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# Organo-Mineral Fertilization Based on Olive Waste Sludge Compost and Various Phosphate Sources Improves Phosphorus Agronomic Efficiency, *Zea mays* Agro-Physiological Traits, and Water Availability

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**Abstract:** In the context of intensive and sustainable agriculture, limiting soil degradation and the loss of organic matter has become an obligation to maintain food security. The use of organo-mineral fertilizer (OMF) products is an innovative technology that may solve the different challenges raised. This study aimed to evaluate the effect of various organo-mineral fertilizer (OMF) formulations on *Zea mays* agro-physiological traits, phosphorus (P)-related parameters, and water conservation during a 90-day pot experiment. The OMF formulations consisted of blending several doses of a stable OMWS compost (10 t /ha(OMF1), 50 t/ha (OMF2), or 100 t/ha (OMF3)) with different sources of mineral P, namely diammonium phosphate (DAP), rock phosphate (RP), or phosphate washing sludge (PWS), compared with separate applications. The results indicated that the effect of an OMF on the soil and plants was strongly dependent on the source of P used and the dose of OMWS compost. The best agronomic performance was attributed to OMF1-based DAP, which resulted in a significant improvement in the shoot and root biomass dry weight by more than 260% and 40%, respectively. However, using an OMF2 formulation was more optimal when using RP and PWS as mineral P sources. Independently of the type of P fertilizer, the addition of stable OM systematically improved multiple soil properties, including water availability, and the nutrient concentrations, such as the available P, exchangeable potassium, and magnesium. Furthermore, the plant's respiration, photosynthetic activity, and nutrient assimilations were positively affected by the OMF formulations. Overall, our results demonstrate that organo-mineral fertilization is a promising solution for increasing the efficiency of low-P and high-P mineral fertilizers in alkaline soils through direct and indirect mechanisms involving improved soil properties and higher P solubilization.

**Keywords:** olive mill waste sludge; *Zea mays*; phosphorus use efficiency; compost; organo-mineral fertilizer; soil fertility; plant growth

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## 1. Introduction

Fulfilling the nutritional needs of the exponentially growing world population, which is estimated to reach 9.5 billion by 2050, will require an increase in agricultural productivity by almost 70%. Hence, there is an obligation to set up models of intensive agriculture to increase crop yields [1]. Nonetheless, those systems have some critical drawbacks related to sustainable fertility management. Actually, in the current eco-environmental context, the deterioration of soil fertility is one of the most pressing issues facing agricultural productivity, primarily due to the loss of soil organic matter (SOM). This latter issue plays a paramount role in the sustainability of critical functionalities of agroecosystems by directly influencing physical, chemical, and biological characteristics [2].

Maize is one of the most important crops for both humans and animals. This plant is cultivated on 197.204.250 hectares throughout the world, a 5.823 kg ha$^{-1}$ average yield is obtained, and the total production value is 1.2 billion tonnes. The production in the Americas and the Oceania region shows yields of around 8 tonnes per hectare (t/ha), followed by 6.3, 5.7, and 2.1 t/ha for Europe, Asia, and Africa; the large fluctuations observed are due to the water availability and seasonal conditions [3].

Due to poor SOM content, maintaining higher maize yields currently requires increasing the consumption of mineral fertilizers, especially phosphorus (P) and nitrogen (N) [4]. SOM depletion is one of the critical indicators of soil degradation, if not the sole palpable and quantifiable indicator, as it is linked to most soil parameters, including the soil's structural stability, fertility, and overall biological functions [5].

Moreover, in the context of global warming, soil degradation associated with the loss of SOM is a phenomenon that should become further conspicuous. Fertilizer use efficiency (FUE) has already reached a plateau, and further increasing the rate of P and N inputs is unlikely to induce higher yields [6]. Additionally, the FUE is directly linked to SOM depletion; long-term fertilization experiments in upland soils have shown a significant yield decline as a consequence of SOM reduction, concomitant with soil nutrient deficiencies [7], in a 40-year field experiment involving a soybean–maize rotation [8]. Nevertheless, interactions of SOM and major plant nutrients remain scarcely investigated, especially with regards to the P dynamic, despite this element's key importance. Indeed, P plays a substantial role in crop productivity and plant development, and various vital physiological functions are P-dependent, including the transfer and storage of energy, photosynthesis, cell division, and seed formation [9]. P represents approximately 0.2% of the total plant dry weight and 0.05% (*w*/*w*) of the soil content, of which only a scant fraction is bioavailable for plants [10]. Commonly, growers resort to applying P fertilizers in excess to make up for P loss by complexation and leaching, which remains a very short-term solution. Such practices are incompatible with the sustainable agriculture concept (based on rational fertilization) and could lead to the disruption of the soil's nutritional balance and serious environmental damage [11].

OMWS, a byproduct of olive oil extraction, is a substrate that is rich in macro- and micronutrients; hence, it may be plausible to use it as a potent organic fertilizer. OMWS recovered from evaporation ponds often shows significant K, Ca, Mg, Fe, and Zn content [12]. The use of OMWS compost results in an improvement in soil fertility by significantly increasing the cation exchange capacity, soil organic carbon, and organic nitrogen compared to those of unamended soil, without any noticeable phytotoxic effects. This change was reflected by improvements in the yields of harvested potato and *Zea mays* (Spunta and MACHA variety), which increased by 9.4% and 58.5%, respectively, compared to that of crops grown in unamended soil without chemical fertilizers [13,14].

OMF products show a high nutrient retention capacity with the significant maintenance of nutrient availability to roots, which can be attributed in part to the high carbon content of the negatively charged functional groups on its surface, including carboxylic acids, hydroxyl groups, and small alkyl chains such as methane groups and phenols, that combine with protons in the soil [13,15]. In addition, OMFs not only improve the soil fertility, but are also associated with a significant improvement to biomass and physiological parameters, including the yield of many crops such as cucumber, maize, and tomato with increases of 53.49, 300, and 340%, respectively, depending on the quality of OM used in the OMF formulations [16–18].

This is a serious dilemma, since the challenge is to develop solutions for optimizing the P bioavailability while bearing in mind the foundation of sustainability and knowing that productivity needs to increase substantially. Consequently, the most logical and rational approaches should focus on developing synergism between mineral and biological resources. In this context, the organo-mineral fertilizer (OMF) approach could be a very efficient option for sustainable soil fertility management, allowing both an equilibrium in soil organic reserves and better yields compared to single applications of both resources.

OMFs are mainly based on formulations that combine mineral fertilizers and various organic amendments [19–21].

OMFs highlight a reactive chemical potential that is way below that of a mineral fertilizer. Nutrient solubilization is slower and follows a gradual dynamic along the period of plant development; consequently, the agronomic efficiency could be much higher. Combining organic matter such as cocoa pods or cow dung with NPK mineral fertilizers into OMF products significantly improves the agro-physiological parameters of maize and increases the nutrient availability and SOM for several years [22,23].

Moreover, OMF products positively affect the dynamics of P fixation and the release of other essential nutrients, which become available for plants for a longer time [24]. There is a close relationship between soil organic matter (type and content) and phosphorus dynamics. A higher OM content is positively correlated with P availability, which may be attributed to direct mechanisms where P adsorption is reduced and P desorption is improved [25], or indirect mechanisms involving phosphate-solubilizing microorganisms whose growth is favored in soil with a high OM content [10]. OMF products offer many advantages during agricultural field applications compared to a single application of mineral fertilizers, namely a better FUE, better soil aggregation, and improved soil biochemistry and microbial diversity [7,26–28]. However, there is a considerable lack of data regarding the effects of OMFs based on RP and by-products of the phosphate industry on maize yield improvement. In addition, the use of stable organic matrices plays a critical role in this OMF formulation. OMWS compost can improve plants' nutrient assimilation with many other commercial organic amendments, without having a negative impact on the soil–plant system [13]. However, to better assess and understand the effect of stable organic matrices on improving the efficiency of formulated products, further evaluations are needed. In particular, the dose impacts the plant and the soil; the solubilization of phosphorus until its assimilation by the plants remains the axis element of growth and has been critically evaluated.

The main objective of this study was to investigate how varying the rate of OM (OMWS compost) and P mineral sources (DAP, RP, and SWP) in OMF formulations may differentially affect soil fertility and plant growth under arid and semi-arid conditions. The impact of OMF on the nutrient status and the correction of organic matter deficiency was directly evaluated, with a focus on P use efficiency (PUE), soil water retention, and maize agro-physiological traits, including crop yields. We hypothesized that depending on the rate of OM, the P fertilizer use efficiency could be improved through direct and indirect mechanisms, including better P bio-solubilization and water use efficiency. The assayed formulations are highly aligned with the principles of sustainable agriculture, as they could plausibly address soil degradation issues concomitantly with the valorization of important agri-waste (OMWS) and by-products of the P fertilizer industry (low-grade RP and PWS).

## 2. Material and Methods

### 2.1. Sampling of Raw Materials and Compost Preparation

Compost was produced using olive mill wastewater sludge (OMWS) and green waste (GW). The OMWS was collected from the evaporation basins of a semi-modern olive oil extraction unit in Chichaoua city, Morocco, and the GW was collected from the Semlalia faculty, Marrakech garden. Composting consisted of mixing both organic matrices at an equivalent rate and was carried out for 4 months. In the first 22 days, the experiment was conducted under controlled conditions in a 100 L stainless steel bioreactor and humidity was maintained at 50–60%; then, the mixture was transferred into perforated bags where it settled for maturation. The physicochemical characteristics of the resulting compost were as follows: pH = 7.9, EC (mS/cm) = 5.58, C/N = 12, exchangeable phosphorus = 0.4%, exchangeable potassium = 22.4 mg/g, $Ca^{2+}$ = 19.6 mg/g, and exchangeable $Mg^{2+}$ = 5.1 mg/kg.

### 2.2. Plant Material and Experimental Design

The agronomic trial was conducted between May and July 2020 (90 days), under greenhouse conditions at the experimental farm of Mohammed VI Polytechnic University

(UM6P) Ben Guerir, Morocco (31.6295° N, 7.9811° W). Before seed sowing, the initial effect of each OMF formulation on the physicochemical properties of plantless soil was determined (Table 1). The OMF formulations consisted of mixing finely ground DAP, RP, and PWS with 3 rates of compost (10, 50, and 100 t/ha, corresponding to OMF1, OMF2, and OMF3, respectively), and they were compared to single applications for a total number of 20 treatments. The experience was carried out in 4 kg pots (one plant per pot) and was arranged according to a completely randomized block design, with five replicates and sixteen treatments. Pots amended solely with compost or P mineral fertilizers were used as control treatments. The rate of P fertilizers was determined following recommendations for optimal maize growth ($P_2O_5$ 120 kg/ha) while considering the available P (AP) content of both the soil and compost. Moreover, all treatments received N fertilizer (180 kg/ha) through equally applying urea before sowing and at the six-leaf stage. Following the incubation period, pregerminated maize seeds (MACHA-certified variety) were transferred to pots (1 seedling per pot). The pots were checked daily for pest control and nutrient deficiency symptoms and watered solely with distilled water to maintain a moisture level of 60%.

**Table 1.** Physicochemical properties of the used soil.

| Parameters | pH | EC (ms/cm) | TOC (%) (mg kg$^{-1}$) | TKN (%) (mg kg$^{-1}$) | Total $P_2O_5$ (mg kg$^{-1}$) | Total $K_2O$ (mg kg$^{-1}$) | Total CaO g/kg | Total MgO (mg kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Average | 8.2 | 0.38 | 0.7 | 0.87 | 50.3 | 325.7 | 12.1 | 646.0 |

Results are expressed per unit dry matter weight; EC: electrical conductivity; TOC: total organic carbon; TKN: total Kjeldahl nitrogen.

### 2.3. Soil Chemical Analysis

The soil was analyzed just before sowing (15 days) and at the end of the experiment (90 days). Briefly, soil samples were air-dried and passed through a 2 mm sieve before the chemical measurements. The soil pH and EC (electrical conductivity) were determined in a 1:2.5 soil–water mixture. The total organic carbon (%TOC) was evaluated by following the Walkley–Black method, which is based on organic matter oxidation by potassium dichromate [29]. The total Kjeldahl nitrogen (TKN) was assayed using the Kjeldahl procedure according to the AFNOR T90-1110 standard. The AP was colorimetrically estimated with the ammonium molybdate method, following an extraction at a pH of 8.5 with sodium bicarbonate [30]. The exchangeable cations ($K^{2+}$, $Ca^{2+}$, and $Mg^{2+}$) were evaluated according to the NF X 31-108 standard. Briefly, the cations were extracted with ammonium acetate (1:20 (m/v)) at a pH of 7, and the values were determined using flame spectrometry. Additionally, other micronutrients (Mn, Cu, Zn, and Fe) were determined using inductively coupled plasma mass spectrometry after digestion in a nitric acid/hydrofluoric acid mixture [31]. All soil measurements were made in three replicates.

The soil water retention was directly determined by the regular weighing of each pot before irrigation and after the pots dried out by following Equation (1). [32]

$$\text{Soil water retention } (\%) = \left(\frac{(WC_{AI} - WC_{BI})}{WC_{BI}}\right) \quad (1)$$

where $WC_{AI}$: water content after irrigation and $WC_{BI}$: water content before irrigation.

### 2.4. Plant Biomass and Agro-Physiological Traits

In the greenhouse experiment, the plant biomass was determined by cutting the cane to a 4 cm height with scissors. The harvested material was weighed and sampled to determine the dry weight (72 h at 70 °C). The roots were sampled after the final harvest and soil sampling. Each sample was then oven-dried (72 h at 70 °C) to determine the dry weight and calculate the root biomass in five replicates.

The plant chlorophyll fluorescence was determined in quintuplicate using a portable modulated fluorometer (OS30P+, Opti-Science Instrument, USA). The fluorescence parameters were measured at mid-day (3500 µmol $m^{-2}$ $s^{-1}$). A pulse-modulated test was used to measure the fluorescence levels; (F0) was the minimal value measured at <0.05 µmol $m^{-2}$ $s^{-1}$ for approximately 1.8 µs. The variable fluorescence of the photosystem (Fv) and the maximal fluorescence value (Fm) ratio was measured after applying saturated red-light actinic illumination of 6000 µmol $m^{-2}$ $s^{-1}$ for 0.7 s. Under similar operating conditions, the same leaf's fluorescence equilibrium state (Fe) was recorded after exposure of the plant to ambient light conditions for 40 min. This measurement was made over five replicates to calculate the maximal quantum efficiency (MQF) using the following equation [33]:

$$\text{MQF} = \text{Fv}/\text{Fm} = (\text{Fm} - \text{F0})/\text{Fm}$$

The membrane stability index (MSI %) was determined using duplicate 0.2 g samples of fully expanded leaf tissue in five replicates of each treatment. Each leaf sample was placed in a test tube containing 10 mL of double distilled water. The contents of the test tube were heated at 40 °C in a water bath for 30 min, and the electrical conductivity (C1) of the solution was recorded using a conductivity bridge. A second sample was boiled at 100 °C for 10 min, and the conductivity was measured (C2) [34]. The MSI was calculated using Formula (1):

$$\text{MSI}\ (\%) = \left(\frac{(\text{C1})}{(\text{C2})}\right) \times 100 \tag{2}$$

The relative water content (RWC %) was estimated based on 2 cm-diameter fully expanded leaf discs over five replicates. The disc fresh mass (FM) was weighed and immediately submerged in double distilled water in Petri dishes for 24 h in the dark to saturate the plant cells with water. The turgid mass (TM) was measured, and any adhering water was blotted dry. The dry mass (DM) was recorded after the discs were dehydrated at 70 °C for 48 h with 5 replications for each treatment [35]. The RWC was then calculated using the following Formula (2):

$$\text{RWC}\ (\%) = \left(\frac{(\text{FM} - \text{DM})}{(\text{TM} - \text{DM})}\right) \tag{3}$$

### *2.5. Yields, Harvest Index (HI), and Water Use Efficiency (WUE)*

Five replicates of each plant's treatment were used to measure the average yield number per plant and the corresponding yield number per hectare on a dry mass basis. Equation (3) was used [16]:

$$\text{WUE} = \left(\frac{\text{Yield (Kg ha} - 1)}{\text{Water applied (m3ha} - 1)}\right) \tag{4}$$

### *2.6. Plant Nutrient Analysis*

The plant's nutrient content was analyzed over three replicates by using finely ground and dried shoot samples. The P concentration was evaluated spectrophotometrically using the phosphovanado-molybdate method, and the N concentration was determined by using the Kjeldahl procedure after digestion with $H_2SO_4/H_2O_2$ [36]. Moreover, shoot samples were digested with 70% $HNO_3$ and 70% $HClO_4$, and the concentrations of copper (Cu), zinc (Zn), manganese (Mn), boron (B,) and iron (Fe) were determined using ICP-OES (Agilent 5110, Santa Clara, CA, USA).

### *2.7. Phosphorus Use Efficiency-Related Parameters*

There are many methods to evaluate the PUE, as the relationship between P and plant traits can be expressed in several manners. To calculate the PUE, we used 2 indicators to determine 1. the impact of the applied P on the biomass yield [37], defined as the P agronomic efficiency, and 2. an evaluation of the P solubilization rate (PSR) by using a proposed second indicator, which determines the impact of the treatment and the rooting system on the P bioavailability. For each parameter, the following formulas were used:

$$\text{P agronomic efficiency (PAE)} = \frac{\text{SDW} - \text{SDW0}}{\text{P(app)}} \quad (5)$$

$$\text{P solubilization rate (PSR\%)} = \frac{\text{SAP} - \text{SAP0}}{\text{SAP0}} \times 100 \quad (6)$$

where SDW: shoot dry weight of the OMF treatment, SDW0: shoot dry weight of the control, P (app): total applied P, SAP: soil-available P in the OMF treatment, and SAP0: soil-available P in the control.

### 2.8. Statistical Analysis

The results for the growth parameters (shoot and root dry weight, number of leaves, minerals, physicochemical properties, soil chemical parameters, and the nutrient content of plants) were the means of the replicates. Data were collected and analyzed by one-way ANOVA using SPWSS 20. Statistically significant differences between means were determined by Tukey's test at $p < 0.05$.

## 3. Results

### 3.1. Effect of OMF Application on Initial Soil Physicochemical Properties

The effect of the OMF application was evaluated after 2 weeks of incubation (before seed sowing). The results revealed that the OMF addition significantly affected the EC, OM, AP, exchangeable $K_2O$, and Mg (Table 2). Conversely, the pH, Ca, total Mn, and Fe values remained unchanged. The $OMF_1$, $OMF_2$, and $OMF_3$ applications initially increased the EC values by 0.3, 0.6, and 2.3 ms/cm. Similarly, the OM% increased by almost 0.23%, 1.1%, and 1.7%, respectively. Moreover, depending on the applied doses of compost, the AP was positively affected when RP and PWS were used, except for $OMF_0$ and $OMF_{1,}$ where the variation in AP was statistically significant only for OMF0-based DAP fertilizer with an increase of 20% compared to the control. Inversely, the OMF1 AP content decreased (not statically significant) compared with OMF0 by 14.5%, 6.15%, and 2.5% for DAP, RP, and PWS, respectively. On the other hand, the increase in the SOM was related directly to the soil AP content, as this latter factor increased in the OMF2 formulation by 68.98%, 39.76, and 62.42% and in the OMF3 formulation by 95.4%, 59.6%, and 76.87% for DAP, RP, and PWS, respectively, compared to the control. The concentration of exchangeable potassium, AK, and Mg increased significantly to 22%, 73.48%, and 156% and to 12.25%, 18%, and 28% for the OMF1, OMF2, and OMF3 product-based DAP, RP, and PWS. However, the total Mn and Fe variations were not affected in any treatments.

### 3.2. Effect of OMF Application on Soil Physicochemical Properties Post-Harvesting

The AP decreased significantly in all the applied treatments after plant harvesting. On the other hand, the only application of DAP increased the AP content by 34% compared with the applications of RP and PWS for both products, and by 16% compared with OMF 1 (dose of 10 t/ha) (Table 3). In addition, the OMF1-based RP and PWS increased the AP by more than 66% and 39% for OMF2 and OMF3, respectively, compared to the controls. Similarly, the OMF-formulated products showed an increase in AP after harvesting of up to 39% and 81% for OMF1 and OMF2, respectively, compared to the unamended control. However, these values decreased by 24% for the OMF3 formulation. Regarding the potassium availability, the use of OMF2 and OMF3 product-based DAP, RP, and PWS maintained a high value of more than 60% and 200%, respectively, compared with the only applications of mineral fertilizer soil (OMF0).

**Table 2.** Physicochemical properties of the plantless soil after 2 weeks of OMF applications.

| Treatment | EC (ms/m) | OM (%) | Available Phosphorus (mg kg$^{-1}$) | Exch $K_2O$ (mg kg$^{-1}$) | Exch MgO (mg/kg) |
|---|---|---|---|---|---|
| Control | 0.39 ± 0.1 $^{ab}$ | 1.2 ± 0.06 $^{a}$ | 50.3 ± 1.5 $^{abc}$ | 325.67 ± 59.04 $^{a}$ | 646.0 ± 18.6 $^{a}$ |
| $OMF_0$ + DAP | 0.39 ± 0.19 $^{ab}$ | 1.21 ± 0.1 $^{a}$ | 60.3 ± 15.9 $^{abcde}$ | 345.0 ± 8.54 $^{ab}$ | 650.7 ± 23.7 $^{a}$ |
| $OMF_0$ + RP | 0.3 ± 0.06 $^{a}$ | 1.16 ± 0.01 $^{a}$ | 49.0 ± 3.6 $^{abc}$ | 285.3 ± 11.0 $^{a}$ | 668.7 ± 16.2 $^{ab}$ |
| $OMF_0$ + PWS | 0.3 ± 0.03 $^{a}$ | 1.18 ± 0.06 $^{a}$ | 52.0 ± 5.3 $^{abc}$ | 300.6 ± 19.3 $^{a}$ | 649.7 ± 2.2 $^{a}$ |
| $OMF_1$ | 0.69 ± 0.1 $^{abc}$ | 1.43 ± 0.08 $^{a}$ | 43.0 ± 1.73 $^{a}$ | 366.0 ± 39.8 $^{abc}$ | 733.0 ± 47.3 $^{abc}$ |
| $OMF_1$ + DAP | 0.77 ± 0.1 $^{abc}$ | 1.42 ± 0.04 $^{a}$ | 56.6 ± 6.6 $^{abcd}$ | 399.6 ± 23.6 $^{abcd}$ | 721.3 ± 94.4 $^{abc}$ |
| $OMF_1$ + RP | 0.74 ± 0.18 $^{abc}$ | 1.47 ± 0.1 $^{a}$ | 43.3 ± 5.13 $^{a}$ | 387.6 ± 34.9 $^{abcd}$ | 747.0 ± 54 $^{abc}$ |
| $OMF_1$ + PWS | 0.82 ± 0.19 $^{abc}$ | 1.37 ± 0.2 $^{a}$ | 47.6 ± 9.1 $^{ab}$ | 380.6 ± 23.6 $^{abcd}$ | 740.7 ± 34.4 $^{abc}$ |
| $OMF_2$ | 0.98 ± 0.18 $^{c}$ | 2.37 ± 0.03 $^{b}$ | 68.0 ± 12.1 $^{abcdef}$ | 572.0 ± 62.23 $^{d}$ | 794.3 ± 35.6 $^{abc}$ |
| $OMF_2$ + DAP | 0.98 ± 0.17 $^{c}$ | 2.39 ± 0.28 $^{b}$ | 85.0 ± 4.4 $^{efg}$ | 567.6 ± 30.6 $^{d}$ | 785.3 ± 94.4 $^{abc}$ |
| $OMF_2$ + RP | 0.91 ± 0.25 $^{bc}$ | 2.33 ± 0.07 $^{b}$ | 70.3 ± 9.07 $^{bcdef}$ | 523.0 ± 153.1 $^{bcd}$ | 737.0 ± 54 $^{abc}$ |
| $OMF_2$ + PWS | 0.9 ± 0.04 $^{bc}$ | 2.4 ± 0.04 $^{b}$ | 81.7 ± 10.2 $^{defg}$ | 548.7 ± 45.8 $^{cd}$ | 766.7 ± 34.4 $^{abc}$ |
| $OMF_3$ | 2.8 ± 0.26 $^{d}$ | 2.9 ± 0.08 $^{c}$ | 73.6 ±6.35 $^{cdefg}$ | 794.3 ± 88.79 $^{e}$ | 808.3± 54.4 $^{bc}$ |
| $OMF_3$ + DAP | 2.7 ± 0.24 $^{d}$ | 3.0 ± 0.17 $^{c}$ | 98.3 ± 6.66 $^{g}$ | 837.3 ± 11.01 $^{e}$ | 838.0± 42.6 $^{c}$ |
| $OMF_3$ + RP | 2.9 ± 0.26 $^{d}$ | 2.98 ± 0.01 $^{c}$ | 80.3 ± 11.6 $^{defg}$ | 813.3 ± 69.3 $^{e}$ | 867.0± 67.3 $^{c}$ |
| $OMF_3$ + PWS | 2.7 ± 0.1 $^{d}$ | 2.92 ± 0.06 $^{c}$ | 88.7 ± 8.6 $^{fg}$ | 795.3 ± 114.6 $^{e}$ | 831.0± 88.6 $^{c}$ |

OMF0 = 0 tonnes of compost, OMF1 = 10 t, OMF2 = 50 t, OMF3 = 100 t, PWS = phosphate sludge. Results are expressed per unit dry matter weight; EC: electrical conductivity; OM: organic matter; Exch: exchangeable; the values represent the means (± standard deviation) of three replicates. Data within the same column followed by different letters are significantly different according to Tukey's test at $p < 0.05$.

**Table 3.** Soil physicochemical properties after harvesting.

| Treatment | EC (ms/m) | OM (%) | Available Phosphorus (mg kg$^{-1}$) | Exch $K_2O$ (mg kg$^{-1}$) | Exch MgO (mg/kg) |
|---|---|---|---|---|---|
| Control | 0.86 ± 0.1 $^{ab}$ | 1.16 ± 0.03 $^{ab}$ | 28.6 ± 3.22 $^{abc}$ | 233.6 ± 28.53 $^{a}$ | 723.3 ± 89.7 $^{a}$ |
| $OMF_0$ + DAP | 0.87 ± 0.5 $^{ab}$ | 1.18 ± 0.1 $^{ab}$ | 38.0 ± 8.7 $^{abcde}$ | 239.3 ± 36.17 $^{a}$ | 769.0 ± 55.7 $^{ab}$ |
| $OMF_0$ + RP | 0.7 ± 0.1 $^{a}$ | 1.06 ± 0.05 $^{a}$ | 27.0 ± 3.5 $^{ab}$ | 267.3 ± 5.589 $^{a}$ | 770.0 ± 27.4 $^{ab}$ |
| $OMF_0$ + PWS | 0.92 ± 0.18 $^{ab}$ | 1.09 ± 0.06 $^{a}$ | 26.3 ± 3.06 $^{ab}$ | 273.3 ± 13.05 $^{a}$ | 965.6 ± 54.8 $^{cde}$ |
| $OMF_1$ | 0.98 ± 0.1 $^{ab}$ | 1.29 ± 0.07 $^{ab}$ | 35.6 ± 5.7 $^{abcde}$ | 283.6 ± 17.6 $^{a}$ | 927.0 ± 58.14 $^{bcd}$ |
| $OMF_1$ + DAP | 0.97 ± 0.3 $^{ab}$ | 1.22 ± 0.12 $^{ab}$ | 40.6 ± 13.01 $^{abcde}$ | 300.3 ± 40.51 $^{a}$ | 988.0 ± 82.2 $^{cde}$ |
| $OMF_1$ + RP | 1.4 ± 0.2 $^{abc}$ | 1.24 ± 0.3 $^{ab}$ | 24.3 ± 5.03 $^{a}$ | 286.6 ± 34.2 $^{a}$ | 907.3 ± 93.8 $^{abc}$ |
| $OMF_1$ + PWS | 1.12 ± 0.3 $^{abc}$ | 1.2 ± 0.13 $^{ab}$ | 32.6 ± 6.6 $^{abcd}$ | 332.3 ± 51 $^{ab}$ | 951.6 ± 42.8 $^{bcde}$ |
| $OMF_2$ | 1.04 ± 0.1 $^{ab}$ | 1.5 ± 0.04 $^{abc}$ | 41.0 ± 1.7 $^{abcde}$ | 455.0 ± 68.6 $^{bc}$ | 922 ± 38.4 $^{bcd}$ |
| $OMF_2$ + DAP | 1.13 ± 0.1 $^{abc}$ | 2.0 ± 0.28 $^{cde}$ | 65.0 ± 1.7 $^{fg}$ | 486.6 ± 65.8 $^{c}$ | 1007 ± 51.3 $^{cde}$ |
| $OMF_2$ + RP | 1.4 ± 0.1 $^{abc}$ | 1.81 ± 0.2 $^{bcd}$ | 40.6 ± 8.5 $^{abcde}$ | 479.3 ± 51.3 $^{bc}$ | 1088 ± 93.1 $^{cde}$ |
| $OMF_2$ + PWS | 1.5 ± 0.29 $^{bc}$ | 1.67 ± 0.5 $^{abc}$ | 50.0 ± 12.5 $^{def}$ | 503.3 ± 46.75 $^{c}$ | 1090 ± 86.6 $^{cde}$ |
| $OMF_3$ | 1.41 ± 0.2 $^{abc}$ | 2.37 ± 0.32 $^{de}$ | 45.6 ± 3.5 $^{bcdef}$ | 851.3 ± 71.14 $^{e}$ | 1107 ± 55.2 $^{de}$ |
| $OMF_3$ + DAP | 1.5 ± 0.4 $^{bc}$ | 2.5 ± 0.28 $^{e}$ | 76.0 ± 10.6 $^{g}$ | 842.6 ± 29.9 $^{e}$ | 1123 ± 55.2 $^{e}$ |
| $OMF_3$ + RP | 1.8 ± 0.04 $^{c}$ | 2.5 ± 0.13 $^{e}$ | 56.0 ± 5 $^{efg}$ | 874.0 ± 102.1 $^{e}$ | 1320 ± 27.19 $^{f}$ |
| $OMF_3$ + PWS | 1.6 ± 0.13 $^{bc}$ | 2.5 ± 0.26 $^{e}$ | 49.6 ± 5.03 $^{cdef}$ | 659.6 ± 21.1 $^{d}$ | 1012 ± 1 $^{cde}$ |

OMF0 = 0 tonnes of compost, OMF1 = 10 t, OMF2 = 50 t, OMF3 = 100 t, PWS = phosphate sludge. Results are expressed per unit dry matter weight; EC: electrical conductivity; OM: organic matter; Exch: exchangeable; the values represent the means (±standard deviation) of three replicates. Data within the same column followed by different letters are significantly different according to Tukey's test at $p < 0.05$.

After harvesting, the OMF product-based DAP increased the soil AP concentration by 48% and 132% for OMF2 and OMF3, respectively, compared to the initial states before implantation. However, a negative value was recorded after the applications of RP and PWS using the OMF0 and OMF1 formulations, with −5.8% and −8.13% for SP, respectively, and only in OMF0 with −15.1% for RP. Nevertheless, this value increased when using OMF2 and OMF3 in combination with RP or SP.

### *3.3. PUE and PSR*

The direct application of DAP and PWS showed an increase in the PUE% of 23% and 48%, respectively, compared with the control (Figure 1a). Similarly, these values increased significantly in OMF1-formulated product-based DAP and SWP, by 35% and 30%, respectively, compared with the control (OMF0). However, this variation was not significant for RP. The increase in the organic fraction in OMF2 and OMF3 showed an increase in the PUE% to 60%, 49%, and 44%, and to 72%, 53%, and 45% for OMF2- and OMF3-based DAP, RP, and PWS, respectively.

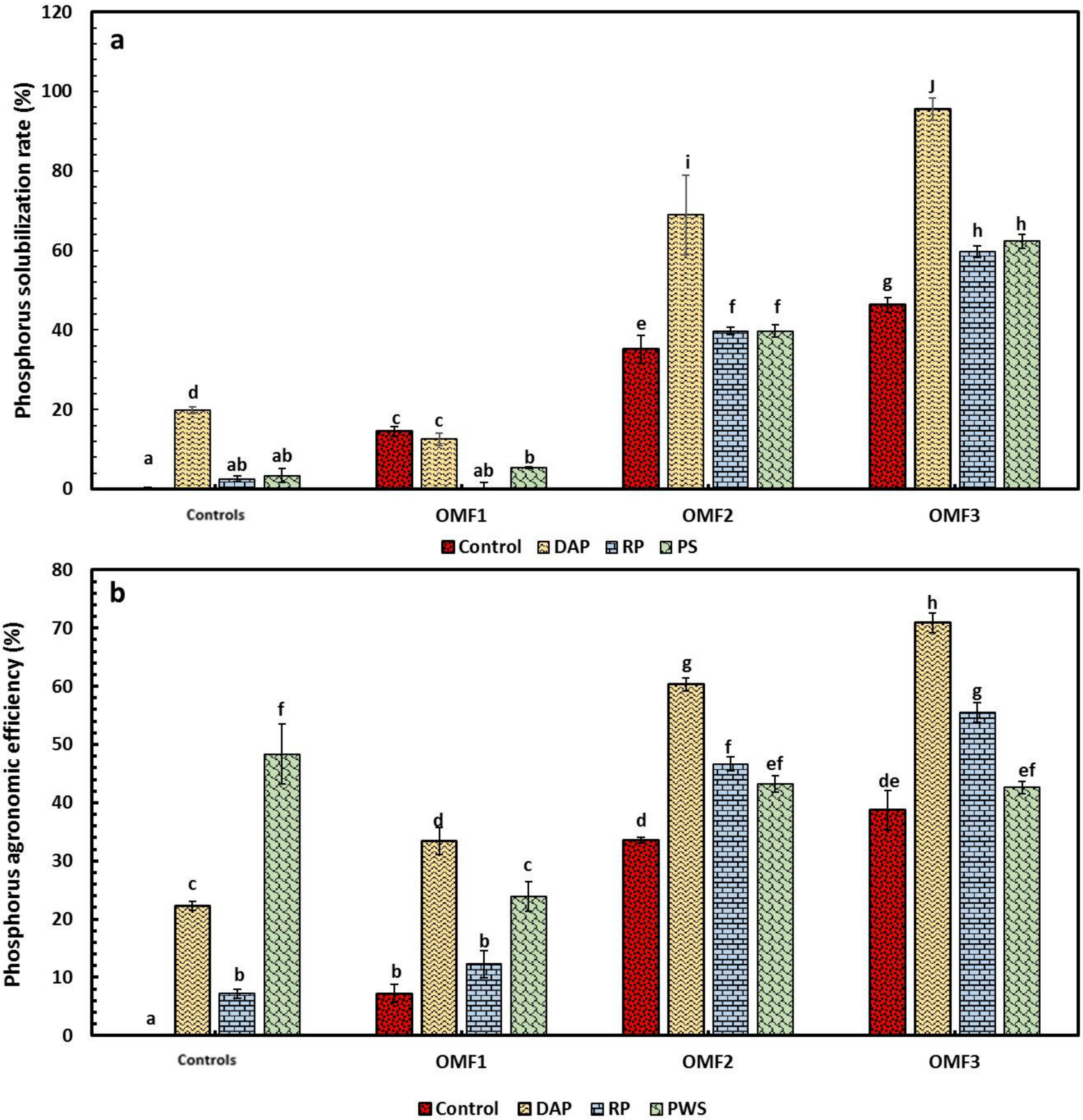


**Figure 1.** Effect of organo-mineral application formulations on phosphorus solubilization rate (%) (**a**) and phosphorus agronomic efficiency (**b**). OMF0 = without compost, OMF1 = 10 t/ha of compost, OMF2 = 50 t/ha of compost, OMF3 = 100 t/ha of compost, RP = rock phosphate, PWS = phosphate sludge. Results represent the means (± standard deviation) of five replicates. Different letters are significantly different according to Tukey's test at $p < 0.05$.

The positive impact on the PSR (%) after the applications of the formulated products was highlighted by the organic fraction additions, showing evidence of a soil phosphorus solubilization improvement of up to 40% and 60% when using OMF2 and OMF3 product-based RP and PWS (Figure 1b). On the other hand, the increase in the organic matter fraction in the formulated product showed a positive impact on the soil phosphorus availability, which contributed to an increase in the phosphorus content of up to 38% and 45%, and up to 70% and 95% for OMF2- and OMF3-based DAP, respectively, compared with the unamended control (OMF0).

### 3.4. Effect of OMF Formulation on Plant's Agro-Physiological Parameters and Nutrient Content

In the case of unamended soil, depending on the added fertilizer, most formulations positively affected plant agronomic traits. The use of OMF0-based DAP and SWP significantly increased the shoot dry weight by 26% and 19.03%, respectively, compared to that of soil only (Figure 2a). However, the root dry weight variation was only significant for OMF0-based DAP, with an increase of 26.14% compared to the control (Figure 2b).

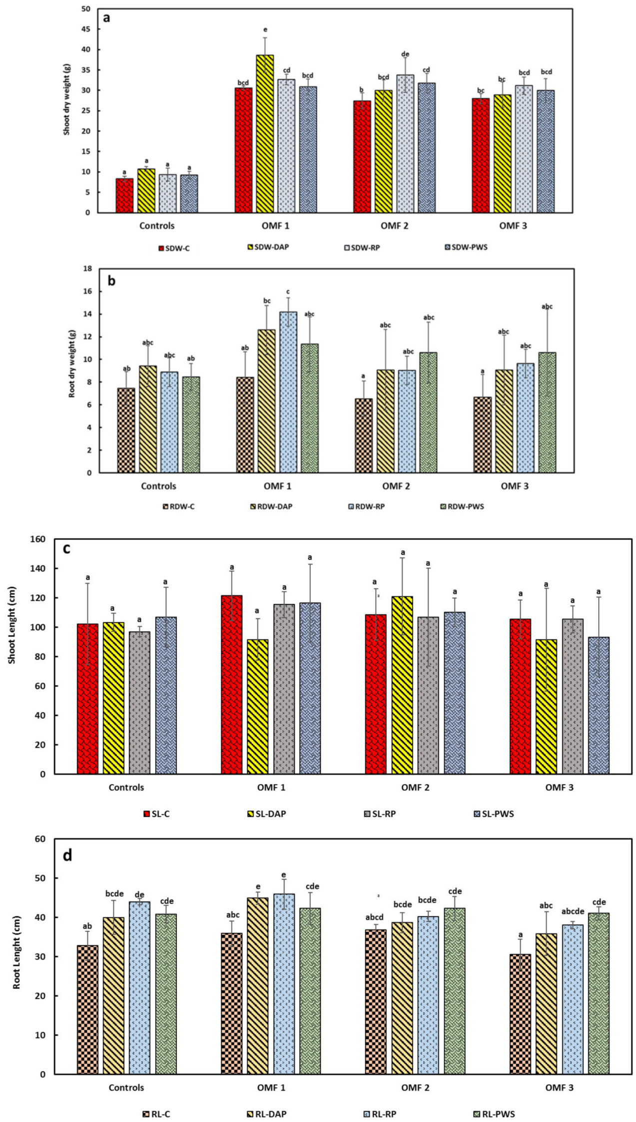


**Figure 2.** Effect of OMF formulations on plant agro-physiology parameters; (**a**) shoot dry weight (SDW), (**b**) root dry weight (RDW), (**c**) shoot length (SL), and (**d**) root length (RL). Results represent the means (± standard deviation) of five replicates. Different letters are significantly different according to Tukey's test at $p < 0.05$.

Remarkably, the additions of OM at the three doses of OMF products directly affected the plant growth parameters by increasing the plant's shoot dry weight from 7.4 g/kg up to 30, 27.4, and 27.97 g/kg (Figure 2a). However, the use of OMF2 and 3 significantly reduced the root dry weight by more than 1 g/kg (Figure 2b). Moreover, the fertilized soil using OMF1 induced a significant increase of 1.95 g/kg of shoot dry weight compared to the controls, followed by OMF1-PWS with an increase of 1.42 g/kg of shoot dry weight. However, using OMF2-DAP and OMF3-based PWS products significantly decreased the plant biomass by 2.54 and 2.02 g/kg for the shoot dry weight, and by 2.5 and 2.4 g/kg for the root dry weight compared with the OMF3-amended soil, respectively. Therefore, in the case of OMF2-based RP, the best production was obtained with the OMF2-RP formulation, which led to a significant increase in the shoot and root biomass of 5.82 g/kg and 2.6 g/kg, respectively. Inversely, the use of the OMF3 formulation significantly decreased the biomass production compared to the OMF2 and OMF2 formulations (dose effects). The results show an increase in plant length when using OMF1 products, except for OMF1-based DAP products, which reduced the length by 12 cm (Figure 2c,d). However, increasing the OM doses in the products induced a significant decrease in the case of OMF3-DAP and OMF3-PWS, with 1.1 and 2.64 g/kg for the shoot dry weight, respectively. Globally, the use of OMF formulations significantly improved the root length (Figure 2d). The best results were obtained by using the OMF1 product, with a significant increase in the roots of 4.17, 5.75, and 2.91 g/kg from DAP, RP, and SWP, respectively.

### 3.5. Effect of OMF Product on Soil Water Retention

Globally, the curve variations (Figure 3) showed two different periods of water retention that were well distinguished, in which the first one (late spring, <40 days) was characterized by a higher water retention capacity. After 9.21- and 31-day growth experiments, the addition of OMF1, OMF2, and OMF3 allowed an increase in the soil water retention to an average of 11.7%, 17%, and 20% compared with the unamended controls, respectively. However, this retention capacity decreased during the second phase (summer period, >40 days) to 8.8%, 12.7%, and 16.7% for OMF1, OMF2, and OMF3, respectively.

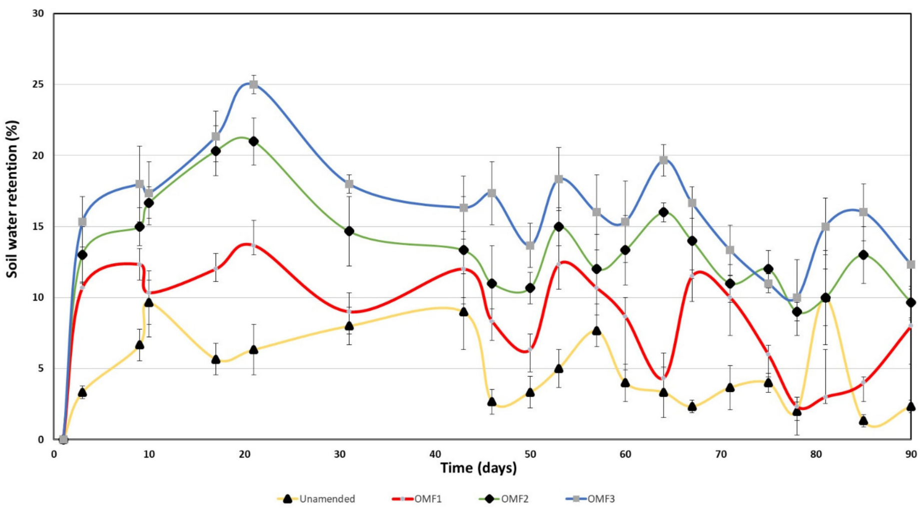


**Figure 3.** Effect of organo-mineral application formulations on maize agro-physiological parameters.

The data introduced in Table 4 show that the WUE was significantly affected by the OMF treatments. High differences were observed in the WUE values depending on the OM doses used among the formulations; as an example, the WUE recorded under OMF1 (13.9 kg $m^{-3}$) was higher by an increase of 353% compared to the corresponding WUE of unamended controls (OMF0). The recorded WUE values for OMF3-based RP and SWP increased to 87% and 172% compared to their controls. However, the use of DAP in the OMF formulations showed that 10 t/ha is the best combination for the maintenance of high production, with 10.45 kg $m^{-3}$ compared to the other doses.

**Table 4.** Effect of organo-mineral applications on maize agro-physiological traits.

| Treatment | MSI (%) | RWC (%) | Ear Yield (g dry Matter) | Leaf Number Per Plant | WUE (kg m$^{-3}$) |
|---|---|---|---|---|---|
| Control | 40.3 ± 0.6 [a] | 65 ± 2.5 [a] | 8.19 ± 0.9 [ab] | 8 ± 0.8 [ab] | 3.94 ± 2.3 [ab] |
| $OMF_0$ + DAP | 42.7 ± 2.2 [abc] | 70.3 ± 1.05 [ab] | 21.04 ± 1.7 [de] | 11.3 ± 0.58 [cdef] | 10.1 ± 0.81 [abc] |
| $OMF_0$ + RP | 40.9 ± 1.6 [a] | 67.13 ± 2.8 [ab] | 10.33 ± 0.98 [abc] | 7.7 ± 0.96 [a] | 4.96 ± 4.2 [ab] |
| $OMF_0$ + PWS | 41.2 ± 1.92 [ab] | 67.26 ± 2.7 [ab] | 7.69 ± 0.33 [a] | 10.2 ± 0.95 [abcde] | 3.7 ± 1.4 [a] |
| $OMF_1$ | 40.7 ± 3.87 [a] | 68.58 ± 1.02 [ab] | 28.9 ± 8.7 [e] | 8.2 ± 0.5 [ab] | 13.9 ± 3.5 [abc] |
| $OMF_1$ + DAP | 42.7 ± 0.83 [abc] | 73.2 ± 0.67 [b] | 13.91 ± 0.9 [abcd] | 13.4 ± 2.4 [f] | 6.68 ± 2.2 [abc] |
| $OMF_1$ + RP | 53.2 ± 1.1 [f] | 71.5 ± 1.4 [ab] | 7.7 ± 1.05 [a] | 8.5 ± 1.2 [abc] | 3.7 ± 0.5 [ab] |
| $OMF_1$ + PWS | 46.16 ± 2.8 [bcd] | 73.1 ± 1.9 [b] | 7.69 ± 1.2 [a] | 9.2 ± 0.5 [abcd] | 3.69 ± 1.4 [abc] |
| $OMF_2$ | 47.9 ± 1.35 [de] | 73.4 ± 2.6 [b] | 9.4 ± 1.2 [abc] | 12.4 ± 0.6 [ef] | 4.5 ± 3.56 [ab] |
| $OMF_2$ + DAP | 41.3 ± 0.67 [abc] | 69.9 ± 3.3 [ab] | 16.5 ± 2.9 [bcd] | 12 ± 1 [def] | 7.81 ± 6.1 [abc] |
| $OMF_2$ + RP | 44.3 ± 0.6 [abcd] | 68.4 ± 2.57 [ab] | 13.5 ± 3.2 [abcd] | 8.75 ± 0.5 [abc] | 6.47 ± 1.18 [abc] |
| $OMF_2$ + PWS | 46.4 ± 1.7 [cd] | 71.48 ± 3.1 [ab] | 14.9 ± 2.4 [abcd] | 11.2 ± 0.5 [cdef] | 7.2 ± 4.08 [abc] |
| $OMF_3$ | 52.9 ± 0.2 [ef] | 72.6 ± 2.57 [b] | 17.6 ± 1.8 [cd] | 9.5 ± 1 [abcde] | 8.45 ± 2.43 [abc] |
| $OMF_3$ + DAP | 53.7 ± 0.5 [f] | 72.9 ± 3.02 [b] | 21.7 ± 1.9 [de] | 10.7 ± 1.7 [bcdef] | 10.45 ± 3.6 [abc] |
| $OMF_3$ + RP | 42.9 ± 1.7 [abcd] | 71.4 ± 0.6 [ab] | 19.4 ± 2.6 [d] | 12.2 ± 1.5 [ef] | 9.31 ± 0.78 [abc] |
| $OMF_3$ + PWS | 43.3 ± 0.7 [abcd] | 69.4 ± 3.7 [ab] | 21.1 ± 2.2 [de] | 13.7 ± 0.6 [f] | 11.3 ± 1.2 [bc] |

OMF0 = 0 tonnes of compost, OMF1 = 10 t, OMF2 = 50 t, OMF3 = 100 t, PWS = phosphate sludge. Results represent the means (± standard deviation) of three replicates. Data within the same column followed by different letters are significantly different according to Tukey's test at $p < 0.05$.

### *3.6. Plant Phytosanitary Properties*

Regarding the OMF product application, our results showed that the potential photosynthetic activity (F0/Fm) rate was differentially affected by the studied treatments (Figure 4). The application of OMF1 (OMWS compost only) increased the Fv/F0 rate by 17% compared with the unamended control. However, this value was statistically not significant. In contradiction, the applications of OMF2 and OMF3 (based on OMWS compost only) showed a significant decrease in the F0/Fm ratio. Globally, the applications of OMF-based DAP and PWS did not induce a positive impact on the plant photosynthetic activity. Moreover, the OMF formulation-based RP induced a significant improvement in the Fv/F0 of up to 14%, 11.7%, and 23.8% for OMF1, 2, and 3, respectively.

The applications of OMF-formulated products on experimental maize plants regarding the maximum quantum efficiency of the PWSII photochemistry (Fv/Fm) value showed a significant positive effect for all treatments. The applications of OMF2 and OMF3 improved the Fv/Fm ratio to 11% compared to the control. However, the use of DAP in the product formulation improved this value by 12% and 22.9% for OMF0 and OMF1, respectively. In contrast, OMF2 and OMF3-based DAP increased it by 4% and was statistically insignificant in the case of the OMF2 products. Moreover, using OMF product-based RP significantly improved the photosynthetic ratio to 14.5%, 20%, 19%, and 18.7% for OMF0, 1, 2, and 3 compared with the unamended control. Similarly, a significant effect was recorded when using the product-based PWS, with fluorescence ratio improvements of up to 19%, 18%, 11%, and 2% for OMF0, 1, 2, and 3, respectively. The results (Figure 4) showed an improvement in plant respiration after 3 months of experiments for all the control treatments with additions of DAP, RP, and SWP from 200 to 241, 210, and 240 gs umol m$^{-2}$, respectively. The best results were obtained by using OMF3-based DAP, with an improvement of 46% compared with the unamended controls (OMF0-DAP). This was significantly reduced by 14% when using OMF2-DAP. In contradiction, the use of OMF2 product-based RP and PWS gave the best results in terms of the plant's respiration, resulting in an improvement of 47% and 46% for OMF2-RP and OMF2-PWS, respectively.

### *3.7. Nutrient Composition of Plants*

Our investigation revealed that the OMF formulation products significantly affected plant nutrient concentrations (Table 5). Overall, the OMF2 and OMF3 formulations increased the shoot N content by 17.6% and 10.29%, respectively, compared with the unamended treatment (OMF0). The shoot P content increased by 88.2% and 147.2%, respectively, compared with the unamended treatment (OMF0).

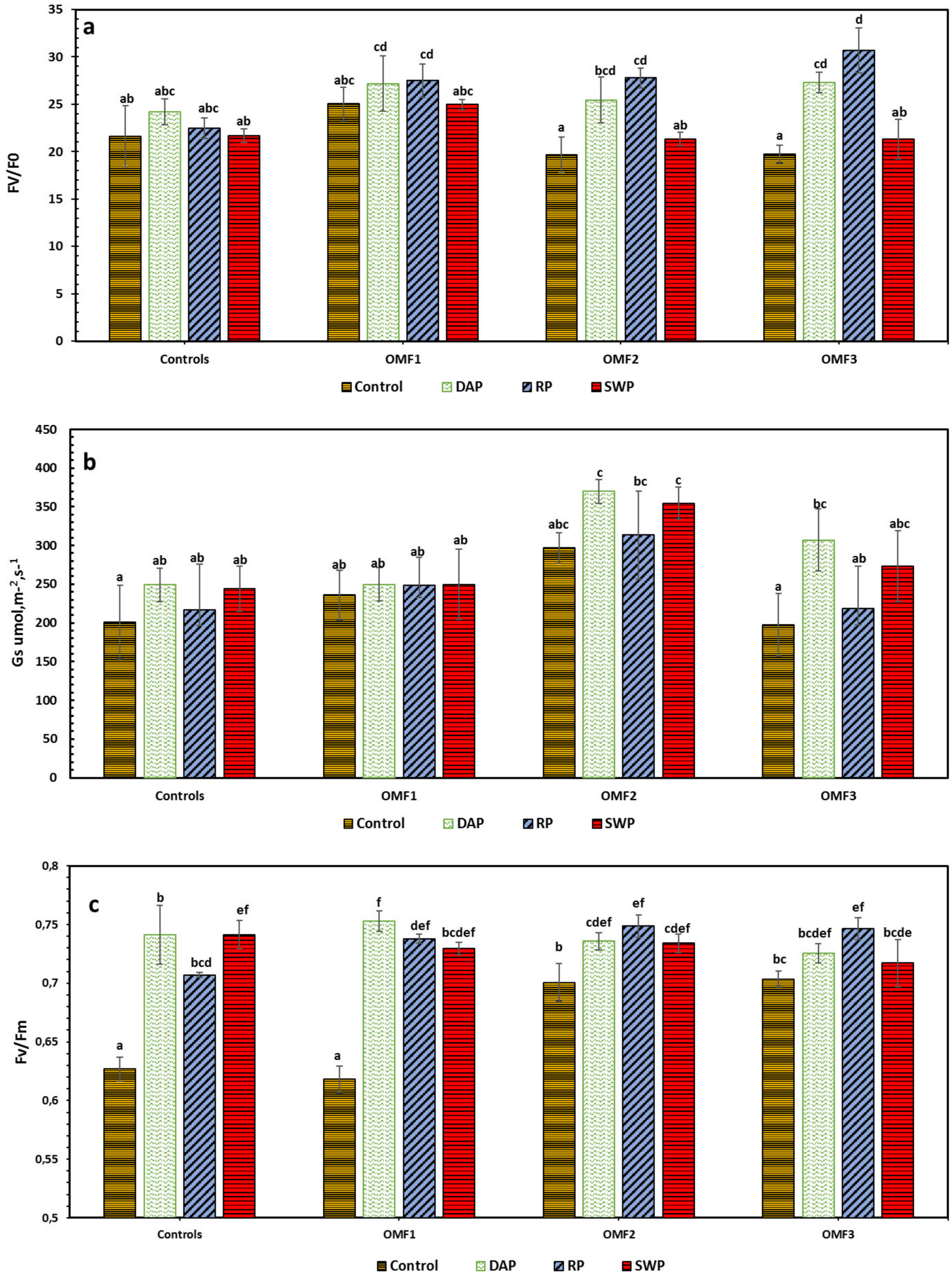


**Figure 4.** Effect of OMF formulations on plant agro-physiology parameters; (**a**) the potential photosynthetic activity (Fv/F0), (**b**) Stomatal conductance gu umol $m^{-2}$. $s^{-1}$, (**c**) maximum quantum efficiency of PWSII (Fv/Fm). Results represent the means (± standard deviation) of five replicates. Different letters are significantly different according to Tukey's test at $p < 0.05$.

For the shoot K and Mg content, the highest increase was 20% and 36%, respectively, for OMF2 and OMF3. The shoot macro-nutrient content remained similar among the treatments where no compost was added (OMF0) except for OMF0-DAP, where the shoot P content increased by 40% compared to OMF0. Globally, the nutrient use efficiency (NUE) was significantly enhanced following the addition of stable organic matter (SOM). Indeed, the use of OMWS compost increased the NUE to 32%, 36%, and 157% for N, P, and K, respectively. The OMF3-DAP formulation significantly increased the NUE by 29.29%, 28.82%, and 180.9% for N, P, and K, respectively, compared to the control (OMF0), and the highest values were recorded for OMF3-RP (26%, 19.3%, and 133.95%) and OMF3-PWS (12.5%, 24.7%, and 109.5%).

**Table 5.** Response of soil physicochemical properties after amendments and fertilization strategies for 3 months of harvesting experiments.

| Treatment | N% | P% | K% | Mg% | Ca% | Zn mg/kg |
|---|---|---|---|---|---|---|
| Control | 0.346 ± 0.006 [a] | 0.07 ± 0.01 [a] | 2.04 ± 0.12 [abc] | 0.3 ± 0.05 [bc] | 0.7 ± 0.02 [bc] | 18.8 ± 6.09 [a] |
| $OMF_0$ + DAP | 0.343 ± 0.05 [a] | 0.11 ± 0.1 [abcde] | 2.087 ± 0.08 [abcd] | 0.29 ± 0.04 [bc] | 0.6 ± 0.01 [a] | 20.37 ± 1.14 [ab] |
| $OMF_0$ + RP | 0.34 [a] | 0.083 ± 0.01 [ab] | 1.9 ± 0.7 [a] | 0.34 ± 0.02 [bcd] | 0.5 ± 0.02 [a] | 23.1 ± 5.41 [ab] |
| $OMF_0$ + PWS | 0.34 ± 0.017 [a] | 0.087 [abc] | 2.02 ± 0.073 [ab] | 0.2 ± 0.01 [a] | 0.6 ± 0.035 [a] | 17.6 ± 1.27 [a] |
| $OMF_1$ | 0.386 ± 0.011 [ab] | 0.083 ± 0.02 [ab] | 2.3 ± 0.14 [abcde] | 0.36 ± 0.03 [cd] | 0.74 ± 0.16 [c] | 21.3 ± 2.39 [ab] |
| $OMF_1$ + DAP | 0.38 ± 0.01 [ab] | 0.13 ± 0.01 [bcdefg] | 2.2 ± 0.12 [abcd] | 0.29 ± 0.01 [bc] | 0.58 ± 0.03 [a] | 20.6 ± 2.2 [ab] |
| $OMF_1$ + RP | 0.37 ± 0.027 [ab] | 0.09 ± 0.005 [abcd] | 1.9 ± 0.08 [a] | 0.32 ± 0.01 [bcd] | 0.59 ± 0.02 [a] | 19.9 ± 7.36 [ab] |
| $OMF_1$ + PWS | 0.38 ± 0.01 [ab] | 0.11 ± 0.005 [abcdef] | 2.02 ± 0.19 [ab] | 0.276 ± 0.03 [ab] | 0.62 ± 0.06 [a] | 19.9 ± 2.2 [ab] |
| $OMF_2$ | 0.42 ± 0.015 [ab] | 0.137 ± 0.02 [bcdefg] | 2.47 ± 0.05 [cde] | 0.32 ± 0.01 [bcd] | 0.65 ± 0.03 [a] | 25.7 ± 7.36 [ab] |
| $OMF_2$ + DAP | 0.46 ± 0.05 [b] | 0.187 ± 0.015 [gh] | 2.79 ± 0.12 [f] | 0.40 ± 0.03 [d] | 0.57 ± 0.03 [a] | 33.7 ± 2.7 [b] |
| $OMF_2$ + RP | 0.43 ± 0.068 [ab] | 0.17 ± 0.01 [fgh] | 2.18 ± 0.2 [abcd] | 0.36 ± 0.02 [cd] | 0.55 ± 0.04 [ab] | 27.6 ± 8 [ab] |
| $OMF_2$ + PWS | 0.38 ± 0.01 [ab] | 0.14 ± 0.016 [cdefgh] | 2.45 ± 0.3 [cdef] | 0.35 ± 0.01 [bcd] | 0.71 ± 0.08 [bc] | 23.7 ± 5.14 [ab] |
| $OMF_3$ | 0.456 ± 0.05 [b] | 0.14 ± 0.02 [cdefgh] | 2.47 ± 0.16 [def] | 0.32 ± 0.01 [bc] | 0.6 ± 0.03 [a] | 33.7 ± 2.7 [b] |
| $OMF_3$ + DAP | 0.41 ± 0.02 [ab] | 0.19 ± 0.04 [h] | 2.7 ± 0.08 [ef] | 0.40 ± 0.06 [d] | 0.5 ± 0.026 [a] | 27.59 ± 8.2 [ab] |
| $OMF_3$ + RP | 0.43 ± 0.08 [ab] | 0.17 ± 0.01 [efgh] | 2.1 ± 0.053 [abcd] | 0.36 ± 0.03 [cd] | 0.5 ± 0.09 [a] | 26.36 ± 1.06 [ab] |
| $OMF_3$ + PWS | 0.39 ± 0.02 [ab] | 0.14 ± 0.04 [defg] | 2.4 ± 0.14 [bcdef] | 0.35 ± 0.03 [bcd] | 0.7 ± 0.1 [bc] | 17.62 ± 4.7 [a] |

OMF0 = 0 tonnes of compost, OMF1 = 10 t, OMF2 = 50 t, OMF3 = 100 t, PWS = phosphate sludge. Results represent the means (± standard deviation) of three replicates. Data within the same column followed by different letters are significantly different according to Tukey's test at $p < 0.05$.

Regarding the leaf number, the results showed that the use of the OMF2 and OMF3 product doses gave the best results, with an improvement of 55% and 17.5%, respectively. However, the use of DAP in the OMF1 product increased this value by 17% compared to DAP with the unamended control. In contrast, an increase in the organic amendment dosage during formulation increased the leaf number up to 56.4% and 35.25% when using OMF3-based RP and PWS compared to their controls. On the other hand, the use of RP and PWS significantly improved (<0.05%) the ear yield by up to 90% and 175% after using OMF3-based RP and PWS compared to their controls. Remarkably, the formulated product-based DAP did not significantly improve the ear production.

The responses of the membrane stability index (MSI%) and relative water content (RWC%) of maize grown under OMFs are presented in Table 4. The statistically analyzed results revealed a significant difference ($p < 0.05$) between each treatment and applied product compared to the unamended control. The MSI% and RWC% were improved by additions of OMWS composting doses.

The applications of OMF showed an important capacity to modify the soil water retention (Figure 3), which positively affected the maize agro-physiological traits. The best results for these parameters were obtained for all experiments treated with the OMF3-formulated product.

## 4. Discussion

Most of the agro-physiological parameters of maize were positively affected by the OMF formulations. Our results showed the beneficial effects resulting from combining organic and mineral resources compared to their single use. Additionally, this work shows a close relationship between the types of phosphate fertilization and the input doses of OMWS compost for optimal improvement to plant growth parameters and soil fertility. The OMF1 product-based DAP generated the highest biomass. Conversely, at a higher dose of compost (50 and 100 t/ha), RP and PSW outperformed DAP, proving that the optimal combination of organic matter during OMF formulations depends on the pedoclimatic conditions and the nature of the used mineral source of fertilization (in our case, the phosphorus source).

The lower yields of the OMF3 products used based on DAP may be attributed to an increase in EC (Tables 1 and 2). In contradiction, the use of OMF3 with RP and PSW resulted in an EC that was higher than the DAP treatment after harvesting. This could be explained by the slow release of P, which may alleviate the P complexation with other minerals [38].

Interestingly, the OMF-applied products significantly affected the *Zea Mays* root length. Due to the lower rhizosphere AP fraction, the use of RP and PWS treatments increased the root depth and affected the root diameter, which indicated important root growth that was presumably responsible for the increased root P uptake and P content in maize shoots [13]. The OMF3-mineral P formulation (100 t/ha) did not show a synergistic effect in the plant growth parameters compared to the other formulations. In the case of OMF3, the negative impact on the plant agronomic traits could be related to the high EC and the quality of the used organic matter, leading to increased ion concentrations. Consequently, nutrient adsorption became stronger. The interaction between organic matter and mineral fertilization into OMF products can significantly improve the SOM residence time, thus inducing the maintenance of high carbon values in the soil and simultaneously maintaining a high value of AP and AK, as well as the concentration of total and exchangeable nutriments such as $Ca^{2+}$ and $Mg^{2+}$ in soils. These results were partly due to the richness of the OMF-used products in the O-H chemical bond specifically, which has the quickest reaction to aliphatic-C, next to Si-O, Fe-O, and Al-O [39]. Water use efficiency is an important issue in arid and semi-arid regions. The WUE results could be due to temperature variations during the experimental conditions, which directly influenced the water irrigation efficiency. In addition, the WUE can positively affect yield production, with an average value of 60% for the field treatments, and can give a better result that is even higher than those of the 80% and 100% field treatment capacities [40].

The relative water content (RWC) is a measure of the plant water status, giving an overview of the metabolic activity in plant tissues. It is used mainly as an index to identify the plant's adaptability to support dehydration tolerance [41]. However, the MSI (%) showed a high sensitivity while decreasing depending on the soil's ionic charge [34]. Our experience shows that an increase in the OM rate in the OMF-formulated products positively affected both the RWC and the fresh dry weight under water-deficit irrigation, and the higher plant biomass could maintain a higher water content in the leaves, which is related to plant drought tolerance [36].

Soil fertility was improved with an increase in the SOM, which directly affects the interactions between physicochemical components [42]. This effect was observed before seed sowing and after harvesting. The increase in the SOM induced an increase in the soil EC values [43,44]. These results are directly related to the higher nutrient content, particularly cations, which contribute to soil salinity [15].

Furthermore, the reduction in the $N\text{-}NH_4^+$ content due to the nitrification process increased, leading to a high EC value [45]. However, using unstable organic matter in OMF products can significantly decrease the crop yield, especially if it contains toxic compounds such as phenols [46]. After 3 months of experiments, the EC values were reduced in all treatments, and likewise for %TOC. This evolution also depended on the richness of the used materials in alkaline metals ($K^+$, $Ca^{2+}$, and $Mg^{2+}$) [44,47].

More importantly, applying OMF products can significantly reduce the initial EC value. This effect is related to the nutrient adsorption of the OM fraction, which reduces the nutrient concentration and availability in the soil solution and leachates [48]. The EC reduction can also be associated with the microbial assimilation of $SO_4^{2-}$ and $N\text{-}NO_3^-$ following the biodegradation of organic matter [49,50]. This effect was identified in our study (Table 5), with a high content of $Ca^{2+}$ in the soil when using OMF formulations. The plant nutrient uptake and microbial community growth may explain the significant decrease in the concentration of soil ions such as Mn, Mg, and Fe. Humic substances in compost are the main components of the organic carbon reservoir. However, organic compounds are less difficult to degrade in compost [51]. The compost and simultaneous application of biochar-compost can also increase and maintain a high percentage of TOC in soil compared to a single application of compost [44,52].

SOM promotes a further role in increasing the soil AP in alkaline soil conditions (pH > 7.5), which favors Ca-P precipitation reactions, resulting in a sequence of products that have a direct effect on the soil pH and phosphorus solubility [53,54]. In most treatments, the AP content increased significantly after 90 days of the experiment (Tables 2 and 3). The soil AK content was positively correlated with the rate of OM in the OMF formulations. In addition, the variations in the soil EC were strongly correlated ($p < 0.001$) to a soil concentration of AP and AK ($p = 0.948$ and 0.978, respectively) [12,55].

The critical factors involved in P mineralization are the plant and microbial biomass, which can produce a considerable quantity of extracellular enzymes (e.g., phytase, phosphatase, and phospholipase) that can hydrolase organic P [56]. The use of OM-based biochar (*Eichornia crassipes)* applications could enhance microbial P mineralization by 3-fold compared to a control [57]. In addition, the OMFS surface area properties and O:C ratio are expected to increase the nutrient retention in the amended soil, especially for negatively charged ions such as $H_2PO_4^-$ /$HPO_4^{2-}$ and low-molecular-weight DOC [58–60]. The SOM could promote the mycorrhizal colonization of plant hosts and enhance P solubilization [61–63]. The soil microbial community is highly involved in efficient nutrient retention and transfer to plants. However, it is susceptible to SOM properties and nutrient quality, which influence microbial diversity, abundance, and activity [15,64]. OM addition into OMF formulations can induce a great change in soil physicochemical properties by affecting the soil solution, mostly under high EC conditions and porosity, where water–air conditions are optimized and directly impact the microbial growth activity and energy options.

The OMF surface can have an increased ability of adsorption/desorption, which negatively affects many substrates and enzymes and slows the decomposition of organic matter and nutrients [65,66]. Compost has a positive impact on bulk density parameters, with a reduction of 10% and 11% compared with the unamended control. Such evolution is concomitant with an increase in the soil-available phosphorus (13% and 20%, respectively) and SOM (27.79% and 20.62%, respectively) compared to untreated soil [67]. Using other sources of OM in the OMF products, such as biochar in OMF, can significantly increase the AP, as it increases the accessibility to the easily soluble $P_2O_5$ content of the treated soil.

By increasing the residual time of carbon in the soil, organic matter aggregation becomes highly associated with negative charges, improving soil aggregation and increasing nutrient availability [68,69]. The soil cation exchange capacity values after OMWS compost applications can be related to composting process conditions, especially the properties of used waste and microbial activity, influencing humic substance quality directly. Soil water retention is influenced by organic matter quality in terms of its wettability and ability to retain water [70,71]. The quality of organic matter also increases the water availability, retention, and aggregate stability after its application to the soil [72].

In addition, each unit of organic matter added to the soil can increase the soil water availability from 2.2 to 3.7% [73]. However, long-term experimental results are significant for a better understanding of how to maintain crop production and soil quality. The water retention capacity is variable and depends on the used waste substrates, composition, and presence of metals and salts, which increase availability and regulatory requirements [74]. The addition of OMF product-based OMWS compost to the soil substrates induces an increase in coarser particles, potentially allowing to increase the soil water holding capacity [75]. The persistence of organic matter in the soil is highly dependent on the raw material's nature, as it directly affects the decomposition degree and rate [76]. In addition to aromatic structures, the stable fraction of OMF contains aliphatic carbon compounds, which are structures that are easily degraded and oxidized [77,78].

A reduction in the SOM increases the risk of nutrient leaching, causing soil depletion and making the soil vulnerable to environmental stress. In addition, this process is favored in acidic soil. Applications of humic acid in neutral sandy clay loam soil could significantly reduce nutrient leaching with almost 61% for $NH_3$ and 20%, 50%, and 73% for potassium, calcium, and magnesium, respectively. Humic substances do not have a uniform molecular structure and are relatively large molecules. A characteristic of humic acid is that it has many carboxyl groups and phenolic alcohol functions in the macro-molecule. These multiple groups can play a bio-stimulant role (ligands in complex chemistry), stably wrapping the mineral components in the soil and efficiently transporting them into plant cells (chelating effect) [79,80].

The used OMWS compost showed interesting results regarding crop yields and soil fertility improvements. In fact, depending on the rate of OM and mineral phosphorus in the OMF formulation products, OMF can adsorb cations due to its surface area being negatively charged and can even adsorb some anions such as phosphorus. Depending on the rate of OMWS compost and the sources of phosphorus fertilizers, OMF products can present different optimums, impacting positively on the *Zea Mays* agro-physiological traits, including the MSI, RWC, fluorescence, and porosity. Such advantage make use of OMF products based on OMWS compost, a potential products to be recoverable in agricultural land, and improvements to crop yield, water holding capacity, and WUE, while reducing the impact of environmental pollution induced by nutrient leaching [81].

## 5. Conclusions

Improving agricultural productivity under arid and semi-arid conditions requires novel fertilizer management strategies, which may simultaneously address soil degradation issues and a reduced fertilizer use efficiency. The current study demonstrates that the application of P-based OMFs improves soil fertility and enhances the PUE, resulting in a higher biomass yield. Interestingly, our findings reveal a clear relationship between the type of phosphate mineral fertilizer and the rate of organic matter, as different combinations yielded contrasting results. Such an observation was peculiarly striking for the agronomic performance, as when a plant-available source of P was used (DAP), a lower rate of OM (10 t/ha) was required to achieve optimal agronomic performance. Conversely, the RP agronomic performance was better under a higher rate of OM (100 t/ha). Moreover, the PUE was positively correlated with the rate of OM independently of the P mineral source, suggesting that the P dynamic (solubilization and mobilization) is strongly affected by the soil OM content.

Overall, the assayed OMF formulations proved to be potent solutions for improving the agronomic efficiency of P mineral fertilizers, including low-available P mineral sources such as low-grade RP and by-products of RP processing (PWS). This is plausibly attributed to improved soil properties and the functions of rhizosphere microbes, leading to better P solubilization and less P complexation. Together, these results can provide a scientific theoretical basis for understanding the impact of OMF products and confirming the feasibility of improving soil fertility, improving plant growth, and supporting organo-mineral interactions.

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## Abbreviations

| | |
|---|---|
| OM | Organic matter |
| PUE | Phosphorus use efficiency |
| OMWS | Olive mill waste sludge |
| OMF | Organo-mineral fertilizers |
| RP | Rock phosphate |
| PWS | Phosphate washing sludge |
| SOM | Soil organic matter |
| FUE | Fertilizer use efficiency |
| AP | Available phosphorus |
| MSI | Membrane stability index |
| RWC | Relative water content |
| WUE | Water use efficiency |
| PAE | Phosphorus agronomic efficiency |
| PSR | Phosphorus solubilization rate |

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