

# Synergistic Effects of Phosphatic Fertilizers and Cow Manure on Wheat Yield and Phosphorus Use Efficiency in Calcareous Soils

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## Abstract

Achieving sustainable phosphorus (P) is a critical for food security in calcareous soils, where P fixation limits crop productivity. This study evaluated the integrated effects of phosphatic fertilizers-single superphosphate (SSP), triple superphosphate (TSP), monoammonium phosphate (MAP), and management cow manure (20 t ha<sup>-1</sup>) on wheat yield, P dynamics, and P use efficiency in a calcareous soil (pH 8.2, 50% CaCO<sub>3</sub>). Seven treatments included: control (no P), SSP, SSP+manure, TSP, TSP+manure, MAP, and MAP+manure. Phosphorus was applied at 37.5 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>. Results demonstrated that MAP with manure significantly (p<0.05) increased grain yield (3.78 t ha<sup>-1</sup>), biological yield (21.86 t ha<sup>-1</sup>), and 1000-grain weight (47.6 g) versus the control. Available P in post-harvest soil was highest with TSP+manure (46.89 mg kg<sup>-1</sup>) and lowest in the control (4.69 mg kg<sup>-1</sup>). The MAP+manure treatment maximized phosphorus use efficiency, PUE, (27.7%), while SSP alone showed the lowest PUE (14.4%). Grain P concentration peaked in TSP+manure (0.46%) and MAP+manure (0.38%). Synergistic interactions between manure and MAP enhanced P availability by reducing Ca-P fixation, improving root uptake, and sustaining fertility. In conclusions: Co-application of MAP (37.5 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>) and cattle manure (20 t ha<sup>-1</sup>) optimizes wheat productivity and PUE in calcareous soils. This integrated strategy mitigates P depletion risks and supports sustainable intensification.

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## Introduction

Achieving food security ranks among the most pressing global challenges in light of rapid population growth and the rising demand for high-quality food. International reports indicate that agricultural production must nearly double by mid-century to meet population needs, that goal requires improving the efficiency of natural resource using and adopting sustainable soil

management practices (Canton, 2021). Soil fertility plays a central role in this context, forming the fundamental basis for crop production, while macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are primary drivers of plant growth and development (Havlin, 2014).

In traditional and semi-arid agricultural regions, where soil fertility is naturally limited, fertilization emerges as one of the most important strategies for increasing productivity. However, improper nutrient management can lead to soil degradation and long-term productivity loss. Therefore, achieving a balanced nutrient supply for plants is considered as one of the primary goals of sustainable agriculture (Tilman *et al.*, 2002).

In recent years, there has been a growing global call to adopt integrated soil and nutrient management practices that not only aim to increase production but also protect the environment and preserve biodiversity (Laboski and Peters, 2012). This trend reflects a heightened awareness that agriculture is not merely an economic activity, but it is an interconnected ecological and social system, where any mismanagement may lead to far-reaching negative consequences.

Phosphorus is an essential nutrient that plays a vital role in plant physiological processes, such as energy production (ATP), nucleic acid synthesis, and promotion of root growth as well as flower and fruit development (Thuynsma *et al.*, 2014). The availability of phosphorus in soil directly affects crop productivity and quality, on the other hand, its deficiency leads to poor vegetative growth, reduced flowering, and lower yield.

Despite of phosphorus in soil importance, is often present in unavailable forms to plants, due to its fixation with calcium in alkaline soils or with iron and aluminum in acidic soils, however, phosphate-solubilizing bacteria can enhance its availability (Mahdi *et al.*, 2010). This limitation often prompts farmers to apply phosphate fertilizers, but excessive use, especially in fragile environments, leads to accumulation it in soil and environmental issues, including runoff-induced water pollution and eutrophication (Carpenter, 2008).

Potassium is one of the essential macronutrients required by plants, is playing a crucial role in numerous physiological functions, including the regulation of cellular water balance, enzyme activation, and enhancing plant resistance to environmental stresses, such as drought and salinity (Mosanaei *et al.*, 2017). Potassium also contributes to improve crop quality in terms of taste, color, and texture, as well as extending their storage potential.

Many agricultural soils exhibit, particularly under prolonged intensive cultivation, declining available potassium, primarily due to nutrient mining and insufficient organic matter recycling (Wang *et al.*, 2023). This depletion directly constrains crop productivity and undermines soil resilience. Hence, potassium effective management necessitates a precision-based strategy that balances short-term yield enhancement with the long-term conservation of soil fertility and ecosystem services.

Organic fertilizers, such as farmyard manure, compost, and crop residues, enhance physical and chemical properties of soil, increase its water and nutrient retention capacity, and stimulate microbial activity that facilitates slow and steady release of nutrients (Falconnier *et al.*, 2023). On the other hand, chemical fertilizers provide nutrients in forms that are readily and quickly available to plants, resulting in a noticeable increase in productivity, especially in intensive farming systems (Mengel and Kirkby, 2012).

However, prolonged and unbalanced application of chemical fertilizers, especially in the absence of organic inputs, has been shown reducing soil organic matter, degrading soil structure, increasing

soil salinity, and elevating nutrient leaching, which threatening both productivity and environmental quality (Zhou *et al.*, 2023). Therefore, current best management practices advocate for integrated nutrient management (INM), which combines organic amendments (e.g., manure, compost) with optimized mineral fertilizer use to enhance crop yields while rebuilding soil health and minimizing ecological risks.

Phosphate rock, the primary raw material for phosphate fertilizers, is a finite and non-renewable resource, with economically viable reserves concentrated in a few geopolitical regions and projected to face increasing scarcity within this century (Scholz *et al.*, 2025). In the absence of scalable alternatives to inorganic phosphorus for sustaining high-yield agriculture, and given the rising energy and environmental costs of mining and processing low-grade ores, optimizing the agronomic efficiency of phosphate fertilizers has become a critical pathway toward resilient and sustainable food systems. The aim of this study evaluated the integrated effects of phosphatic fertilizers-single superphosphate (SSP), triple superphosphate (TSP), monoammonium phosphate (MAP), and cow manure on wheat yield, P dynamics, and use efficiency in a calcareous soil.

## Materials and Methods

### 1. Study Area

The study was conducted during the 2023–2024 cropping season at the Farm of the Faculty of Agriculture, Damascus University (Abi Jerash), located at 30.33° N latitude and 18.36° E longitude, with an elevation of 743 m above sea level. The area receives an annual rainfall of 191.72 mm. Winter maximum and minimum temperatures were 27°C and 6°C, respectively, while summer maximum and minimum temperatures reached 40°C and 21°C. The agricultural soil in this region is clay loam with high calcium carbonate content, classifying it as calcareous soil.

### 2. Plant Material

The spring wheat cultivar Sham 3 was selected for this study. This spring variety has a plant height of 89 cm, medium-sized grains of good quality, and demonstrates high yield potential across diverse growing environments. It is also tolerant to boron deficiency. Sowing was carried out from 15 November to 15 December (GCSAR, 2022). Key agronomic characteristics of the Sham 3 cultivar are summarized in Table 1.

**Table 1. Main characteristics of the Sham 3 cultivar**

Productivity		1.946 (t h <sup>-1</sup> )	
<b>Growing period (emergence)</b>	126 days	<b>Physiological maturity</b>	164 days
<b>Spike length (cm)</b>	8-7	<b>Lodging resistance</b>	Resistant
<b>Spike shape</b>	Pyramidal	<b>Shattering resistance</b>	Resistant
<b>Spike color</b>	Creamy	<b>Grain shape</b>	Oval
<b>Grain color</b>	Amber	<b>Awn color</b>	Creamy

Source: GCSAR (2022).

### 3. Soil

Single random soil samples were collected from the top 0–30 cm layer using a random sampling method and thoroughly mixed to obtain a composite sample. Some key soil properties before planting are presented in Table 2.

**Table 2. Selected soil properties before planting**

Parameter						EC, $\text{dS}\cdot\text{m}^{-1}$ , 1:5 soil:water extract	pH (1:2.5 soil:water suspension)	Mechanical composition			
Exchangeable potassium	Available phosphorus	Mineral nitrogen	Organic matter	Active lime	$\text{CaCO}_3$			texture	clay	silt	sand
mg $\text{kg}^{-1}$			%					%			
568	15.6	7.191	2.55	18	50	0.54	8.20	Clay loam	42	30	28

The studied soil was classified as clay loam according to the USDA textural triangle and contained high calcium carbonate content (50%). Organic matter was relatively abundant (2.55%) due to accumulated crop residues and repeated previous organic amendments. The soil exhibited moderate alkalinity (pH 8.20) and was non-saline. Mineral nitrogen was low (7.19 mg  $\text{kg}^{-1}$ ), whereas exchangeable potassium was high (568 mg  $\text{kg}^{-1}$ ). Available phosphorus measured 15.6 mg  $\text{kg}^{-1}$ , which is considered as moderate to relatively high rather than excessive, particularly in calcareous soils, reflecting the effect of phosphorus fertilization. Accordingly, and following the guidelines of (Laboski and Peters, 2012), only half of the depleted phosphorus amount was supplemented.

### 4. Organic Fertilizer

Composted cow manure, obtained from the cattle barn at the Faculty of Agriculture farm in Abi Jerash, was used as organic fertilizer. It was applied at a rate of 12 kg per 6 m<sup>2</sup>, equivalent to 20 t ha<sup>-1</sup>. Chemical analysis of the manure was conducted to determine its phosphorus content. Results of the chemical and fertility analyses of the organic fertilizer are presented in Table 3.

**Table 3. Chemical and fertility analysis of the organic fertilizer**

pH (1:10 suspension)	EC (dS·m <sup>-1</sup> , 1:10 extract)	OM	C	N	P	K	C/N
		%					
8.5	3.4	53.65	31.12	2.21	0.70	0.91	1:14

As shown in Table 3, the pH of the manure was moderately alkaline (8.5), and the electrical conductivity (EC) was 3.4 dS m<sup>-1</sup>. Organic matter content was high at 53.65%, while nitrogen (N), phosphorus (P), and potassium (K) contents were 2.21%, 0.70%, and 0.91%, respectively.

### 5. Experimental Design and Treatments

The experiment was conducted using a completely randomized block design (CRBD) on a total plot area of 200 m<sup>2</sup>. The field was divided into three replicates, with seven treatments and three replicates, resulting in a total of 21 experimental plots. Each plot measured 2 × 3 m, corresponding to an area of 6 m<sup>2</sup> per plot. Experimental plots were separated by 1 m-wide service alleys.

### 6. Measurement of Wheat Yield and Components, (CIMMYT, 1988), as:

#### Grain Yield (GY, t ha<sup>-1</sup>)

$$GY = \frac{\text{Weight of grains per plot (kg)} \times 10,000}{\text{Plot area (m}^2\text{)}}$$

#### Biological Yield (BY, t ha<sup>-1</sup>)

$$BY = \frac{\text{Total aboveground plant weight per plot (kg)} \times 10,000}{\text{Plot area (m}^2\text{)}}$$

#### 1000-Grain Weight (TGW, g)

$$TGW = \text{Weight of 1000 randomly counted grains (g)}$$

#### Grain Phosphorus Concentration (P, %)

Measured using standard acid digestion and spectrophotometry, (Murphy and Riley, 1962), as:

$$P (\%) = \frac{\text{Phosphorus content in mg per sample}}{\text{Grain dry weight (mg)}} \times 100$$

#### Phosphorus Use Efficiency (PUE, %)

$$PUE = \frac{GY_{\text{fertilized}} - GY_{\text{control}}}{P_{\text{applied}}} \times 100$$

Where  $GY_{\text{fertilized}}$  is grain yield from fertilized plots,  $GY_{\text{control}}$  is grain yield from the control plot, and  $P_{\text{applied}}$  is the amount of phosphorus applied (kg ha<sup>-1</sup>). To maintain unit consistency, grain yield (GY) values, originally expressed in t ha<sup>-1</sup>, were converted to kg ha<sup>-1</sup> (1 t = 1,000 kg) before calculating PUE, so that both the numerator and denominator are expressed in kg ha<sup>-1</sup>.

## 7. Treatments Used in the Experiment

Soil phosphorus content was sufficient (15.6 ppm); therefore, according to (Laboski and Peters, 2012), only half of the depleted phosphorus amount for wheat (75 kg P<sub>2</sub>O<sub>5</sub>) was applied, corresponding to 37.5 kg P<sub>2</sub>O<sub>5</sub> per hectare. Based on the wheat phosphorus requirements according to the Ministry of Agriculture fertilizer recommendations, the following treatments were used in Table 4:

**Table 4. Phosphorus Fertilizer Treatments and Application Rates**

Treatment Code	Description
T0	Control (no fertilizer application)
T1	Triple superphosphate (46% P <sub>2</sub> O <sub>5</sub> ) at 37.5 kg P <sub>2</sub> O <sub>5</sub> /ha
T2	Triple superphosphate + cow manure at 20 t/ha
T3	Single superphosphate (15% P <sub>2</sub> O <sub>5</sub> ) at 37.5 kg P <sub>2</sub> O <sub>5</sub> /ha
T4	Single superphosphate + cow manure at 20 t/ha
T5	Monoammonium phosphate (61% P <sub>2</sub> O <sub>5</sub> ) at 37.5 kg P <sub>2</sub> O <sub>5</sub> /ha
T6	Monoammonium phosphate + cow manure at 20 t/ha

## 8. Planting and Fertilization

The field was sown on December 10, 2023, following the application of phosphorus fertilizers (triple superphosphate, single superphosphate, and monoammonium phosphate) to all treatments in a single pre-planting application, cow manure was applied to 9 experimental plots before sowing.

Nitrogen fertilizer (urea) was applied to all treatments in three splits according to the Ministry of Agriculture recommendations. The total nitrogen applied was 4,200 g, distributed as 200 g per plot over three splits:

First split: 20% of total nitrogen, applied 20 days after sowing (40 g per plot)

Second split: 40% of total nitrogen, applied 30 days after sowing (80 g per plot)

Third split: 40% of total nitrogen, applied 30 days after the second split (80 g per plot)

The soil was plowed after the adding the organic and phosphorus fertilizers to incorporate and mix the amendments. Planting rows were prepared using a hoe, with eight rows per experimental plot. All plots were irrigated by surface irrigation at emergence, and irrigation was continued throughout the growing season. Crop topping was performed after April 15, 2024 to ensure proper grain filling and vitamin storage. The crop was monitored continuously, and manual weeding was performed whenever necessary.

## 9. Harvesting

The crop was harvested on May 28, 2024 by cutting the plants at ground level.

## Statistical Analysis

All experimental data were analyzed using one-way analysis of variance (ANOVA) to evaluate the effects of different fertilizer treatments. Means were compared using the Least Significant Difference (LSD) test at a significance level of  $p \leq 0.05$ . Data were checked for normality and homogeneity of variances prior to analysis. All statistical analyses were performed using SPSS version 27. (IBM Corp, 2017) Differences among treatment means were considered statistically significant when  $p \leq 0.05$ .

## Results and Discussion

### 1. Grain Yield ( $t\ h^{-1}$ )

Table 5. shows a significant superiority for the treatment Monoammonium phosphate + cow manure, which produced the highest grain yield of  $3.78\ t\ h^{-1}$ , while the lowest yield was observed in the control treatment ( $2.87\ t\ h^{-1}$ ). Other treatments exhibited intermediate yields ranging from  $3.00$  to  $3.57\ t\ h^{-1}$ .

The superior performance of monoammonium phosphate is attributed to the enhanced phosphorus availability and increased nutrient uptake efficiency, in addition to the supplementary contribution of cow manure. The organic matter also plays a role in chelating calcium, preventing its reaction with phosphorus to form poorly soluble calcium phosphates. The combined effect of phosphate fertilization and cow manure amendments resulted in a gradual increase in wheat grain yield, reflecting the critical importance of phosphorus for wheat growth under the studied soil conditions.

Several studies have confirmed a positive effect of phosphate fertilization on grain yield (Bashir *et al.*, 2015). Similar findings were reported by (Khan *et al.*, 2021), who indicated that grain yield increases with higher phosphorus rates, likely due to sufficient nutrient availability during seed filling, which enhances the genetic potential for seed development. Furthermore, the combined application of organic and chemical fertilizers significantly increased grain yield compared to chemical fertilization alone (Hou HongQian *et al.*, 2011). This improvement can also be linked to the increase in 1000-grain weight, as organic fertilizer promotes nutrient storage in the grains through enhanced growth and nutrient uptake.

**Table 5. Effect of fertilizer treatments on grain yield ( $t\ h^{-1}$ )**

Treatment	Grain yield ( $t\ h^{-1}$ )
Control	2.87 c
Triple superphosphate	3.17 bc
Triple superphosphate + cow manure	3.34 abc
Single superphosphate	3.00 c
Single superphosphate + cow manure	3.35 abc
Monoammonium phosphate	3.57 ab
Monoammonium phosphate + cow manure	3.78 a
<b>LSD 5%</b>	<b>0.56</b>

Note: Different letters indicate significant differences at  $P \leq 0.05$ .

## 2. Yield Components

### 2.1. Thousand-Grain Weight (g)

Table 6. shows the effect of different fertilizer treatments on thousand-grain weight, which reflects the degree of grain filling. Thousand-grain weight is an important component of yield, along with grain number and weight per spike and the number of spikes per unit area.

It can be observed that the studied treatments a significantly effect on thousand-grain weight, which ranged from  $42.57$  to  $47.60\ g$ . The highest value was recorded for Monoammonium phosphate + cow manure ( $47.60\ g$ ), while the lowest was in the control ( $42.57\ g$ ), with no significant differences between the remaining treatments and the control.

The improvement in thousand-grain weight is due to combining organic and inorganic fertilizers which attributed to increased grain yield and enhanced soil fertility. As reported by (Yang and Yang, 2021), organic fertilizers increase soil field capacity and available water for plants, positively affecting nutrient uptake during periods of low soil moisture. This supports the findings of (Hou HongQian *et al.*, 2011), who concluded that combining organic and inorganic fertilizers enhances both crop productivity and thousand-grain weight.

**Table 6. Effect of different fertilizer treatments on thousand-grain weight (g)**

Treatment	Thousand-grain weight (g)
Control	42.57 b
Triple superphosphate	45.73 ab
Triple superphosphate + cow manure	46.90 ab
Single superphosphate	44.90 ab
Single superphosphate + cow manure	45.33 ab
Monoammonium phosphate	46.00 ab
Monoammonium phosphate + cow manure	47.60 a
<b>LSD 5%</b>	<b>4.54</b>

Least Significant Difference (5%) = 4.54, Note: Different letters indicate significant differences at  $P \leq 0.05$ .

## 2.2. Biological Yield (t h<sup>-1</sup>)

Biological yield significantly differed among treatments Table 7. The highest biological yield was recorded in the Monoammonium phosphate + cow manure treatment (21.86 t ha<sup>-1</sup>), followed by Triple superphosphate + cow manure (21.10 t ha<sup>-1</sup>). The lowest yield occurred in the control treatment (18.42 t ha<sup>-1</sup>). The increase in biological yield with integrated application of phosphorus fertilizers and cow manure is attributed to improved nutrient availability and soil fertility, which enhanced dry matter accumulation during the growth period. These results are consistent with findings reported by (Jamal *et al.*, 2023), who demonstrated that combining phosphorus fertilizer with organic amendments increases biomass production and phosphorus availability in calcareous soils.

**Table 7. Effect of fertilizer treatments on biological yield (t h<sup>-1</sup>)**

Treatment	biological yield (t h <sup>-1</sup> )
Control	15.40 e
Triple superphosphate	16.45 d
Triple superphosphate + cow manure	17.74 c
Single superphosphate	16.19 d
Single superphosphate + cow manure	19.94 b
Monoammonium phosphate	18.03 c
Monoammonium phosphate + cow manure	21.86 a
<b>LSD 5%</b>	<b>0.28</b>

Least Significant difference (5%) = 0.28. Note: Different letters in the column indicate significant differences at  $P \leq 0.05$ .

## 3. Soil Available Phosphorus Content After Harvest (mg kg<sup>-1</sup>)

Table 8 shows the soil available phosphorus content after harvest. Soil phosphorus content varied according to the fertilizer applied. The triple superphosphate + cow manure treatment recorded the highest value among the treatments, reaching 46.89 mg kg<sup>-1</sup>, without significant difference from triple superphosphate alone (42.10 mg kg<sup>-1</sup>). The control treatment exhibited the lowest phosphorus

content at 4.96 mg kg<sup>-1</sup>. Statistical analysis using one-way ANOVA followed by LSD test ( $p \leq 0.05$ ; LSD = 6.5) indicated that there were significant differences among the treatments overall. Lower phosphorus content in the monoammonium phosphate and monoammonium phosphate + cow manure treatments is likely due to higher phosphorus uptake by wheat plants, which is consistent with findings in wheat reported by (Luo *et al.*, 2023).

**Table 8. Effect of fertilizer treatments on soil phosphorus content (mg kg<sup>-1</sup>)**

Treatment	Soil Phosphorus Content (mg kg <sup>-1</sup> )
Control	4.69 d
Triple superphosphate	42.10 a
Triple superphosphate + cow manure	46.89 a
Single superphosphate	34.66 b
Single superphosphate + cow manure	28.02 c
Monoammonium phosphate	24.12 c
Monoammonium phosphate + cow manure	28.02 c
<b>LSD 5%</b>	<b>6.5</b>

Least Significance Difference (5%) = 6.5.

#### 4. Soil Mineral Nitrogen Content After Harvest (mg kg<sup>-1</sup>)

Table 9. shows the soil mineral nitrogen content after harvest. The mineral nitrogen content varied with the fertilizer treatments. The highest value was recorded in the Monoammonium phosphate + organic fertilizer treatment, reaching 16.76 mg kg<sup>-1</sup>, while the lowest value was observed in the control treatment, at 4.45 mg kg<sup>-1</sup>. Some treatments did not differ significantly from the control, while others showed significant increases.

The reduction in soil mineral nitrogen is attributed to plant uptake, as well as partial loss through ammonia volatilization. Nitrogen is a key factor for wheat growth after irrigation and has a significant effect on nitrogen uptake in cereal crops. The lower nitrogen content in the soil under the monoammonium phosphate treatment is linked to increased grain productivity and higher nitrogen uptake (Yu *et al.*, 2022), which is consistent with findings reported by (Ma *et al.*, 2023).

**Table 9. Effect of Fertilizer Treatments on Soil Mineral Nitrogen Content (mg kg<sup>-1</sup>)**

Treatment	Soil Mineral Nitrogen (mg kg <sup>-1</sup> )
Control	4.45 c
Triple superphosphate	6.76 c
Triple superphosphate + cow manure	15.40 ab
Single superphosphate	7.16 c
Single superphosphate + cow manure	13.46 ab
Monoammonium phosphate	12.60 b
Monoammonium phosphate + cow manure	16.76 a
<b>LSD 5%</b>	<b>3.87</b>

Least Significance difference (5%) = 3.87. Different letters within the same column indicate statistically significant differences at  $p \leq 0.05$ .

#### 5. Plant Phosphorus Content

##### 5.1. Phosphorus Content in Grains (%)

Table 10 shows the effect of different fertilizer treatments on phosphorus content (%) in wheat grains. The highest values were obtained with triple superphosphate + cow manure (0.46%) and monoammonium phosphate + cow manure (0.38%), which did not differ significantly from each

other (difference = 0.08% < LSD = 0.107). The control treatment recorded the lowest phosphorus content (0.14%). Other treatments (e.g., TSP or MAP applied alone) showed intermediate values; while they did not differ significantly from each other in some cases, most were significantly higher than the control.

The enhanced grain phosphorus in treatments combining inorganic P fertilizers with cow manure is likely due to improved phosphorus availability and uptake efficiency resulting from organic–inorganic interactions. These results are consistent with findings by (Bashir *et al.*, 2015).

**Table 10. Effect of different fertilizer treatments on phosphorus content in wheat grains (%)**

Treatment	Phosphorus content in wheat grains (%)
Control	0.14 c
Triple superphosphate	0.29 b
Triple superphosphate + cow manure	0.46 a
Single superphosphate	0.29 b
Single superphosphate + cow manure	0.34 b
Monoammonium phosphate	0.30 b
Monoammonium phosphate + cow manure	0.38 ab
<b>LSD 5%</b>	<b>0.107</b>

Least Significant difference (5%) = 0.107. Different letters in the same column indicate significant differences at  $P \leq 0.05$ . *Note:* Different letters in the same column indicate significant differences at  $P \leq 0.05$ .

## 5.2. Phosphorus Content in Straw (%)

Table 11 shows the phosphorus content in straw. It can be observed that there were no significant differences between most treatments; however, significant differences were detected for Triple superphosphate + cow manure compared to Single superphosphate and the control.

Phosphorus fertilization had a limited role in increasing phosphorus content in straw. This is attributed to the translocation of absorbed phosphorus from the vegetative parts during the heading stage toward the newly formed grains, where it is stored as phytic acid. Additionally, a significant portion of absorbed phosphorus is stored in the plant roots, contributing to cell division and root elongation, and is involved in energy compounds (ADP, ATP) required for nutrient absorption by roots (Mengel and Kirkby, 2012).

**Table 11. Effect of different fertilizer treatments on phosphorus content in wheat straw (%)**

Treatment	Phosphorus content in straw (%)
Control	0.056 b
Triple superphosphate	0.072 ab
Triple superphosphate + cow manure	0.094 a
Single superphosphate	0.045 b
Single superphosphate + cow manure	0.070 ab
Monoammonium phosphate	0.062 ab
Monoammonium phosphate + cow manure	0.070 ab
<b>LSD 5%</b>	<b>0.035</b>

Least Significant Difference (5%) = 0.035. *Note:* Identical letters indicate no significant differences at  $P \leq 0.05$ .

### 3.6. Phosphorus Utilization Efficiency (PUE %)

Table 12 shows the calculated PUE for the studied soil. A slight increase in phosphorus utilization was observed with higher phosphorus fertilization rates, but the increase was not significant among treatments, except for Single Superphosphate compared with MAP and MAP + cow manure treatments. The highest efficiency values were recorded for MAP + cow manure and MAP alone (27.70% and 27.62%, respectively), while PUE significantly decreased (14.42%) for the Single Superphosphate treatment.

The lower efficiency of single superphosphate is attributed to its slow dissolution rate, which limits phosphorus availability and absorption. A portion of phosphorus may become fixed in the soil by binding to clay, calcium carbonate, or iron oxides, rendering it unavailable to plants. These processes contribute to phosphorus loss, reducing overall utilization efficiency (Han *et al.*, 2022).

**Table 12. Effect of fertilizer treatments on phosphorus utilization efficiency (%)**

Treatment	Phosphorus Utilization Efficiency (%)
Triple Superphosphate	18.95 ab
Triple Superphosphate + cow manure	26.14 ab
Single Superphosphate	14.42 b
Single Superphosphate + cow manure	19.43 ab
Monoammonium phosphate	27.62 a
Monoammonium phosphate + cow manure	27.70 a
<b>LSD 5%</b>	<b>12.81</b>

Note: Identical letters indicate no significant difference at  $P \leq 0.05$ .

### Conclusions

Organic fertilization (composted cow manure) positively influenced wheat growth and yield, with the best results observed in treatments combining organic and chemical phosphorus fertilizers. The chemical form of phosphorus significantly affected its solubility and release in soil. Among the treatments, MAP + cow manure produced the highest wheat yield and improved traits such as total plant biomass, grain yield, 1000-grain weight, and spike length, whereas the lowest values were recorded in the control plots. No significant differences were observed in phosphorus content in straw among treatments, which ranged from 0.056–0.070%. Phosphorus utilization efficiency (PUE) was highest with MAP + cow manure (27.70%) and lowest with Single Superphosphate (14.42%). Based on these results, practical recommendations for wheat cultivation in calcareous soils are: *A.* Phosphate fertilizer rates should be determined according to soil analysis, taking into account the utilization efficiency of each fertilizer type. *B.* Integrated use of organic and chemical phosphorus fertilizers is advised to improve grain yield and quality while reducing production costs, particularly under rising fertilizer prices. *C.* MAP combined with composted cow manure at 20 t ha<sup>-1</sup> is recommended as the most effective treatment to maximize wheat productivity and phosphorus use efficiency.

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### Author Contribution

The first, second, and third authors wrote the original draft, while the fourth and fifth authors edited and finalized the manuscript. All authors have read and approved the submission of the manuscript to the journal.

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