crops. For example, humic acid can activate P-immobilized P by releasing H⁺ [19], complexing with Fe and Al cations [20], and adsorbing metal oxides [21] in soils.

In this study, we prepare different types of value-added P-potassium (K)-activator fertilizers (VPAFs). The main goal is to evaluate the effect of VPAF to improve
P fertilizer use efficiency and other soil nutrient availabilities and its impact on crop growth and development.

2. Materials and methods

2.1 Site description, management and field plot design

The pot experiment was conducted from October 2017 to October 2018 in Taian City, Shandong Province, China (36°09′40″N, 117°9′48″E). The crops were grown in rotation included wheat (T. aestivum ‘Jimai 22’) and maize (Z. Mays ‘Zhengdan 958’), which are common species in North China Plain. The soil type was cinnamon soil classified as Typic Hapli-Asiatic Argosols according to the Chinese Soil Taxonomy [22]. Before planting, the pH and EC of soil depth (0–20 cm) were measured in a 1:5 water/soil ratio and the values were 7.97 and 118.1 μS cm⁻¹, respectively. Additional soil properties were as follows: nitrogen 22.35 mg kg⁻¹, total P content 0.64 g kg⁻¹, available P18.02 mg kg⁻¹, available K121.42 mg kg⁻¹, exchangeable calcium (Ca²⁺) 2.28 g kg⁻¹, exchangeable magnesium (Mg²⁺) 0.43 g kg⁻¹ and orange matter 7.12 g kg⁻¹.

Standard fertilizers used included urea (46% N) to supply N, calcium superphosphate (13% P₂O₅) to supply P, K sulfate (50% K₂O) to supply K. The activators tested included: Lignite humic acid (produced in Holingola, China, with 60% humic acid contents); diatomite (produced in Wuhan, China, with 91% SiO₂ contents); zeolite powder (produced in Henan Province, with porosity of more than 48%, 68%-70% SiO₂ contents and 13%-14% Al₂O₃ content); and sepiolite (with 54%-60% SiO₂ contents and 21%-25% MgO contents).

Two cereal wheat and maize crops were cultivated in rotation, wheat was sown on 15 October 2017 and harvested on 5 June 2018. After wheat harvest, maize was planted on 25 June 2018 and harvested on 2 October 2018. The randomized block design was used, with three replications and the following eight treatments (Table 1): no P addition (NP); conventional fertilization (NPK); NPK combined with humic acid application (HAI); and five types of VPAFs including P and K-humic acid fertilizer (HAF), P and K-sepiolite fertilizer (HASF), P and K-zeolite-sepiolite fertilizer (ZSF), P and K-humic acid-diatomite fertilizer (HADF), and P and K-humic acid-diatomite-sepiolite fertilizer (HADSF). For the manufacturing of the five VPAFs, firstly, the ingredients of each VPAF in Table 1 were mixed proportionally (the amount of humic acid was 10% of the total weight of P and K fertilizers, and the other activators were 8% of the total weight of P and K fertilizers). After complete blending, the P and K fertilizers were crushed for 5 min in a high-speed machine with 2000 rpm to make them fully homogenized and mixed with the activators. After that, the mixture was passed through a 60-mesh sieve. Then, the mixture was granulated by using granulation machine (30 rpm) and water was sprayed slowly to prevent caking. When a large number of small granules started appearing in the granular machine, dry mixture of the fertilizer was added and a small amount of water was sprayed. After each VPAF was formed, the machine speed was adjusted to 50 rpm for about 20 min to increase the hardness of the fertilizer. Finally, VPAF granules with a diameter of 2–3 mm were manufactured by air drying.

2.2 Soil and plant sampling

For all treatments, wheat and maize were harvested at the end of the season to determine plant biomass including yield parameters. Soil samples were collected at the depth of (0–20 cm) on different growth stages. For each pot, treated pot soil samples (root free soil) were separated from the plant roots, sieved (<2 mm) and mixed thoroughly. Then, all the soil samples were air-dried prior to measurements.

2.3 Soil and plant analyses

Wheat and maize crops were manually harvested to determine grain yields and components at the end of

| Table 1. Different treatments of fertilizers used in the study kg ha⁻¹. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Crops | Treatment | N-P₂O₅-K₂O | Calcium superphosphate | Lignite humic acid | Zeolite | Diatomite | Sepiolite |
|-------|-----------|------------|-----------------------|------------------|--------|----------|---------|
| Wheat | NK | 225-0-150 | 0 | 300 | – | – | – |
|       | NPK | 225-180-150 | 1384 | 300 | 168.40 | – | – |
|       | HA1 | 225-180-150 | 1384 | 300 | 168.40 | – | – |
|       | HAF | 225-180-150 | 1384 | 300 | 168.40 | – | – |
|       | HASF | 225-180-150 | 1384 | 300 | 168.40 | – | – |
|       | ZSF | 225-180-150 | 1384 | 300 | 168.40 | – | – |
|       | HADF | 225-180-150 | 1384 | 300 | 168.40 | 134.72 | 134.72 |
|       | HADSF | 225-180-150 | 1384 | 300 | 168.40 | 134.72 | 134.72 |
| Maize | NK | 225-0-150 | 0 | 300 | – | – | – |
|       | NPK | 225-120-150 | 923 | 300 | 122.30 | – | – |
|       | HA1 | 225-120-150 | 923 | 300 | 122.30 | – | – |
|       | HAF | 225-120-150 | 923 | 300 | 122.30 | – | – |
|       | HASF | 225-120-150 | 923 | 300 | 122.30 | – | – |
|       | ZSF | 225-120-150 | 923 | 300 | 122.30 | 97.84 | 97.84 |
|       | HADF | 225-120-150 | 923 | 300 | 122.30 | 97.84 | 97.84 |
|       | HADSF | 225-120-150 | 923 | 300 | 122.30 | 97.84 | 97.84 |
the growing season. In the laboratory, the plants and grains were processed for analyses by first being placed in an oven for 30 min at 105°C to deactivate enzymes, and then dried at 75°C to a constant weight, then weighed, followed by grinding the samples to pass through a 60 mesh. The plant samples were digested with H2SO4 and H2O2 at 280°C, then total P concentrations were analyzed using an automated chemistry analyzer (Smatrix200), and the total K concentrations were analyzed using a Model 410 Flame Photometer.

Soil samples at the depth of 0–20 cm were collected with wheat and maize from each pot at different growth stages, then air-dried, passed through a 60 mesh, and finally transferred to paper bags for nutrient analysis. Total P and available P of the soil samples were analyzed using the automated chemistry analyzer. The contents of soil available K were analyzed using the automated chemistry analyzer (Smatrchem200), and the soil exchangeable calcium (Ca) and exchangeable magnesium (Mg) were determined by an atomic absorption spectrophotometer (TAS-990).

2.4 Data analysis

There are three common types of fertilizer use efficiencies. P use efficiencies include P apparent efficiency (PUE), agronomic P use efficiency (aPUE) and internal P use efficiency (iPUE).

PUE (%) = [(accumulation P uptake with P treatment – accumulation amount without P treatment)/the P application amount] × 100%,

aPUE (kg kg−1) = the yield of crop in P treatment/the P application amount,

iPUE (kg kg−1) = the yield of crop in P treatment/accumulation P uptake in P treatment.

Analogously, K use efficiencies include K apparent efficiency (KUE), agronomic K use efficiency (aKUE) and internal K use efficiency (iKUE) [23], which can be determined use the same methods.

Microsoft Excel 2016 was used for processing data and drawing figures. Data were analyzed using the analyses of variance (ANOVAs) with mean separations performed with Duncan tests (P= 0.05), all conducted with IBM SPSS Statistics 19.

3. Results

3.1 Effects of VPAF on wheat-maize yields

Wheat yield and yield components were remarkably enhanced by VPAFs (Table 2). Compared with the treatment of NPK, VPAF treatments increased the wheat yield by 6.59%–18.61% with an average increase of 14.16%. HADSF treatment had the highest yield, which increased the wheat yield by 18.61% compared with NPK treatment.

Similarly, maize yields and other growth parameters were also markedly enhanced by VPAFs (Table 2). There was no significant variation in spike and 100-grain weight among different treatments, but the different treatment effects were different on seeds per spike. Compared to NPK treatment, HAF, HASF and HADF treatments significantly increased the number of maize seeds per spike by 7.21%, 5.79%, and 9.50%, respectively. Compared to that of NPK treatment, the yields of HAF, HASF, HADF, HADSF treatments increased by 6.04%–15.58%, but the yield of ZSF treatment decreased by 0.22%. Therefore, the average yield increase of VPAF treatments was 6.76%. Among them, HADF treatment increased maize yield by 15.58% with a significant difference. Based on the experimental results, we conclude that VPAF can increase the wheat and maize yield by increasing the seeds per spike. Combined with the annual yields of two crops, the annual yield of each VPAF treatment increased by 5.05%–14.20% compared to that of the NPK treatment. HADF treatment showed the best effect on increasing annual yield, about 14.20%, followed by HASF treatment, with an increase of 11.24%.

Table 2. Effects of different fertilizer treatments on wheat and maize yields.

| Crop     | Treatment | Spike | Seeds per spike | 1000-grain weight (g) | Grain yield (g pot−1) | Yield increase (%) |
|----------|-----------|-------|-----------------|-----------------------|-----------------------|--------------------|
| Wheat    | NK        | 94.00 a| 25.10 c         | 38.52 b               | 53.23 e               |                   |
|          | NPK       | 97.00 a| 27.23 b         | 39.41 ab              | 58.46 d               |                   |
|          | HA1       | 98.33 a| 27.07 bc        | 40.48 ab              | 58.56 d               | 0.17               |
|          | HAF       | 100.33 a| 27.33 b       | 40.18 ab              | 62.31 cd              | 6.59               |
|          | HASF      | 97.67 a| 28.80 ab        | 41.83 a               | 69.01 a               | 18.05              |
|          | ZSF       | 93.33 a| 30.60 a         | 40.42 ab              | 68.00 ab              | 16.32              |
|          | HADF      | 100.00 a| 30.60 a        | 40.45 ab              | 65.03 bc              | 11.24              |
|          | HADSF     | 92.33 a| 29.20 ab        | 41.50 a               | 69.34 a               | 18.61              |
| Maize    | NK        | 1      | 440.33 d        | 32.88 a               | 111.76 d              |                   |
|          | NPK       | 1      | 484.00 c        | 34.77 a               | 124.93 c              |                   |
|          | HA1       | 1      | 501.67 abc      | 35.22 a               | 132.92 bc             | 6.40               |
|          | HAF       | 1      | 521.33 ab       | 34.68 a               | 132.48 bc             | 6.04               |
|          | HASF      | 1      | 512.00 ab       | 35.58 a               | 134.99 b              | 8.05               |
|          | ZSF       | 1      | 495.00 bc       | 33.65 a               | 124.65 c              | 0.22               |
|          | HADF      | 1      | 530.00 a        | 34.19 a               | 144.40 a              | 15.58              |
|          | HADSF     | 1      | 486.67 c        | 35.48 a               | 130.83 bc             | 4.72               |
3.2 Effects of VPAF on soil available P

Soil available P contents were markedly affected by the VPAFs (Table 3). At the green return period of wheat, the soil available P contents were between 14.89 and 42.63 mg kg\(^{-1}\). Compared with NPK treatment, HAF, ZSF, HADF and HADSF treatments significantly increased the soil available P contents by 21.71%, 31.30%, 41.96% and 24.34%, respectively. At the shooting period, the available P contents were between 14.57 and 29.02 mg kg\(^{-1}\). Compared with NPK treatment, HAF, ZSF and HADSF treatments significantly improved the soil available P contents by 14.28%, 10.95% and 15.11%, respectively. At the grain filling stage, the soil available P contents were between 14.82 and 33.08 mg kg\(^{-1}\).

HAF, HASF, ZSF, HADSF treatments had significantly higher soil available P by 18.78%, 44.14%, 10.81% and 15.12% than NPK treatment, respectively. At the harvesting period, the soil available P of VPAF treatments was higher than that of NPK treatment. The soil available contents of HASF, ZSF and HADF treatment significantly increased by 26.54%, 22.88% and 20.95%, respectively.

After the wheat experiment, the available P contents of NPK treatment showed a significant trend. At the shooting period and bellbottom period of maize, there was no significant difference between VPAF and NPK treatments on soil available P content. At the milky and the harvest period, compared with that of NPK treatment, the soil available P contents significantly increased by 10.76%-40.18% and 18.92%-41.21%.

From all the above results, we conclude that VPAF can improve the soil available P contents as well as the growth of wheat and maize, particularly in the middle and late stages of the crops.

3.3. Effects of VPAF on soil available K, exchangeable Ca\(^{2+}\) and Mg\(^{2+}\)

The available K contents and exchangeable Ca\(^{2+}\) and Mg\(^{2+}\) in soil were affected by VPAFs. The contents of available K and exchangeable Ca\(^{2+}\) and Mg\(^{2+}\) were determined in the soil during wheat and maize harvesting stage (Table 4). The results showed that available K contents in soil treated with VPAF treatments increased by 14.27%–23.88%, in comparison with that of NPK treatment, and the difference was statistically significant. K in soil treated with VPAFs at the maize harvesting stage was significantly higher than that in soil treated with NPK. Soil available K content increased by 1.93%-9.64% compared to that of NPK treatment. There was no significant difference in soil exchangeable Ca\(^{2+}\) content between the treatments of VPAFs and NPK at wheat harvesting stage, but VPAF treatments increased the soil exchangeable Ca\(^{2+}\) content significantly at the maize harvesting stage. In

### Table 3. Soil available P in different treatments at different time (mg kg\(^{-1}\)).

| Crop    | Treatment | Green return period | Shooting period | Grain filling period | Harvest period |
|---------|-----------|---------------------|----------------|---------------------|---------------|
| Wheat   | NK        | 14.89 d             | 14.57 d        | 14.82 e             | 12.00 d       |
|         | NPK       | 30.03 c             | 25.21 bc       | 22.95 cd            | 15.54 c       |
|         | HA1       | 30.86 c             | 28.84 a        | 22.12 d             | 15.65 c       |
|         | HAF       | 36.55 b             | 28.81 a        | 27.26 b             | 16.94 bc      |
|         | HASF      | 27.32 c             | 26.96 ab       | 33.08 a             | 19.66 a       |
|         | ZSF       | 39.43 ab            | 27.97 a        | 26.01 bc            | 19.10 ab      |
|         | HADF      | 42.63 a             | 24.33 c        | 25.43 bc            | 18.80 ab      |
|         | HADSF     | 37.34 b             | 26.62 bc       | 29.02 a             | 17.62 abc     |
| Maize   | NK        | 12.49 b             | 11.13 c        | 11.36 d             | 7.74 d        |
|         | NPK       | 17.82 a             | 21.04 ab       | 17.47 c             | 14.85 c       |
|         | HA1       | 17.69 a             | 20.51 ab       | 17.92 c             | 19.71 b       |
|         | HAF       | 16.88 a             | 21.48 ab       | 22.95 a             | 18.66 ab      |
|         | HASF      | 17.81 a             | 19.18 b        | 23.01 a             | 19.67 ab      |
|         | ZSF       | 17.47 a             | 18.55 b        | 19.35 ab            | 17.66 ab      |
|         | HADF      | 18.71 a             | 18.68 b        | 20.18 b             | 18.70 ab      |
|         | HADSF     | 18.75 a             | 22.22 a        | 24.49 a             | 20.97 a       |

### Table 4. Soil available K, exchangeable Ca\(^{2+}\) and Mg\(^{2+}\) in different treatments.

| Available K (mg kg\(^{-1}\)) | Exchangeable Ca (g kg\(^{-1}\)) | Exchangeable Mg (g kg\(^{-1}\)) |
|-------------------------------|--------------------------------|--------------------------------|
| Treatment | Wheat | Maize | Wheat | Wheat | Wheat | Wheat |
| NK    | 86.03 c | 96.59 d | 2.23 b | 2.01 b | 0.42 a | 0.41 a |
| NPK   | 93.34 c | 114.21 c | 2.28 ab | 2.05 b | 0.46 a | 0.43 a |
| HA1   | 103.66 b | 116.41 bc | 2.26 ab | 2.41 a | 0.42 a | 0.42 a |
| HAF   | 111.14 ab | 121.55 ab | 2.37 ab | 2.45 a | 0.43 a | 0.42 a |
| HASF  | 107.65 ab | 118.61 bc | 2.39 ab | 2.40 a | 0.43 a | 0.41 a |
| ZSF   | 106.66 ab | 125.22 a | 2.38 a | 2.54 a | 0.44 a | 0.42 a |
| HADF  | 112.64 ab | 121.55 b | 2.35 ab | 2.44 a | 0.42 a | 0.39 a |
| HADSF | 115.63 ab | 116.41 bc | 2.28 ab | 2.36 a | 0.43 a | 0.38 a |
addition, different treatments had no significant effect on the exchangeable Mg\(^{2+}\) content in the soil.

### 3.3 Effects of VPAF on P accumulation and utilization

The ability of crops to absorb nutrients and the ability of soil and fertilizers to supply nutrients are the main factors determining fertilizer use efficiency [24]. Through the one-year wheat-maize rotation experiment, VPAF played a significant role in improving crop P uptake and P fertilizer utilization (Table 5). Compared to that of NPK treatment, the absorption of P fertilizer of VPAF treatments increased significantly in the wheat season. The utilization rate of P fertilizer of VPAF treatments reached 21.44%-27.27%, increased by 10.87% on average compared with that of NPK treatment. The utilization rate of P fertilizer of HASF was the highest, at about 27.27%. In maize season, the utilization rates of VPAF treatments were between 14.64% and 25.77%, increased by 5.75% on average compared to that of NPK. Among them, HADF treatment had the highest utilization rate of P fertilizer, which was 25.77%. The difference of the treatments was statistically significant. Other VPAF treatments also increased the utilization rates of P fertilizer in varying degrees. During the whole growth period, the annual utilization rate of P fertilizer treated with VPAF was 17.72%-29.30%. Among them, the annual utilization rate of HASF treatment was the highest, at about 29.30%, which was much higher than that of NPK treatment.

### 3.4 Effects of VPAF on K accumulation and utilization

The uptake of K by wheat-maize was measured, and the partial productivity and internal utilization rates of K fertilizer were calculated (Table 6). Compared with that of NPK treatment in wheat season, K uptake of VPAF treatments increased by –5.12%-7.14%. Wheat treated with ZSF showed the highest difference among all treatments. Partial productivity and internal utilization efficiency of K fertilizer of VPAF treatment increased by 6.59%-18.63% and 3.85%-17.07% compared to those of NPK treatment, respectively. The absorption and utilization efficiencies of K fertilizer of HASF and HADSF treatments remained at high levels. Compared with that of NPK treatment, K uptake of HASF and HADSF treatments increased by 16.27% and 18.48%, and partial productivity of K fertilizer increased by 8.04% and 15.58%, respectively. The difference was statistically significant, but there was no significant difference in the intrinsic utilization rate of K fertilizer between NPK treatment and VPAF treatments. After a one-year experiment, the effect of HASF treatment was remarkable on K uptake and utilization efficiency of K fertilizer in maize.

### 3.5 Economic benefits of VPAF

The economic benefits of wheat-maize of different treatments were different (Table 7). The total income of wheat treated with VPAFs reached 14,954.40–16,562.40 yuan ha\(^{-1}\), and the net income was 7724.80–9339.54 yuan ha\(^{-1}\), which was 21.28%-46.64% higher than that treated with NPK. The total income of maize of VPAF
treatments was 21,190.50–24,848.00 yuan ha\(^{-1}\), and the net income was 1376.72–17,021.29 yuan ha\(^{-1}\), increased by \(-1.60\%\)-21.75\% in comparison with that of NPK treatment. Annual income and annual net income were calculated for wheat-maize economic. Compared with those of NPK treatment, the annual income and net income of wheat-maize treated with VPAFs increased by 2207.50–4886.70 and 1823.37–4247.16 yuan ha\(^{-1}\). The annual income of wheat-maize treated with P-K-humic acid-sepiolite fertilizer and P-K-humic acid-diatomite fertilizer was the highest, about 39,510.70 and 4247.16 yuan ha\(^{-1}\). In this study, humic acid was used in this experiment, which has strong physio-chemicals and biological activities [25]. Some studies have shown that humic acid can be used as soil conditioner to improve the physical and chemical properties of soils and enhance their ability to conserve segregated properties because of their abundant acidic functional groups and high cation exchange capacities [26,27]. The application of humic acid in soils can reduce the P fixation and improve the K availability [28,29]. In this study, humic acid application significantly increased soil available P content at the jointing stage of wheat and harvest stage of maize (Table 3). Compared with NPK treatment, HA1 treatment also increased soil available K content (Table 4).

Diatomite and sepiolite powders have the characteristics of large specific surface area and good porous structure. They also have strong ion adsorption capacities [30,31]. As a result, they can reduce P fixation and K leaching in soils, and increase the utilization rate of P and K fertilizer. In this study, ZSF, HADF and HADSF treatments improved soil available P in the growth of wheat and maize (Table 3). In addition, they significantly increased the soil available K content during wheat and maize harvest (Table 4).

### 4.2 Synergistic mechanism of activated P-K fertilizer

In the process of fertilizer development, VPAF treatments may increase the specific surface area of the activators to enhance their P absorption capacities. Increasing fineness and contact area with the activators reduce the risk of P fertilizer being fixed in soil. At the same time, K fertilizer was modified, which can reduce the fixation and leaching of K fertilizer in soil, and increase the absorption and utilization efficiency of K fertilizer [29,32]. During the whole growth period, the annual utilization rates of P fertilizer treated with VPAFs were 17.72\%–29.30\%, which increased by 39.06–90.76\% in comparison with that of NPK treatment (Table 5).

There were also some differences in the treatments of different VPAFs in this experiment. HADSF treatment had the best effect on wheat yield, and HADF treatment had the best effect on Maize yield. These two treatments mainly promote the crops’ P uptake by increasing soil available P content in green return and the shooting period of wheat and milky period and harvest period of maize, respectively.

In this study, different VPAF treatments showed different effects in wheat and maize. HASF and HADF showed the best effects considering crop yield, fertilizer utilization efficiency and economic benefit. There are two common points between the two treatments. The first one is that both treatments contain humic acid, and the second one is that both treatments add two kinds of activators. Therefore, it can be inferred that adding another activator with humic acid has a better application effect.

### 5 Conclusions

VPAF treatments showed many advantages over NPK treatment by supplying P at rates that more closely correspond to crop needs at different growth stages. They thus may supply wheat and maize more efficiently while avoiding waste of fertilizer to reduce the use of environmental pollutants. Findings form this
study indicate that VPAF fertilizers have the excellent ability for reducing the soil fixing and leaching of P and K fertilizer, lowering non-point source pollution, improving soil fertility, increasing crops grain yields, and increasing economic benefits. These novel fertilizers, particularly HASF and HADF, thus are recommended to be used in wheat-maize production for the advantages of crop yield, fertilizer utilization efficiency, and economic benefit, as well as reduce environmental pollutants and increase fertilizer bioavailability.

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