# EFFECT OF THE PHOSPHOROUS SUPPLY ON PHOSPHOROUS UPTAKE AND UTILIZATION EFFICIENCY OF MAIZE GENOTYPES UNDER DRIP IRRIGATION

ZHOU, G. W. – ZHU, Q. – ZHANG, S. M.*

*Institute of Nuclear technology and Biotechnologies, Xinjiang Academy of Agricultural Sciences, Urumqi, China*

*Key Laboratory of Crop Ecophysiology and Farming System in Desert Oasis Region, Ministry of Agriculture and Rural Affairs, Urumqi, China*

*Xinjiang Key Laboratory of Crop Biotechnology, Urumqi, China*

*The State Key Laboratory of Genetic Improvement and Germplasm Innovation of Crop Resistance in Arid Desert Regions (Preparation), Urumqi, China*

**Corresponding author*
*e-mail: zhangshaomin8698@126.com*

(Received 21st Nov 2022; accepted 20th Jan 2023)

**Abstract.** Improving maize phosphorus use efficiency (PUE) through phosphorus uptake and utilization efficiency (PUPE and PUTE) is one of the effective ways to breed and increase yield in maize. The purpose of this study was to evaluate the effects of different maize genotypes and phosphorus supply on PUE, PUPE, PUTE and related traits under drip irrigation conditions, and to classify them according to PUE. The experiment was conducted at Dianba Town, Changji City in Xinjiang Province, northwest of China. In the experiment, treatments were the factorial combination of 22 genotypes of maize and two P fertilization rates (0 and 120 kg P $ha^{-1}$ -P and +P, respectively). On average, total dry matter, P concentrations and P uptakes were reduced 23.01, 6.31 and 29.45% by -P, respectively. On the contrary, -P increased PUTE, PUPE, and thus also PUE. All traits were influenced by genotype, phosphorus application and their interaction ($P < 0.05$). PUE was highly correlated with grain yield, total dry matter, P uptake and PUPE but not with PUTE. Genotypes from Xianyu1679 and Xianyu1111 were among the best in terms of PUE under -P and +P treatment. In a wide range of genotypes, PUPE contributes more than PUTE to determining PUE.
**Keywords:** *dry matter yield, harvest index, P harvest index, phosphorus concentration, genotypic variation*

## Introduction

Phosphorus is considered to be an important factor limiting crop productivity. Although phosphorus is fairly abundant in many soils, it is largely unable to be absorbed by plants because phosphorus forms insoluble complexes with cations under acidic and alkaline conditions (Yang et al., 2021; Johan et al., 2021; Weeks et al., 2019). Therefore, it is a common practice to over-apply mineral phosphate fertilizers in the pursuit of higher yields (Yan et al., 2021). Overuse of phosphate fertilizer can lead to phosphorus loss from the soil, resulting in eutrophication of water bodies and toxic algal blooms in aquatic ecosystems (Zak et al., 2018). In addition, P in mineral fertilizers is mainly derived from phosphate rock, which is a non-renewable resource (Pradel et al., 2019). Therefore, breeding low-input phosphorus fertilizer cultivars with high yield and high efficiency is an important strategy to protect global phosphorus resources and reduce environmental pollution.

Phosphorus uptake efficiency (PUPE) is the ability of crops to absorb phosphorus from soil and fertilizer, and phosphorus utilization efficiency (PUTE) is the ability of crops to convert absorbed phosphorus into yield. Improving phosphorus use efficiency (PUE) in crops requires increasing the phosphorus uptake efficiency (PUPE) of plants from the soil and enhancing the use of P in processes leading to rapid growth and greater allocation of biomass to harvestable plant components (PUTE) (Emami et al., 2020). However, for some cultivars, a large amount of absorbed P is retained in organs that no longer play a role in later development, such as senescent leaves, and cannot be transported to organs that need it to maintain their growth levels, resulting in inefficient P utilization (Wang et al., 2020). PUE is the yield capacity of a crop genotype at low available P concentrations. To improve the PUE, it is necessary to improve the component traits such as PUPE (absorption/uptake), translocation (transport/partitioning/remobilization) and PUTE (Malhotra et al., 2018). To improve PUE in crops, it is important to explore genetic variation in all relevant traits.

Maize is a worldwide crop. Thousands of varieties have been bred. Phosphorus-efficient maize genotypes are beneficial for enhancing the utilization of soil P and residues of P applied as fertilizer in low P soils and in soils with adequate P supply (Kadirimangalam et al., 2022). Significant genotypic differences in PUE have been reported in some crops, including: maize, rice and wheat (Weiß et al., 2022; Adem et al., 2020; Hari-Gowthem et al., 2019). The relationship between relevant physiological traits that have an effect on PUPE and PUTE by different maize genotypes has not been well evaluated. These studies will increase our understanding of PUE variability in maize crops under field conditions on genotype and P supply. It is of great significance for rational application of phosphate fertilizer and maize breeding in drip irrigation agricultural system in arid areas.

The objectives of this study was to evaluate the contribution of PUPE and PUTE and traits related to PUE of maize genotypes and to classify the genotypes on the basis of their performance (PUE) at low and high P supply under drip irrigation conditions.

## Materials and methods

### *Site description*

The experiment was conducted at Dianba Town, Changji City in Xinjiang Province, northwest of China (44°7′N, 87° 20′ E) during the 2021 growing season. The region is classified as a temperate arid zone with a continental climate. There are 2700 h of sunshine a year, the annual ≥10 °C accumulated temperature is 3450 °C, the annual average temperature is 6.8 °C, the annual average precipitation is 190 mm and the annual frost-free period is 160–190 days. The soil at the site is an alluvial, gray desert soil, classified as a Calcaric Fluvisol in the FAO/UNESCO System. Some of the physical and chemical properties of the soil (0–20 cm depth) in 2021 are as follows: pH, 8.53; electrical conductivity (EC) in 1:5 soil: water extract, 0.04 dS/m; organic matter, 12.71 g/kg; ammonium nitrogen, 6.55 mg/kg; and nitrate nitrogen, 47.79 mg/kg; Olsen P, 26.73 mg/kg; available potassium, 233 mg/kg.

### *Experimental design*

The experiment was arranged in a split-plot design. P rates were classified to main plots and genotypes to subplots randomized into three blocks. In the experiment,


http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2102_13611374

treatments were the factorial combination of 22 genotypes of maize (*Table 1*) and two P fertilization rates (0 and 120 kg $P_2O_5$ $ha^{-1}$ indicate -P and +P, respectively). Each plot was mulched with one sheet of transparent polyethylene film (1.2 m wide × 3 m long). The plastic film was held in place by burying the edges with soil. Two drip irrigation lines were installed under the plastic film. There was a 0.6-m-wide bare strip between each plot. Each plot had four rows of maize plants. The maize plants were sown at 25-cm intervals within each row. Row spacing configuration of 30 cm + 60 cm + 30 cm. See *Figure 1* for a diagram of the plot planting. The plant population was $8.9 \times 10^4$ plants/ha. Maize was sown on 27 April 2021.

***Table 1.*** *Origin and most important agronomic properties of maize genotypes*

| Genotypes | Origin | Agronomic properties |
|---|---|---|
| 108XDB | Xinjiang, China | Ear tube type; spike length 18.8 cm |
| L75X81F | Xinjiang, China | Ear tube type; spike length 19.2 cm |
| MC670 | Beijing, China | Ear tube type; spike length 18.6 cm |
| Dongdan507 | Liaoning, China | Ear tube type; spike length 19.1 cm |
| Dongdan1331 | Liaoning, China | Ear tube type; spike length 22 cm |
| Heyu187 | Jilin, China | Ear tube type; spike length 23 cm |
| Jiushenghe235 | Beijing, China | Ear tube type; spike length 19 cm |
| JiuyuY02 | Beijing, China | Ear tube type; spike length 18 cm |
| Xianyu1111 | Liaoning, China | Ear intermediate type; spike length 19.7 cm |
| Xianyu1224 | Liaoning, China | Ear intermediate type; spike length 17.8 cm |
| Xianyu1331 | Liaoning, China | Ear short tube type; spike length 16.9 cm |
| Xianyu1420 | Liaoning, China | Ear intermediate type; spike length 19.6 cm |
| Xianyu1440 | Liaoning, China | Ear intermediate type; spike length 18.5 cm |
| Xianyu1483 | Liaoning, China | Ear intermediate type; spike length 19 cm |
| Xianyu1509 | Liaoning, China | Ear tube type; spike length 17 cm |
| Xianyu1531 | Liaoning, China | Ear intermediate type; spike length 18.7 cm |
| Xianyu1679 | Liaoning, China | Ear tube type; spike length 19.1 cm |
| XinyinKWS2564 | Xinjiang, China | Ear tube type; spike length 17.9 cm |
| XinyinKX3564 | Xinjiang, China | Ear tube type; spike length 19.4 cm |
| XinyinM751 | Xinjiang, China | Ear tube type; spike length 19 cm |
| Xinyu24 | Xinjiang, China | Ear tube type; spike length 21.3 cm |
| Xinyu108 | Xinjiang, China | Ear tube type; spike length 22 cm |

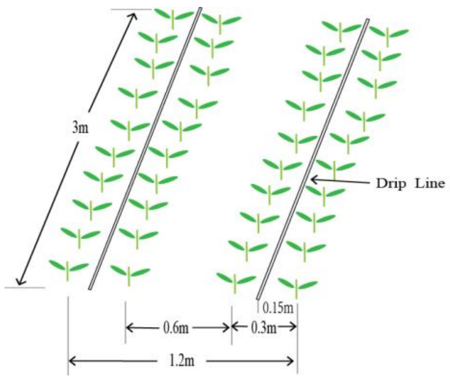


***Figure 1.*** *Diagram of plot planting*


http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2102_13611374

Phosphate fertilizer (potassium dihydrogen phosphate), nitrogen fertilizer (urea), and potassium fertilizers (potassium sulfate) were applied through the drip irrigation system. The fertilizer was applied in five equal amounts 44, 56, 66, 89, and 98 days after planting. The fertilizer solution was stored in a 15-L plastic container and pumped into the irrigation system. All plots were fertilized with 300 kg N/ha and 90 kg $K_2O$/ha. The plots were irrigated nine times (every 7 to 10 days) between June and August. These irrigation practices were similar to those used by local farmers.

Manual weeding was performed after each irrigation and fertilization. Two mid-tillings were conducted throughout the maize growing stage (in V2 and V8-V10 stage, respectively). Maize borer was controlled with 20% chlorothalonil suspension in two field sprays (in V12 and R2 stage, respectively). Maize aphid were controlled by spraying 3% acetamiprid at the time of aphid infestation (in V12 and R4 stage, respectively).

### *Sampling and measurement methods*

At maturity stage, the maize plants were cut at the soil surface and partitioned into two parts: stovers and grains. Plant samples were dried at 105 °C for 30 min, and then at 75 °C to constant weight. The dry weight was recorded. The samples were then ground to pass through a 1 mm sieve before digestion with $H_2SO_4$-$H_2O_2$. Phosphorus concentrations were analyzed by molybdenum antimony anti-colorimetric method.

The measured traits, abbreviations, calculations and units are shown in *Table 1*. P uptake in stovers and grains was calculated as the product of dry matter yield and P concentration. P harvest index was calculated as the ratio between P uptake in grain and total P uptake. Harvest index was determined as the ratio between grain dry matter yield and total dry matter yield (grain plus stover biomass). PUE (grain dry matter yield (kg ha$^{-1}$)/P supply (kg P ha$^{-1}$)) was calculated as the product of PUTE and PUPE (*Table 2*), following the approach of previous studies assessing P and/or other nutrients (Sandaña, 2016; Valle et al., 2011). PUTE was calculated as the ratio between grain dry matter yield and total P uptake (grain dry yield (kg ha$^{-1}$)/P uptake (kg P ha$^{-1}$)), while the PUPE was calculated as the ratio between total P uptake and P supply (P uptake (kg P ha$^{-1}$)/P supply (kg P ha$^{-1}$)).

***Table 2.*** *Traits, abbreviations, calculation and units of traits measured in 22 genotypes of maizes under 0 (-P) and 120 kg P ha$^{-1}$ (+P)*

| Trait | Abbreviation | Calculation | Unit |
|---|---|---|---|
| Grain dry matter yield | GDY | | kg ha$^{-1}$ |
| Stover dry matter yield | SDY | | kg ha$^{-1}$ |
| Total dry matter yield | TDY | | kg ha$^{-1}$ |
| Harvest index | HI | GDY/TDY | kg kg$^{-1}$ |
| Grain P concentration | GPC | | % |
| Stover P concentration | SPC | | % |
| Grain P uptake | GPU | GPC× GDY | kg ha$^{-1}$ |
| Stover P uptake | SPU | SPC× SDY | kg ha$^{-1}$ |
| Total P uptake | TPU | GPU + TPU | kg ha$^{-1}$ |
| P harvest index | PHI | GPU/TPU | kg kg$^{-1}$ |
| P utilization efficiency | PUTE | GDY/TPU | kg grain dry matter yield kg$^{-1}$ P uptake |
| P uptake efficiency | PUPE | TPU/P supply | kg total P uptake kg$^{-1}$ P supply |
| P use efficiency | PUE | PUTE× PUPE | kg grain dry matter yield kg$^{-1}$ P supply |


http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2102_13611374

P supply was estimated as the sum of potential soil P supply at planting (in -P) plus P fertilization (in +P) (Valle et al., 2011). In the experiment, the potential of soil to supply P at planting was estimated using the initial soil Olsen P content (mg $kg^{-1}$) in the top 20 cm of soil and soil bulk density of 1400 kg $m^{-3}$.

### *Data analyses*

The data were analyzed using SPSS statistical software v.22.0 (SPSS Inc., 1996) with a two-factor split-zone test ANOVA at a significance level of 0.05, with maize genotypes and P application rate as the independent variables. A Duncan multiple range test was carried out to determine if there were significant differences between individual treatments at $P < 0.05$. Correlation and regression analysis were used SPSS statistical software v.22.0 (SPSS Inc., 1996), and principal component analysis (PCA) were used Origin software v. 21.0.

## Results

### *Analysis of variance and genotypic variation in traits*

The mean, coefficient of variation and ANOVA of the measured traits are shown in *Table 2*. All traits were influenced by genotype, phosphorus application and their interaction ($P < 0.05$) (*Table 3*). The variation coefficients of each trait reflected the variability of maize genotypes at +P and -P levels (*Table 3*). On average, -P resulted in reductions of 23.01, 6.31 and 29.45% in dry matter (grains, stovers and total), P concentration (in grains and stovers) and P uptake (in grains, stovers and total), respectively. As expected, +P reduces PUTE, PUPE, and therefore PUE (*Table 3*).

***Table 3.*** *Mean, coefficient of variation (CV %) and analysis of variance (phosphorus (P), genotype (G) and P × G interaction effects) for traits measured in 22 maize genotypes under 0 (-P) and 120 kg P $ha^{-1}$ (+P)*

| Trait | -P | | +P | | Analysis of variance (*P* value) | | |
|---|---|---|---|---|---|---|---|
| | **Mean** | **CV (%)** | **Mean** | **CV (%)** | **P** | **G** | **P×G** |
| Grain DM yield | 8924.57 | 21.00 | 12451.00 | 23.63 | *<0.001* | <0.001 | <0.001 |
| Stover DM yield | 9197.6858 | 19.75 | 11088.27 | 17.27 | <0.001 | <0.001 | <0.001 |
| Total DM yield | 18122.26 | 17.07 | 23539.27 | 16.90 | <0.001 | <0.001 | <0.001 |
| Harvest index | 0.49 | 12.08 | 0.53 | 12.43 | 0.003 | <0.001 | <0.001 |
| Grain P concentration | 0.33 | 13.62 | 0.35 | 9.21 | 0.014 | <0.001 | <0.001 |
| Stover P concentration | 0.09 | 17.46 | 0.10 | 19.07 | <0.001 | <0.001 | <0.001 |
| Grain P uptake | 29.36 | 25.26 | 42.78 | 9.61 | *<0.001* | <0.001 | <0.001 |
| Stover P uptake | 8.81 | 29.71 | 11.32 | 20.88 | <0.001 | <0.001 | <0.001 |
| Total P uptake | 38.17 | 22.75 | 54.10 | 21.82 | *<0.001* | <0.001 | <0.001 |
| P harvest index | 0.77 | 8.11 | 0.78 | 8.62 | 0.011 | <0.001 | <0.001 |
| PUTE | 236.03 | 10.88 | 229.89 | 9.53 | <0.001 | <0.001 | <0.001 |
| PUPE | 0.51 | 22.75 | 0.28 | 21.82 | *<0.001* | <0.001 | <0.001 |
| PUE | 119.15 | 21.00 | 63.88 | 23.63 | *<0.001* | <0.001 | <0.001 |


http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2102_13611374

### *Dry matter yield and total P uptake*

On average, -P decreased ($P < 0.05$) grain dry matter yield by 28.32% (*Table 3*). However, -P resulted in yield reductions ranging from 4.52-48.26% across genotypes. The reduction in grain dry matter yield under -P conditions was positively correlated with ($P < 0.05$; $R^2 = 0.4036$) the reduction in total dry matter yield (*Fig. 2a*). -P decreased the total P uptake by 29.45%. Total P uptake in the -P treatment was positively correlated ($P < 0.05$; $R^2 = 0.5173$) with total P uptake in +P treatment, but the slope was lower than 1; therefore, the total phosphorus uptake in the -P treatment was significantly lower than the total phosphorus uptake in the +P treatment (*Fig. 2b*). Under both fertilization conditions, total phosphorus uptake was positively correlated with total dry matter yield, with no difference in regression slope (*Fig. 2c*). More interestingly, different total phosphorus uptake was observed at the same total dry matter yield (*Fig. 2c*), indicating an important variation in PUPE. Grain dry matter yield was positively correlated with total P uptake under the -P treatment ($P < 0.05$; $R^2 = 0.7846$) and +P treatment ($P < 0.05$; $R^2 = 0.8738$) (*Fig. 2d*). Moreover, at the same level of total phosphorus uptake (under -P and +P conditions), grain dry matter yields varied considerably among genotypes (*Fig. 2d*).

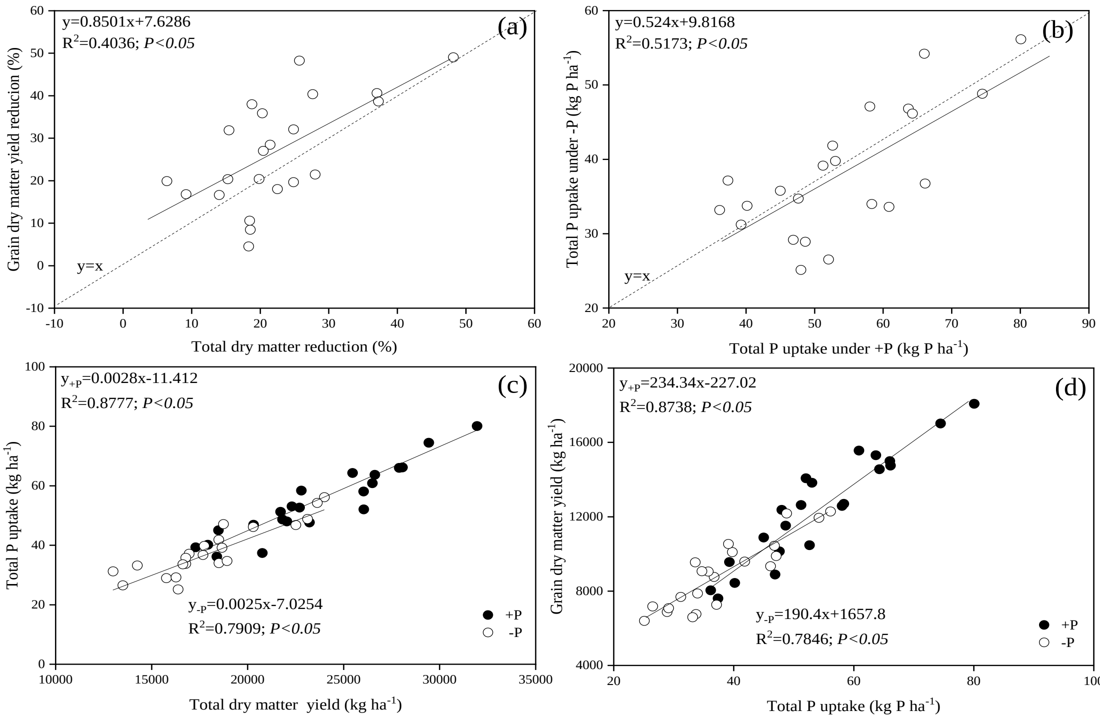


***Figure 2.** Relationships between Grain dry matter yield and total dry matter yield reductions (a), between total P uptake under -P and +P (b), between total P uptake and total dry matter yield (c) and between Grain dry matter yield and total P uptake (d) in 22 maize genotypes under 0 (-P) (open symbols) and 120 kg P ha$^{-1}$(+P) (closed symbols)*

### *PUTE, PUPE and their importance to PUE*

In this experiment, the variation of PUTE (189.72–283.92 kg grain dry matter yield kg$^{-1}$ total P uptake) was different in response to P levels, genotypes and their interactions (*Table 4*). Under +P conditions, PUTE ranged from 189.72–270.36 kg grain


http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2102_13611374

dry matter yield kg$^{-1}$ total P uptake. These values were higher under -P conditions (196.03–283.92). On average, +P decreased PUTE by 2.6%. However, the sensitivity of PUTE to -P varied among maize Genotypes. Under -P conditions, the genotypes Xinyu108, XinyinKWS2564 and Xianyu1531 exhibited the highest PUTE (268.98–283.92 kg grain dry matter yield kg$^{-1}$ total P uptake), while Dongdan507, JiuyuY02 and L75X81F had the lowest PUTE (196.03–199.91 kg grain dry matter yield kg$^{-1}$ total P uptake) (*Table 4*). Under +P conditions, the genotypes XinyinKWS2564, XinyinM751 and Xianyu1420 exhibited the highest PUTE (257.85–270.36 kg grain dry matter yield kg$^{-1}$ total P uptake), while MC670, XinyinKX3564 and Dongdan507 had the lowest PUTE (189.72–203.46 kg grain dry matter yield kg$^{-1}$ total P uptake) (*Table 4*).

***Table 4.*** *P utilization efficiency (PUTE, kg grain dry matter yield kg$^{-1}$ total P uptake), P uptake efficiency (PUPE, kg total P uptake kg$^{-1}$ P supply) and P use efficiency (PUE, kg grain dry matter yield kg$^{-1}$ P supply) in 22 maize genotypes under 0 (-P) and 120 kg P ha$^{-1}$ (+P)*

| Genotype | PUTE | | PUPE | | PUE | |
|---|---|---|---|---|---|---|
| | -P | +P | -P | +P | -P | +P |
| 108XDB | 222.96ghB | 240.39defgA | 0.62bA | 0.33cdB | 139.32bA | 78.55cdB |
| L75X81F | 199.91iA | 209.88jklA | 0.45efA | 0.21iB | 90.21hiA | 43.27lmB |
| MC670 | 229.39fgA | 199.38lmB | 0.56cA | 0.27fB | 127.96bcdeA | 53.71iB |
| Dongdan507 | 196.03iA | 203.46klmA | 0.50deA | 0.19jB | 96.94ghiA | 39.02mB |
| Dongdan1331 | 238.66efA | 222.89hijB | 0.49deA | 0.34cB | 116.93efA | 75.65cdeB |
| Heyu187 | 202.49iB | 226.46fghijA | 0.62bA | 0.33cdB | 124.65cdeA | 74.68defB |
| Jiushenghe235 | 246.62deA | 243.46cdefA | 0.42fghA | 0.20jB | 102.56ghA | 49.05jkB |
| JiuyuY02 | 199.02iB | 222.20hijA | 0.44efgA | 0.19jB | 87.97iA | 41.23lmB |
| Xianyu1111 | 218.57ghA | 225.68ghijA | 0.75aA | 0.41aB | 163.92aA | 92.74aB |
| Xianyu1224 | 238.30efA | 236.73efghA | 0.39hiA | 0.25fghiB | 91.76ghiA | 59.10hB |
| Xianyu1331 | 209.76hiA | 216.65ijkA | 0.63bA | 0.30eB | 131.94bcdA | 64.56gB |
| Xianyu1420 | 255.09cdA | 257.85abcA | 0.34iA | 0.25ghiB | 85.44iA | 63.46gB |
| Xianyu1440 | 231.71fgA | 217.55ijkB | 0.45efA | 0.30eB | 105.09fgA | 65.13gB |
| Xianyu1483 | 220.31ghA | 227.25fghijA | 0.72aA | 0.34cB | 159.43aA | 76.93cdB |
| Xianyu1509 | 253.59cdA | 241.67cdefgA | 0.48deA | 0.23iB | 120.78deA | 55.80hiB |
| Xianyu1531 | 283.92aA | 255.85abcdB | 0.45efA | 0.31deB | 127.37bcdeA | 79.80cB |
| Xianyu1679 | 249.27cdeA | 228.44fghiB | 0.65bA | 0.38bB | 162.55aA | 87.29bB |
| XinyinKWS2564 | 270.28bA | 270.36aA | 0.35iA | 0.27fgB | 95.73ghiA | 72.16efB |
| XinyinKX3564 | 242.83defA | 189.72mB | 0.39ghiA | 0.24hiB | 94.47ghiA | 45.59klB |
| XinyinM751 | 253.90cdA | 260.73abA | 0.53cdA | 0.27fB | 134.76bcA | 70.95fB |
| Xinyu24 | 261.12bcA | 214.23ijklB | 0.46efA | 0.24ghiB | 120.99deA | 51.99ijB |
| Xinyu108 | 268.98bA | 246.82bcdeB | 0.52cdA | 0.26fghB | 140.60bA | 64.80gB |

Different lowercase letters in the same column and different capital letters for the same item in the same row indicate significant differences at the 0.05 level

There was a wide range of variability in the response of PUPE (0.19–0.75 kg total P uptake kg$^{-1}$ P supply) to P levels, genotypes and their interactions in this experiment (*Table 4*). Under +P conditions, PUPE ranges from 0.19–0.41 kg total P uptake kg$^{-1}$ P supply. As expected, the PUPE increases greatly with -P treatment. More interestingly, there were important differences in PUPE between maize genotypes under -P


http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2102_13611374

conditions, as PUPE varied between 0.34–0.75 kg total P uptake $kg^{-1}$ P supply. In the experiments, the genotypes Xianyu1679, Xianyu1483 and Xianyu1111 showed the highest PUPE (0.65–0.75 kg total P uptake $kg^{-1}$ P supply) under -P treatment, whereas Xianyu1420, XinyinKWS2564, XinyinKX3564 and XinyinKX3564 had the lowest PUPE (0.34–0.39 kg total P uptake $Kg^{-1}$ P supply) (*Table 4*). The genotypes Xianyu1679 and Xianyu1111 showed the highest PUPE (0.38–0.41 kg total P uptake $kg^{-1}$ P supply) under +P, whereas Dongdan507, JiuyuY02 and Jiushenghe235 had the lowest PUPE (0.19–0.20 kg total P uptake $Kg^{-1}$ P supply) (*Table 4*).

PUE varied between 41.23 to 163.92 kg grain dry matter yield $kg^{-1}$ P supply (*Table 4*). With +P, the PUE was reduced by 46.49%. On average, the PUE was 63.88 kg grain dry matter yield $kg^{-1}$ P supply under +P conditions, while this value was 119.15 kg grain dry matter yield $kg^{-1}$ P supply under -P conditions. Interestingly, the PUE under -P conditions ranged from 85.44–163.92 kg grain dry matter yield $kg^{-1}$ P supply due to the influence of maize genotype. In the experiment, Xianyu1483, Xianyu1679 and Xianyu1111 showed the highest PUE (159.43–163.92 kg grain dry matter yield $kg^{-1}$ P supply) under -P conditions, whereas Xianyu1420, JiuyuY02 and L75X81F had the lowest PUE (85.44–90.21 kg grain dry matter yield $kg^{-1}$ P supply) (*Table 4*). Xianyu1679 and Xianyu1111 showed the highest PUE (87.29 –92.74 kg grain dry matter yield $kg^{-1}$ P supply) under +P conditions, whereas L75X81F, Dongdan507 and JiuyuY02 had the lowest PUE (39.02–43.27 kg grain dry matter yield $kg^{-1}$ P supply) (*Table 4*). In this experiment, PUE was significantly correlated with ($P < 0.01$; $R^2 = 0.78–0.87$) PUPE (*Fig. 3a*) and not to PUTE (*Fig. 3b*).

### *Correlations between traits under +P and -P conditions*

*Tables 5* and *6* show the correlations of traits under +P and -P conditions, respectively. In general, the correlations between the traits were consistent at both P levels. Grain dry matter yield was positively correlated ($P < 0.01$; r = 0.84–0.95) with total dry matter yield, grain P uptake and total P uptake. By contrast, at both P levels, Stover dry matter yield was positively correlated ($P < 0.01$; r = 0.71–0.83) with total dry matter yield. Total dry matter yield was significantly correlated with total P uptake and grain P uptake ($P < 0.01$; r = 0.77–0.93).

***Table 5.*** *Pearson correlations among traits measured in 22 maize genotypes under 120 kg P $ha^{-1}$ (+P)*

| | GDY | SDY | TDY | HI | GPC | SPC | GPU | SPU | TPU | PHI | PUTE | PUPE | PUE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GDY | 1 | 0.31* | 0.89** | 0.71** | 0.05 | -0.41** | 0.95** | -0.14 | 0.93** | 0.77** | 0.42** | 0.92** | 1.00** |
| SDY | | 1 | 0.71** | -0.45** | 0.38** | -0.36** | 0.41** | 0.49** | 0.51** | -0.04 | -0.43** | 0.52** | 0.31* |
| TDY | | | 1 | 0.31* | 0.22 | -0.48** | 0.90** | 0.14 | 0.93** | 0.55** | 0.11 | 0.93** | 0.89** |
| HI | | | | 1 | -0.24 | -0.14 | 0.59** | -0.52** | 0.49** | 0.78** | 0.72** | 0.48** | 0.71** |
| GPC | | | | | 1 | -0.30* | 0.30* | 0.01 | 0.31* | 0.15 | -0.57** | 0.31* | 0.05 |
| SPC | | | | | | 1 | -0.48** | 0.61** | -0.36** | -0.66** | -0.25* | -0.36** | -0.41** |
| GPU | | | | | | | 1 | -0.13 | 0.98** | 0.79** | 0.16 | 0.98** | 0.95** |
| SPU | | | | | | | | 1 | 0.07 | -0.67** | -0.56** | 0.07 | -0.14 |
| TPU | | | | | | | | | 1 | 0.66** | 0.05 | 1.00** | 0.93** |
| PHI | | | | | | | | | | 1 | 0.49** | 0.66** | 0.77** |
| PUTE | | | | | | | | | | | 1 | 0.05 | 0.42** |
| PUPE | | | | | | | | | | | | 1 | 0.92** |
| PUE | | | | | | | | | | | | | 1 |

*, ** and ns significant at $P < 0.05$, $P < 0.01$ and not significant, respectively. Traits and units are presented in *Table 1*


http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2102_13611374

***Table 6.*** *Pearson correlations among traits measured in 22 maize genotypes under 0 kg P ha$^{-1}$ (-P)*

| | GDY | SDY | TDY | HI | GPC | SPC | GPU | SPU | TPU | PHI | PUTE | PUPE | PUE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GDY | 1 | 0.41$^{**}$ | 0.84$^{**}$ | 0.54$^{**}$ | 0.06$^{ns}$ | 0.18$^{ns}$ | 0.89$^{**}$ | 0.41$^{**}$ | 0.88$^{**}$ | 0.36$^{**}$ | 0.09$^{ns}$ | 0.88$^{**}$ | 1.00$^{**}$ |
| SDY | | 1 | 0.83$^{**}$ | -0.55$^{**}$ | 0.01$^{ns}$ | 0.31$^{*}$ | 0.40$^{**}$ | 0.84$^{**}$ | 0.59$^{**}$ | -0.47$^{**}$ | -0.46$^{**}$ | 0.59$^{**}$ | 0.41$^{**}$ |
| TDY | | | 1 | 0.05ns | 0.04$^{ns}$ | 0.29$^{*}$ | 0.77$^{**}$ | 0.74$^{**}$ | 0.88$^{**}$ | -0.06$^{ns}$ | -0.22$^{ns}$ | 0.88$^{**}$ | 0.84$^{**}$ |
| HI | | | | 1 | 0.06$^{ns}$ | -0.12$^{ns}$ | 0.45$^{**}$ | -0.40$^{**}$ | 0.27$^{*}$ | 0.78$^{**}$ | 0.49$^{**}$ | 0.27$^{*}$ | 0.54$^{**}$ |
| GPC | | | | | 1 | 0.05$^{ns}$ | 0.47$^{**}$ | 0.01$^{ns}$ | 0.40$^{**}$ | 0.37$^{**}$ | -0.75$^{**}$ | 0.40$^{**}$ | 0.06$^{ns}$ |
| SPC | | | | | | 1 | 0.11$^{ns}$ | 0.77$^{**}$ | 0.32$^{**}$ | -0.58$^{**}$ | -0.36$^{**}$ | 0.32$^{**}$ | 0.18$^{ns}$ |
| GPU | | | | | | | 1 | 0.35$^{**}$ | 0.96$^{**}$ | 0.49$^{**}$ | -0.28$^{*}$ | 0.96$^{**}$ | 0.89$^{**}$ |
| SPU | | | | | | | | 1 | 0.60$^{**}$ | -0.63$^{**}$ | -0.48$^{**}$ | 0.60$^{**}$ | 0.41$^{**}$ |
| TPU | | | | | | | | | 1 | 0.23$^{ns}$ | -0.38$^{**}$ | 1.00$^{**}$ | 0.88$^{**}$ |
| PHI | | | | | | | | | | 1 | 0.23$^{ns}$ | 0.23$^{ns}$ | 0.36$^{**}$ |
| PUTE | | | | | | | | | | | 1 | -0.38$^{**}$ | 0.09$^{ns}$ |
| PUPE | | | | | | | | | | | | 1 | 0.88$^{**}$ |
| PUE | | | | | | | | | | | | | 1 |

** and ns significant at $P < 0.01$ and not significant, respectively. Traits and units are presented in *Table 1*

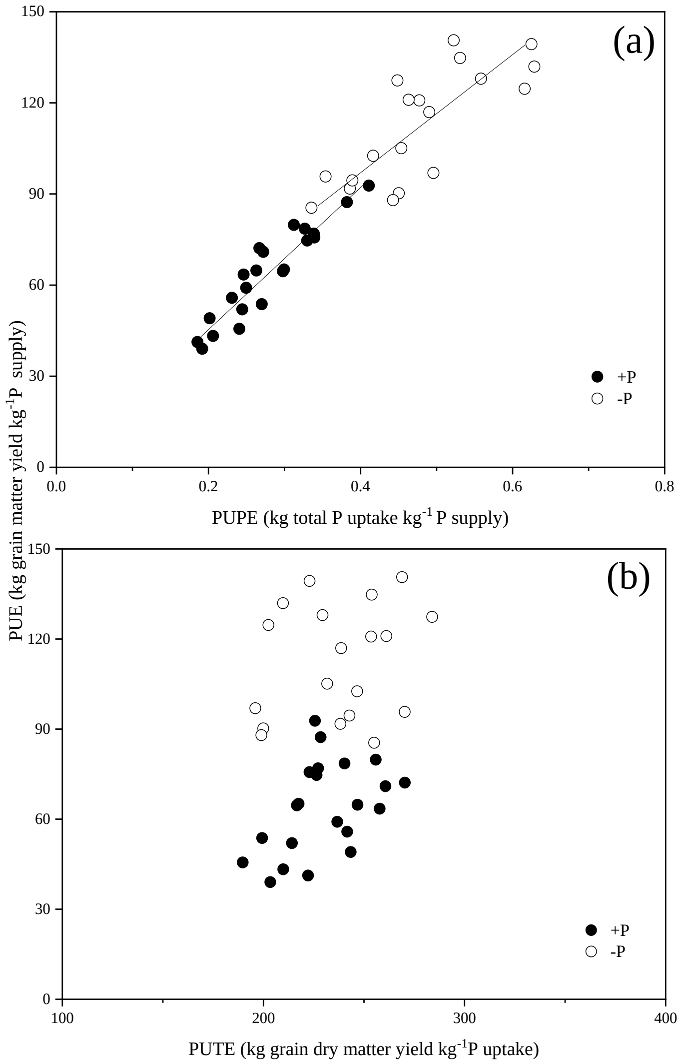


***Figure 3.*** *Relationship between PUE and PUPE (a) and between PUE and PUTE (b) in 22 maize genotypes under 0 (-P) (open symbols) and 120 kg P ha$^{-1}$ (+P) (closed symbols)*


http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2102_13611374

Grain P uptake was highly correlated ($P < 0.01$; r = 0.96–0.98) with total P uptake. PUTE was significantly negatively correlated ($P < 0.01$; r = -0.57–0.75) with grain P concentration (*Tables 5* and *6*). PUPE was positively correlated with grain dry matter yield, total dry matter yield, grain P uptake and total P uptake ($P < 0.01$; r = 0.88–1.00) under both P conditions (*Tables 5* and *6*).

### *Principal components analyses under -P and +P conditions*

At the -P levels (*Fig. 4*), principal Component (PC) 1 accounted for 50.9% of variance and was dominated by variables describing productivity (total dry matter yield and grain dry matter yield), P uptake (in grain and total), PUPE and PUE. PC2 accounted for 27.3% of the variance and was dominated by P harvest index, harvest index and to a lesser extent to PUTE. The acute angle between the load vectors indicated that PUE was strongly and positively correlated with total dry matter yield and grain dry matter yield, P uptake (in grain and total) and PUPE (*Fig. 4a*). Conversely, the harvest index was positively correlated with the P harvest index and these traits moderately correlated with PUTE. The PUTE was negatively correlated with stover P uptake, Stover P concentration and stover dry matter yield. Similar to -P levels, PC1 and PC2 with +P levels (*Fig. 4b*) accounted for 56.4 and 23.3% of the variance, respectively. PC1 was dominated by variables describing productivity, P uptake, PUPE and PUE, whereas PC2 was dominated by stover dry matter yield, stover P uptake and grain P concentration. PUE was significantly correlated with grain dry matter yield, total dry matter yield, grain P uptake, total P uptake and PUPE, while harvest index, P harvest index and PUTE were negatively correlated with stover P uptake and stover P concentration. In both P conditions, genotypes in quadrant I (such as Xianyu1111 and Xianyu1679) were characterized by high productivity, P uptake, harvest index, P harvest index, PUPE and PUE. Conversely, genotypes in quadrant II and III were characterized by lower values in productivity, P uptake, PUPE and PUE (such as L75X81F and JiuyuY02) (*Fig. 4a, b*).

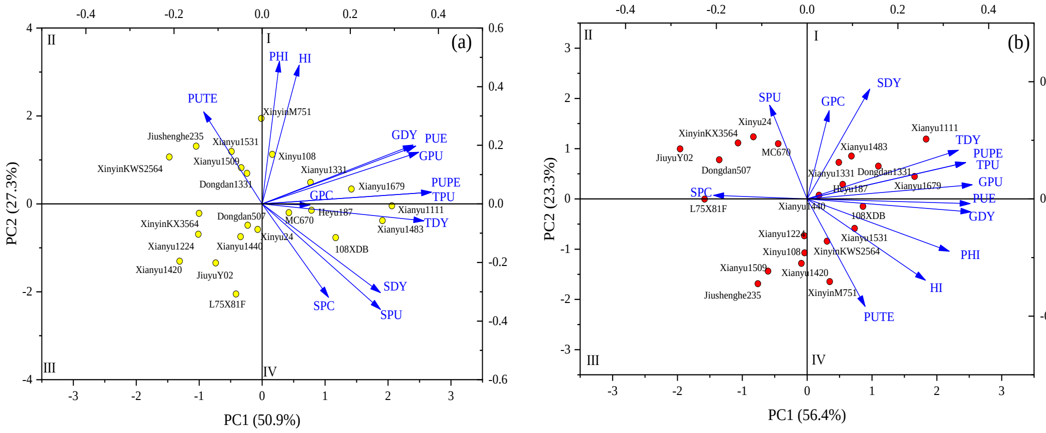


***Figure 4.*** *Principal components analysis for 22 maize genotypes under 0 (−P) (a) and 120 kg P ha$^{-1}$ (+P)(b)*

## Discussion

In recent years, there has been much interest in research to exploit the potential for PUPE and PUTE and thus improve the PUE of maize. Selection and breeding of low


http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2102_13611374

phosphorus tolerant and phosphorus efficient varieties is one of the effective ways to solve the low PUE of crops. Our study shows that PUE, PUPE, PUTE and related traits have significant genotypic differences at different phosphorus levels, and similar results are found in many crops (Yang et al., 2022; Iqbal et al., 2019; Reddy et al., 2021). This study showed that PUPE was more significant than PUTE in determining grain dry matter yield and PUE of maize under drip irrigation conditions. Similarly, Genotypic variation in PUPE usually seems to be higher than in PUTE under -P conditions and +P conditions (Spolaor et al., 2018). However, it has been shown that under -P conditions and +P conditions, PUTE explained most of the genetic variation in PUE (Yang et al., 2022).

In this study, there were significant differences in PUPE among maize genotypes. PUPE was positively correlated with grain dry matter yield, total dry matter yield, grain P uptake and total P uptake. Therefore, one way to increase PUPE in the presence of phosphorus deficiency is to increase total dry matter production. However, significant differences in total phosphorus uptake in the presence of similar total dry matter suggested significant genotypic differences in PUPE. Under low P conditions, maize genotypes with larger PUPE (such as Xianyu1111 and Xianyu1679) require lower soil P thresholds for fertilizer response compared to cultivars with low PUPE (such as Xianyu1420 and XinyinKWS2564). These genotypes increase the efficient use of phosphate fertilizers, reduce environmental problems of erosion, runoff and leaching into water bodies due to excessive phosphate fertilizer application, and significantly increase crop productivity in cropping systems (Gadaleta et al., 2022; Cong et al., 2020; Emami et al., 2018). Improving the ability of crops to capture phosphorus involves multiple mechanisms. In our study, root traits were not evaluated. Enhanced research on root characteristics (morphology and physiology) affecting PUPE will be important for the selection of phosphorus-efficient cultivars as well as for improving PUE. Therefore, further studies on PUPE and related root traits will be necessary.

PUTE is higher in the presence of phosphorus deficiency; therefore, phosphorus deficiency increases the utilization of phosphorus (Yang et al., 2022). An increase in PUTE under phosphorus deficiency conditions has been observed in many crops (Nguyen and Stangoulis, 2019; Reddy et al., 2021). About the secondary correlated traits, increasing the P harvest index and harvest index, or decreasing the phosphorus concentration of the plant can increase the PUTE (Lizana et al., 2021). In this study, the negative correlation between grain P concentration and PUTE at both phosphorus levels suggests that selecting maize genotypes with lower grain phosphorus concentrations may be a way to obtain cultivars with increased PUTE. Furthermore, since grain phosphorus concentration is not correlated with grain dry matter yield and is highly heritable, varieties with low phosphorus concentration can be selected without affecting yield. Thus, although the PUTE contribution to PUE is less important, selecting maize genotypes that reduce phosphorus concentrations in grains and remove small amounts of phosphorus from the soil can promote sustainable land use by reducing soil phosphorus extraction by maize production systems. Concerns have been raised that lower seed total P concentration may negatively affect seedling growth, but these concerns are not supported by recent studies showing that seedling growth of rice is unaffected by seed total P concentration (Julia et al., 2018).

The present study showed that some genotypes from Xianyu1679 and Xianyu1111 were among the best maize genotypes in terms of PUE under P deficiency and sufficient supply. These maize cultivars provide a rich resource for breeding objectives to improve


http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2102_13611374

PUPE and PUE. On the other hand, JiuyuY02 and L75X81F were identified as inefficient cultivars in the use of P for grain dry matter production, grain yield and response to P application. All this information will also be useful in assisting the P fertilization management, as this would allow phosphorus-sensitive genotypes to use lower fertilizer application rates to obtain higher yields.

## Conclusions

This study showed that there were genotypic differences in PUPE, PUTE, PUE and related traits among different maize genotypes under low and high P supply under drip irrigation conditions in the field. Consistent with previous findings in many crops, the differences in PUE were mainly attributed to PUPE rather than PUTE. Moreover, PUPE was significantly associated mainly with dry matter yield and P uptake. PUTE was highly negatively correlated with P concentration in grains. Therefore, a comparative study of different maize genotypes under different P supply can provide germplasm resources and a theoretical basis for the selection and breeding of phosphorus-efficient maize varieties and the improvement of PUE. This study showed that Xiananyu1679 and Xiananyu1111 were among the best maize genotypes in terms of PUE under both low and high P supply. In addition, this information is useful for the management of phosphorus in the field, aiming to adjust fertilizer application for different maize genotypes in response to low and high phosphorus to improve phosphorus use efficiency.

**Acknowledgements.** The research work was financially supported by the National Natural Science Foundation of China (32160747), the Special Incubation Project of Science & Technology Renovation of Xinjiang Academy of Agricultural Sciences (xjkcpy-2022001), the Project of Fund for Stable Support to Agricultural Sci-Tech Renovatio (xjnkywdzc-2022002), and the Key Laboratory of Crop Ecophysiology and Farming System in Desert Oasis Region, Ministry of Agriculture and Rural Affairs, China (25107020-201904).

**Conflict of interests.** Authors stated no conflict of interests.

## REFERENCES

[1] Adem, G. D., Ueda, Y., Hayes, P. E., Wissuwa, M. (2020): Genetic and physiological traits for internal phosphorus utilization efficiency in rice. – PLoS One 15(11): e0241842.
[2] Cong, W. F., Suriyagoda, L. D., Lambers, H. (2020): Tightening the phosphorus cycle through phosphorus-efficient crop genotypes. – Trends in Plant Science 25(10): 967-975.
[3] Emami, S., Alikhani, H. A., Pourbabaei, A. A., Etesami, H., Motashare Zadeh, B., Sarmadian, F. (2018): Improved growth and nutrient acquisition of wheat genotypes in phosphorus deficient soils by plant growth-promoting rhizospheric and endophytic bacteria. – Soil Science and Plant Nutrition 64(6): 719-727.
[4] Emami, S., Alikhani, H. A., Pourbabaee, A. A., Etesami, H., Motasharezadeh, B., Sarmadian, F. (2020): Consortium of endophyte and rhizosphere phosphate solubilizing bacteria improves phosphorous use efficiency in wheat cultivars in phosphorus deficient soils. – Rhizosphere 14: 100196.
[5] Gadaleta, A., Lacolla, G., Giove, S. L., Fortunato, S., Nigro, D., Mastro, M. A., Corato, U. D., Caranfa, D., Cucci, G., de Pinto, C. M., Vita, F. (2022): Durum Wheat Response to Organic and Mineral Fertilization with Application of Different Levels and Types of Phosphorus-Based Fertilizers. – Agronomy 12(8): 1861.


http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2102_13611374

[6] Hari-Gowthem, G., Kaur, S., Sekhon, B. S., Sharma, P., Chhuneja, P. (2019): Genetic variation for phosphorus-use efficiency in diverse wheat germplasm. – Journal of Crop Improvement 33(4): 536-550.

[7] Iqbal, A., Gui, H., Zhang, H., Wang, X., Pang, N., Dong, Q., Song, M. (2019): Genotypic variation in cotton genotypes for phosphorus-use efficiency. – Agronomy 9(11): 689.

[8] Johan, P. D., Ahmed, O. H., Omar, L., Hasbullah, N. A. (2021): Phosphorus transformation in soils following co-application of charcoal and wood ash. – Agronomy 11(10): 2010.

[9] Julia, C. C., Rose, T. J., Pariasca-Tanaka, J., Jeong, K., Matsuda, T., Wissuwa, M. (2018): Phosphorus uptake commences at the earliest stages of seedling development in rice. – Journal of Experimental Botany 69(21): 5233-5240.

[10] Kadirimangalam, S. R., Jadhav, Y., Nagamadhuri, K. V., Putta, L., Murugesan, T., Variath, M. T., Pasupuleti, J. (2022): Genetic approaches for assessment of phosphorus use efficiency in groundnut (Arachis hypogaea L.). – Scientific Reports 12(1): 1-13.

[11] Lizana, X. C., Sandaña, P., Behn, A., Ávila-Valdés, A., Ramírez, D. A., Soratto, R. P., Campos, H. (2021): Potato. – In: Sadras, V., Calderini, D. (eds.) Crop Physiology Case Histories for Major Crops. Academic Press, New York.

[12] Malhotra, H., Sharma, S., Pandey, R. (2018): Phosphorus Nutrition: Plant Growth in Response to Deficiency and Excess. – In: Hasanuzzaman, M. et al. (eds.) Plant Nutrients and Abiotic Stress Tolerance. Springer, Singapore.

[13] Nguyen, V. L., Stangoulis, J. (2019): Variation in root system architecture and morphology of two wheat genotypes is a predictor of their tolerance to phosphorus deficiency. – Acta Physiologiae Plantarum 41(7): 1-13.

[14] Pradel, M., Aissani, L. (2019): Environmental impacts of phosphorus recovery from a "product" Life Cycle Assessment perspective: allocating burdens of wastewater treatment in the production of sludge-based phosphate fertilizers. – Science of the Total Environment 656: 55-69.

[15] Reddy, V. R. P., Dikshit, H. K., Mishra, G. P., Aski, M., Singh, A., Bansal, R., Pandey, R., Nair, R. M. (2021): Comparison of different selection traits for identification of phosphorus use efficient lines in mungbean. – PeerJ 9: e12156.

[16] Sandaña, P. (2016): Phosphorus uptake and utilization efficiency in response to potato genotype and phosphorus availability. – Eur J Agron 76: 95-106.

[17] Spolaor, L. T., Guirado, G. C., Scapim, C. A., Kuki, M. C., Bertagna, F. A. B., Ferreira, J. M., Zucareli, C., Gonçalves, L. S. A. (2018): Brazilian maize landraces variability under high and low phosphorus inputs. – Maydica 63(1): 8.

[18] Valle, S. R., Pinochet, D., Calderini, D. F. (2011): Uptake and use efficiency of N P, K, Ca and Al by Al-sensitive and Al-tolerant cultivars of wheat under a wide range of soil Al concentrations. – Field Crops Res 121: 392-400.

[19] Wang, F., Cui, P. J., Tian, Y., Huang, Y., Wang, H. F., Liu, F., Chen, Y. F. (2020): Maize ZmPT7 regulates Pi uptake and redistribution which is modulated by phosphorylation. – Plant Biotechnol J 18: 2406-2419.

[20] Weeks Jr, J. J., Hettiarachchi, G. M. (2019): A review of the latest in phosphorus fertilizer technology: possibilities and pragmatism. – Journal of Environmental Quality 48(5): 1300-1313.

[21] Weiß, T. M., Li, D., Roller, S., Liu, W., Hahn, V., Leiser, W. L., Würschum, T. (2022): How can we breed for phosphate efficiency in maize (Zea mays)? – Plant Breeding 141(6): 733-744.

[22] Yan, X., Chen, X., Ma, C. (2021): What are the key factors affecting maize yield response to and agronomic efficiency of phosphorus fertilizer in China? – Field Crops Res 270: 108221.

[23] Yang, F., Sui, L., Tang, C., Li, J., Cheng, K., Xue, Q. (2021): Sustainable advances on phosphorus utilization in soil via addition of biochar and humic substances. – Science of the Total Environment 768: 145106.

[24] Yang, H., Chen, R., Chen, Y., Li, H., Wei, T., Xie, W., Fan, G. (2022): Agronomic and physiological traits associated with genetic improvement of phosphorus use efficiency of wheat grown in a purple lithomorphic soil. – The Crop Journal 10: 1151-1164.
[25] Zak, D., Kronvang, B., Carstensen, M. V., Hoffmann, C. C., Kjeldgaard, A., Larsen, S. E., Audet, J., Egemose, S., Jørgensen, C. A., Feuerbach, P., Gertz, F., Jensen, H. (2018): Nitrogen and phosphorus removal from agricultural runoff in integrated buffer zones. – Environ Sci Technol 52: 6508-6517.


http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2102_13611374