EFFECT OF UREA-PHOSPHATE AND ITS APPLICATION METHODS ON MAIZE (*ZEA MAYS* L.) GROWTH, YIELD AND NUTRIENT USE EFFICIENCY

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Abstract. An experiment was conducted to investigate the effects of different doses and application methods of urea-phosphate on the growth, yield, and nutrient use efficiency of maize. The experiment included four urea-phosphate application methods: control (no urea-phosphate) (T_1), 50% of the recommended rate (T_2), 75% of the recommended rate (T_3), and the recommended rate (T_4). The application methods comprised soil application (A_1), soil application with fertigation (A_2) and foliar application (A_3). The experiment followed a completely randomized design with three replications. Various growth attributes, yield parameters, and nutrient use efficiency were measured, including plant height, number of leaves per plant, cob length, number of grain lines per cob, number of grains per cob, biological yield, grain yield, 1000 grain weight, harvest index, Photosynthetic rate, Transpiration rate, Sub-stomatal CO_2 growth rate. Quality parameters like starch and protein were also measured. The collected data were subjected to statistical analysis using the Tukey test followed by analysis of variance technique. Soil application and fertigation generally yielded better outcomes compared to foliar application. Fertigation resulted in the highest average plant height, number of leaves per plant, cob length number of grain lines per cob and grain yield. Overall, the application methods and doses of urea-phosphate had a significant influence on maize growth, yield, and nutrient use efficiency. Soil application and fertigation methods were found to be more effective than foliar application. The study suggested that urea-phosphate, particularly when applied at the recommended rate through soil or fertigation, can enhance maize growth and yield.
Keywords: *cob, photosynthetic rate, grain, yield, urea, fertigation*

Introduction

Maize (*Zea mays* L.) is a vital summer crop and a significant member of the Poaceae family. The maize grain, commonly known as corn grain, contains various essential nutrients, including moisture, ether extracts, ash, fiber, oil, protein, and carbohydrates. In Pakistan, maize cultivation occupies a substantial land area, ranking third after wheat and rice. However, the average grain yield of maize in Pakistan is lower than the global average, indicating the need for improved agricultural practices and nutrient management (Wu et al., 2022; Bastiaanssen and Ali, 2003).

Crop nutrition plays a critical role in plant development, with mineral elements in soil and solution influencing plant growth. The lack of integrated nutrient management and the use of high-yielding crop varieties in Pakistan has led to the depletion of organic matter in the soil, resulting in nutritional deficiencies and reduced corn yields. To maximize agricultural output and meet the increasing food demand, it is crucial to provide plants with the necessary nutrients in the right amounts and proportions (Azam and Shafique, 2017).

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Fertilizer use has been a significant contributor to crop production worldwide, increasing yields by over 50%. However, there is a need to enhance the efficiency of fertilizer use to achieve sustainable production and minimize environmental pollution. Nutrient efficiency, encompassing uptake efficiency and physiological utilization of nutrients, plays a crucial role in maximizing crop yield per unit application of nutrients (Amin, 2011).

Although fertilizer application rates have increased in Asia, Europe, and America, the efficiency of fertilizer use remains low. Excessive application rates, particularly of nitrogen (N) and phosphorus (P), have led to environmental degradation, including soil and water pollution. Low nutrient use efficiency and inefficient recovery rates of nutrients from agricultural systems pose significant challenges to sustainable farming (Azam and Shafique, 2017; Eissa, 2016). Optimizing efficient fertilization programs that consider crop requirements, soil capacity, and the use of appropriate sources, doses, and application methods is essential. Balanced fertilization and the supply of all essential nutrients are prerequisites for improving crop productivity, especially in the face of changing climatic patterns and increasing fertilizer prices. Breeding efforts to enhance crop yield potential have not shown satisfactory improvement in nutrient use efficiency, highlighting the need for comprehensive nutrient management strategies (Hammad et al., 2012; Gheysari et al., 2015).

Phosphorus availability to crops is often limited due to its reactions with minerals and organic matter in the soil, resulting in fixation and low inherent P content. Fertilizer use efficiency depends on the type of fertilizer, its characteristics, and the method of application. Various application methods, such as soil application, fertigation, and foliar spray, have advantages and disadvantages depending on soil conditions and crop types (Iqbal et al., 2003; Patel et al., 2017).

To improve fertilizer, use efficiency and minimize nutrient loss, it is crucial to develop fertilizers that have advantages over conventional ones, meeting plant needs, reducing soil reactions, and minimizing environmental pollution.

In this study, the objectives were to explore the release pattern of N and P from a formulated urea-phosphate fertilizer, determine the most effective fertilizer application method (soil, fertigation, or foliar) for maize crop production, and compare the fertilizer use efficiency of commercially available fertilizers with the formulated urea-phosphate fertilizer (Swify et al., 2022; Yaseen et al., 2021; Gheysari et al., 2015). Overall, this research aims to address the challenges of nutrient management in maize cultivation and contribute to sustainable agricultural practices, enhancing crop productivity while minimizing environmental impacts.

Materials and methods

The study was conducted at the wire house of ISES, University of Agriculture, Faisalabad, using a pot experiment to investigate the impact of different doses and application methods of urea-phosphate on the growth, yield, and nutrient use efficiency of maize. The treatment plan consisted of the following urea-phosphate application methods: (1) Control group (no urea-phosphate), (2) 50% of the recommended rate of urea-phosphate, (3) 75% of the recommended rate of urea-phosphate and (4) Recommended rate of urea-phosphate. The Recommended rate of fertilizers were at the rate of 175 kg N ha^{-1}, 125 kg P_2O_5 ha^{-1}, and 125 kg K_2O ha^{-1} for maize crop. In cases where reduced rates of urea-phosphate were used, the

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remaining amounts of nitrogen (N) and phosphorus (P) were applied in the form of urea and single super phosphate (SSP) to ensure adequate nutrient supply. In the case of the full rate of urea-phosphate, phosphorus supply was fulfilled with urea-phosphate, and the remaining amount of nitrogen was applied through urea. The application methods used were as follows: (A1) Soil application (common practice), (A2) Soil application + Fertigation at a 6:4 ratio (practiced by progressive farmers), and (A3) Soil application + Fertigation + Foliar application at a 5:4:1 ratio (integrated approach). Foliar application was done at the V4, V5, and V6 stages of growth and according to BBCH scale there is Principal growth stage 5: (Inflorescence emergence, heading) in this experiment. The experiment was set up using a completely randomized design in factorial arrangements with three replications. The pots were filled with 10 kg of soil, which had physicochemical properties as pH 7.5, EC 1.41 dS m^{-1}, available phosphorus 7.34 mg kg^{-1}, total nitrogen 0.04%, organic matter 0.84%, extractable potassium 131 mg kg^{-1}, saturation percentage 35%, CEC 4.41 $cmol_c$ kg^{-1}, Clay 21%, Silt 28%, Sand 51% and Textural class was sandy clay loam. Two seeds of the maize variety "Sohni Dharti 3575" were sown in each pot, and after germination, one plant was maintained through manual thinning. The uprooted seedling was chopped and buried back into the same pot's soil. Data on growth attributes and yield were recorded at the crop's maturity. Nutrient use efficiency was calculated to assess the effectiveness of urea-phosphate in improving maize yield. The crop was sown on February 5th, 2019 and harvested on June 12th, 2019. Data collection included the following measurements and observations: Plant height (cm), Number of leaves per plant, Cob length (cm) Number of grains lines per cob, Number of grains per cob, Biological yield (t ha^{-1}), Grain yield (t ha^{-1}), 1000 grain weight, Harvest index and Growth rate (g m^{-2} day^{-1}). Photosynthetic rate, Transpiration rate (µmol m^{-1} s^{-1}), Sub-stomatal CO_2 (µmol mol^{-1}) estimated using CIRAS-3 gas analyzer. Estimation of Starch (%) were determined by method described by Sullivan (1935) and protein (%) was determined burette method described by Gornall et al. (1949).

Urea-phosphate use efficiency was calculated following *Equation 1:*

$$\text{Urea-phosphate use efficiency} = \frac{\text{Grain yield fertilized pot} - \text{Grain yield in control}}{\text{Applied urea-phosphate}} \quad \text{(Eq.1)}$$

The collected data were statistically analyzed using Tukey's test which is a post hoc statistical procedure utilized following an analysis of variance (ANOVA) to identify statistically significant differences between multiple group means, assuming homoscedasticity, and is employed for the specific purpose of pairwise comparisons among means.

Results and discussion

The use of urea phosphate offers a range of advantages, including enhanced nutrient availability, reduced environmental impact, and improved nutrient use efficiency. These factors collectively contribute to its potential as a more efficient and eco-friendly option for providing nitrogen and phosphorus to crops. The efficiency of urea phosphate in nutrient delivery can result in cost savings for farmers due to reduced fertilizer requirements and improved crop yields.

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Plant height

Plant height was significantly affected by all application methods and different rates of urea-phosphate, as depicted in *Table 1*. Urea-phosphate applied as foliar application at 50% of recommended dose enhanced plant height up to 16.6% in comparison to control. Similarly, 75% of recommended rate increased maize plant height up to 21% than control. While 100% recommended rate did not give much attractive results as it showed 18.7% increment in the plant height as compared to control and it was less than shown by application of 75% of recommended rate. A similar trend was shown by fertigation and soil method that gave 21, 28.6 and 22%, and 21, 34 and 33% increase in plant height, respectively in comparison to their respective control. Among application methods soil method was the best, as it gave maximum (7.5% higher than foliar application) plant height, though fertigation application also improved 2.8% higher plant height than foliar application. However, foliar application of urea-phosphate was found least effective. The study showed that all treatment techniques and various urea-phosphate rates significantly affected plant height. The reasoning behind this is that urea-phosphate is a source of crucial nutrients for plant growth, and that the technique and pace of administration affect the minerals' availability and absorption by the plants (Aina et al., 2020; Alam et al., 2003). In comparison to the control, the foliar treatment at 50% of the prescribed dose resulted in the greatest increase in plant height, demonstrating that urea-phosphate absorption through the leaves may efficiently stimulate plant development. However, the methods of soil application and fertigation typically produced superior outcomes, with fertigation exhibiting the greatest average plant height. This may be explained by the direct nutrient supply to the root zone through fertigation and the plants' improved capacity to obtain nutrients from the soil with soil application.

Number of leaves per plant

Effect of urea-phosphate and its application methods on number of leaves per plant is presented in *Table 1*. Application of urea-phosphate via foliar decreased number of leaves as number of leaves per plant were found less as compared to the fertigation applied and soil applied urea-phosphate. However, fertigation application was found best among application methods. Among different doses of urea-phosphate application, recommended dose was found best, as it produced 21, 38 and 24% more number of leaves than control in foliar, fertigation and soil applied urea-phosphate, respectively. Urea-phosphate applied at the rate of 75% of recommended also gave promising results, as it stimulated 14, 30 and 22% higher number of leaves per plant than control via soil, fertigation and foliar application, respectively. The study discovered that the application of urea-phosphate and the amount of it had an impact on the number of leaves per plant. In comparison to fertigation and soil treatment, foliar spraying reduced the number of leaves on the plant. This can be explained by the fact that foliar treatment delivers nutrients directly to the leaves, perhaps causing a shift in the allocation of resources from leaf formation to leaf development (Al-Marsumy and Jarallah, 2019; Amin, 2011). The most successful technique for raising the number of leaves was fertigation treatment, especially when done at the recommended dose. A more even distribution of nutrients in the soil is made possible through fertigation, which encourages the growth and development of leaves and general plant health (Arif et al., 2010) as in this study.

Table 1. *Effect of urea-phosphate and its application methods on studied traits*

Treatment	Traits	A1	A2	A3	Mean
T1 = Control (no urea-phosphate)	Plant height	121.01d	120.35d	121.47d	120.95
	Number of leaves per plant	10.70 d	10.65 d	10.70 d	10.68
	Growth rate (g m^{-2} day^{-1})	12.85 d	12.95 d	12.31 d	12.57
	Cob length (cm)	8.74	12.14	8.03	09.64 C
	Number of grain lines per cob	07.53 c	07.43 c	07.27 cd	7.11
T2	Plant height	141.08c	145.65c	147.38bc	144.71
	Number of leaves per plant	12.71 c	13.16 c	13.33 bc	13.07
	Growth rate (g m^{-2} day^{-1})	12.36 c	12.09 bc	14.89 bc	14.78
	Cob length (cm)	12.19	12.87	12.68	12.58 B
	Number of grain lines per cob	08.20 b	08.25 b	08.54 b	8.33
T3	Plant height	146.43bc	154.79ab	162.74 a	154.65
	Number of leaves per plant	12.21 bc	13.80 a	13.03 ab	13.02
	Growth rate (g m^{-2} day^{-1})	14.98 bc	14.87 a	14.95 ab	14.94
	Cob length (cm)	12.77	13.99	13.45	13.41 A
	Number of grain lines per cob	09.34 ab	09.57 a	08.47 b	9.3
T4	Plant height	143.60 c	146.84 bc	161.85 a	150.76
	Number of leaves per plant	12.95 c	14.72 a	13.26 bc	13.65
	Growth rate (g m^{-2} day^{-1})	14.65 c	15.51 b	15.03 bc	15.49
	Cob length (cm)	12.46	12.09	12.81	13.13 A
	Number of grain lines per cob	09.10 ab	09.66 a	08.58 b	9.08
Mean	Plant height	138.03	141.91	148.36	
	Number of leaves per plant	13.41	14.42	13.79	
	Growth rate (g m^{-2} day^{-1})	14.21	15.27	14.61	
	Cob length (cm)	11.54 B	13.28 A	11.75 B	
	Number of grain lines per cob	8.49	8.74	8.7	
Q Value	Plant height	A = 5.3905 T = 3.6801 A×T = 8.297			
	Number of leaves per plant	A = 0.4082 T = 0.3465 A × T = 0.7919			
	Growth rate (g m^{-2} day^{-1})	A = 0.2862 T = 0.4333 A × T = 1.0503			
	Cob length (cm)	A = 0.6384 T = 0.3633 A × T = NS			
	Number of grain lines per cob	A = 0.1103 T = 0.4741 A ×T = 1.0835			

T_1 = Control (no urea-phosphate), T_2 = 50% urea-phosphate, T_3 = 75% urea-phosphate, T_4 = Recommended rate, A_1 = Common practice (Soil application), A_2 = Practice by progressive farmer (Soil application + fertigation), A_3 = Integrated approach (Soil application + fertigation + foliar application)

Growth rate (g m^{-2} day^{-1})

Growth rate was found excellent with soil application of urea-phosphate, as it showed highest growth rate at all rates of application as compared to the respective rate used by foliar application and fertigation application as mentioned in *Table 1*. Urea-phosphate applied at recommended rate was found much effective as compared to reduced rate in all application methods. However, 75% of recommended dose of urea-phosphate showed highest growth rate after recommended rate of application. But 50% of recommended rate showed least growth rate among urea-phosphate treatments,

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though it gave significantly higher growth rate than control. The study revealed that soil application of urea-phosphate yielded the highest growth rate compared to foliar and fertigation application methods (Azam and Shafique, 2017; Bakht et al., 2007). This can be attributed to the direct contact between the roots and the nutrients present in the soil, enabling efficient uptake and utilization of nutrients. The recommended rate of urea-phosphate consistently outperformed reduced rates in all application methods, emphasizing the significance of providing an adequate amount of nutrients for optimal growth (Asghar et al., 2010) as similar results found in the present study.

Photosynthetic rate

Figure 1 showed the effect of different doses of urea-phosphate applied via various methods of fertilizer application on photosynthetic rate in maize plants. Among rates of fertilizer application, 75% of recommended rate of urea-phosphate stimulated highest photosynthetic activity followed by recommended rate. Among application methods, though soil application gave promising results in terms of photosynthetic rate but at 75% of recommended and recommended rate of urea-phosphate, fertigation mode of application performed relatively better. Foliar application was not much effective in comparison to other fertilizer application methods. The study demonstrated that the photosynthetic rate of maize was influenced by different doses of urea-phosphate applied through various methods. Among the fertilizer application rates, 75% of the recommended rate of urea-phosphate stimulated the highest photosynthetic activity, followed by the recommended rate (Gheysari et al., 2015). Soil application showed promising results in promoting the photosynthetic rate, while fertigation application performed relatively better at 75% of the recommended rate and the recommended rate. Foliar application showed minimal effectiveness compared to other methods (Mahmood et al., 2001; Nedunchezhiyan et al., 2017).

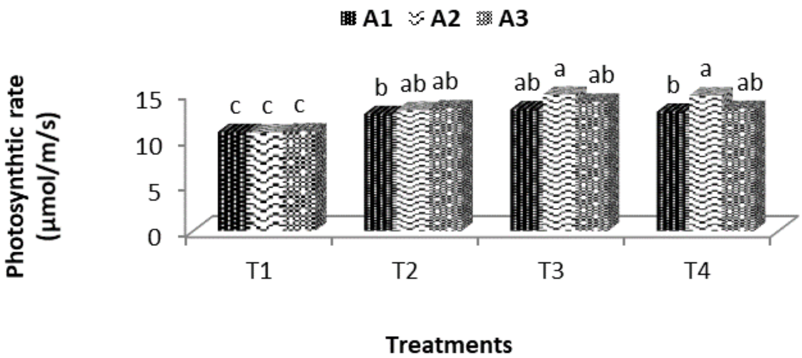

Figure 1. *Effect of urea-phosphate and its application methods on photosynthetic rate (µmol/m/s) of maize. T_1 = Control (no urea-phosphate), T_2 = 50% urea-phosphate, T_3 = 75% urea-phosphate, T_4 = Recommended rate, A_1 = Common practice (Soil application), A_2 = Practice by progressive farmer (Soil application + fertigation), A_3 = Integrated approach (Soil application + fertigation + foliar application)*

Transpiration rate

Unlike photosynthetic rate, transpiration rate was found highest with recommended rate of urea-phosphate application followed by 75% of recommended rate (*Fig. 2*). Fertigation mode of urea-phosphate application was found best in terms of transpiration rate, though

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soil application also gave nearby results. Foliar application was not much effective for transpiration rate also. 50% of recommended rate of urea-phosphate did not show much effective results though it gave higher transpiration rate in foliar, fertigation and soil application in comparison to respective control. The recommended rate of urea-phosphate application resulted in the highest transpiration rate, followed by 75% of the recommended rate. Fertigation application showed the best results in terms of transpiration rate, indicating that direct nutrient supply to the root zone facilitated efficient water uptake and transpiration. Soil application also yielded satisfactory results. Foliar application exhibited a relatively lower effectiveness in enhancing the transpiration rate, although it still showed higher rates compared to the control group for each application method (Gheysari et al., 2015; Ogola et al., 2002). The 50% reduced rate of urea-phosphate had a less significant effect on the transpiration rate compared to higher application rates.

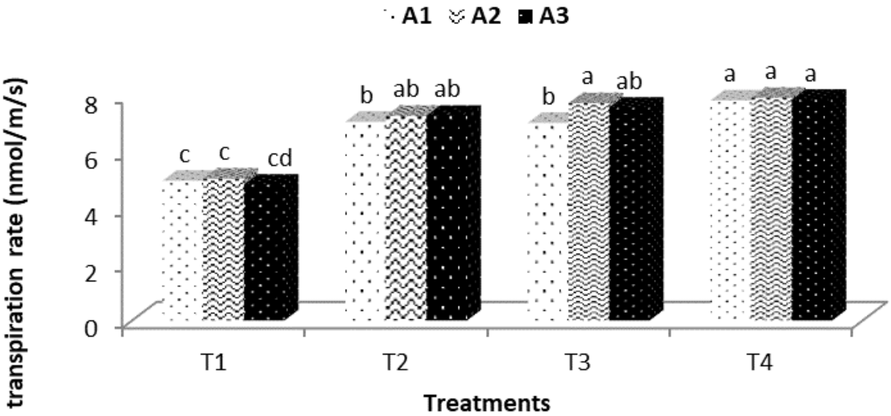

Figure 2. *Effect of urea-phosphate and its application methods on transpiration rate (µmol/m/s) of maize. T_1 = Control (no urea-phosphate), T_2 = 50% urea-phosphate, T_3 = 75% urea-phosphate, T_4 = Recommended rate, A_1 = Common practice (Soil application), A_2 = Practice by progressive farmer (Soil application + fertigation), A_3 = Integrated approach (Soil application + fertigation + foliar application)*

Sub-stomatal CO_2

In this study, *Figure 3* elaborates a strong influence of urea-phosphate rates and application methods on sub-stomatal CO_2 of maize plants. Among urea-phosphate application rates, 75% of recommended rate of urea-phosphate showed highest performance by indicating higher levels of sub-stomatal CO_2 applied via foliar, fertigation and soil application. Full recommended rate of urea-phosphate gave second highest level of sub-stomatal CO_2 by showing less sub-stomatal CO_2 than 75% of recommended rate but higher than 50% of recommended rate of urea-phosphate applied via foliar, fertigation and soil application. 50% of recommended rate of urea-phosphate did not show much promising results. Urea-phosphate rates and application methods exerted a strong influence on sub-stomatal CO_2 levels in maize plants. Among the application rates, 75% of the recommended rate exhibited the highest sub-stomatal CO_2 levels across foliar, fertigation, and soil application methods. Fertigation consistently displayed higher sub-stomatal CO_2 levels followed by soil application. Foliar application showed the lowest effectiveness in promoting sub-stomatal CO_2 levels (Parent et al., 2020; Patel et al., 2017).

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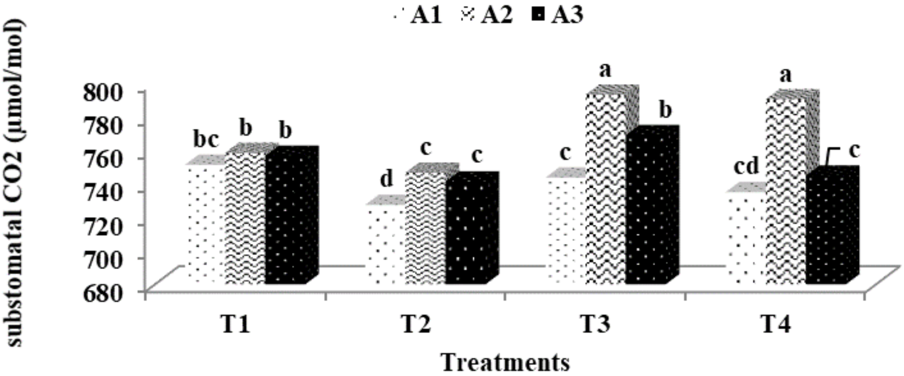

Figure 3. *Effect of urea-phosphate and its application methods on sub-stomatal CO_2 (µmol/mol) of maize. T_1 = Control (no urea-phosphate), T_2 = 50% urea-phosphate, T_3 = 75% urea-phosphate, T_4 = Recommended rate, A_1 = Common practice (Soil application), A_2 = Practice by progressive farmer (Soil application + fertigation), A_3 = Integrated approach (Soil application + fertigation + foliar application)*

Cob length (cm) of maize

Data on cob length showed a different trend, as fertigation application of urea-phosphate was found effective in comparison to other modes of application *Table 1*. Dose response was also different here as 75% of recommended rate of urea-phosphate gave maximum length of cob. Even cob length was less in recommended rate than 75% of recommended rate. At 75% of recommended rate, fertigation application showed 9.5 and 4% longer cobs in comparison to that of same rate with foliar and soil application, respectively. Recommended rate produced 5.6 and 3% less cob length with fertigation application than same rate with soil and foliar application, unlike to that of 50% of recommended rate where cob length was 1.5 and 5.6% higher with fertigation application than soil and foliar application. Fertigation application of urea-phosphate emerged as the most effective method in terms of cob length when compared to other application methods (Bastiaanssen and Ali, 2003; Dawadi and Sah, 2012). This can be attributed to the continuous and precise delivery of nutrients through fertigation, ensuring an optimal nutrient supply during the elongation phase of cob development. The results indicated that applying 75% of the recommended rate of urea-phosphate resulted in the maximum cob length. Fertigation application generally outperformed foliar and soil application methods, highlighting the importance of nutrient availability during the critical stage of cob development (Eissa, 2016).

Number of grain lines per cob

On an average 75% of recommended rate of urea-phosphate produced highest grain lines per cob followed by recommended rate of application. Among urea-phosphate treatments, 50% of recommended rate of urea-phosphate gave least grain lines per cob but these were still 17% higher than control. Fertigation application gave highest response in terms of number of grain lines per cob over foliar application and soil. On an average that was 2.9 and 0.5%, respectively (*Table 1*). In a close perspective highest number of grain lines per cob were observed with fertigation application of recommended rate of urea-phosphate followed by 75% of recommended rate of urea-phosphate. In foliar application, highest number of grain lines per cob were detected in

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75% of recommended rate of urea-phosphate followed by recommended rate, while in soil highest number of grain lines per cob were seen with recommended rate of urea-phosphate followed by 50% of recommended urea-phosphate and 75% of recommended rate of urea-phosphate gave least number of grain lines per cob among fertilizer applied via soil treatments. However, control gave least values. Fertigation application of urea-phosphate yielded the highest number of grain lines per cob compared to foliar and soil application methods. Fertigation allows for precise nutrient delivery to the root zone, ensuring efficient uptake and utilization of nutrients (Fang and Su, 2019; Gheysari et al., 2015). The recommended rate consistently outperformed reduced rates in terms of grain lines per cob. The control group (no urea-phosphate) exhibited the lowest number of grain lines per cob, underscoring the significance of urea-phosphate in promoting grain development.

Number of grains per cob

Data regarding effect of urea-phosphate and its application methods on number of grain per cob is presented in *Table 2*. Results showed significant effect of urea-phosphate and its application methods on number of grain per cob. Among the urea-phosphate application treatments, 75% of recommended rate of urea-phosphate produced maximum number of grain per cob followed by recommended rate. Minimum number of grains per cob was observed in control (no urea-phosphate). According to application methods, fertigation application method showed maximum number of grain per cob while minimum number of grain per cob was observed in foliar application method. The number of grains per cob was significantly influenced by urea-phosphate and its application methods. Fertigation consistently demonstrated the highest number of grains per cob, while foliar application exhibited the lowest values. This can be attributed to the direct and continuous nutrient supply through fertigation, ensuring optimal grain development and filling. The number of grains per cob increased with higher rates of urea-phosphate application. The recommended rate and 75% of the recommended rate generally led to higher grain numbers compared to reduced rates. The control group (no urea-phosphate) had the lowest number of grains per cob, highlighting the importance of urea-phosphate in maximizing grain yield (Kim et al., 2008; Liu et al., 2017).

1000 grain weight (g)

Effect of urea-phosphate and its application methods on 1000 grain weight is presented in *Table 2*. Results revealed that among urea-phosphate application rates, 75% of recommended rate of urea-phosphate treatment gave maximum 1000 grain weight in all application methods followed by recommended rate and minimum 1000 grain weight was observed in control (no urea-phosphate) (Swify et al., 2022). While in case of application methods, fertigation application method showed maximum 1000 grain weight at all rates of application and minimum 1000 grain weight was observed in foliar application methods among all application rates. Among the urea-phosphate application rates, 75% of the recommended rate consistently yielded the maximum 1000 grain weight in all application methods, followed by the recommended rate. The control group (no urea-phosphate) exhibited the lowest 1000 grain weight, underscoring the importance of urea-phosphate in achieving higher grain weight (Rodríguez-Blanco et al., 2015; ShrEStha et al., 2018).

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Table 2. *Effect of urea-phosphate and its application methods on studied traits*

Treatment		A1	A2	A3	Mean
T1	Number of grains per cob	251.24 d	258.29 d	256.52 d	255.35
	1000 grain weight (g)	198.07 c	190.97 c	197.62 c	195.56 C
	Biological yield (t ha^{-1})	06.81 d	06.51 d	06.15 d	6.49
	Grain yield (t ha^{-1})	1.97 d	2.05 d	1.83 d	2.11
	Harvest index (%)	33.45 cd	33.77 cd	33.02 d	33.42
T2	Number of grains per cob	227.34 c	346.42 bc	241.18 c	338.32
	1000 grain weight (g)	234.57 b	235.48 b	231.35 b	237.14 B
	Biological yield (t ha^{-1})	09.67 c	10.12 bc	10.28 bc	10.03
	Grain yield (t ha^{-1})	4.07 bc	4.28 bc	4.28 bc	4.69
	Harvest index (%)	37.06 bcd	42.11 ab	39.41 bcd	39.53
T3	Number of grains per cob	343.55 bc	392.94 a	368.85 ab	368.45
	1000 grain weight (g)	243.84 b	272.11 a	242.49 b	252.82 A
	Biological yield (t ha^{-1})	10.19 bc	11.00 ab	11.77 a	10.99
	Grain yield (t ha^{-1})	4.03 bc	4.73 a	4.57 ab	4.81
	Harvest index (%)	41.84 bcd	40.46 bc	39.88 bcd	40.72
T4	Number of grains per cob	334.96 c	390.23 a	344.77 bc	356.66
	1000 grain weight (g)	238.93 b	270.56 a	244.54 b	251.35 A
	Biological yield (t ha^{-1})	09.94 c	09.23 bc	11.69 a	10.62
	Grain yield (t ha^{-1})	3.83 c	4.92 a	4.85 a	4.89
	Harvest index (%)	39.96 abc	43.27 a	37.87 bcd	41.37
Mean	Number of grains per cob	314.28	346.97	327.84	
	1000 grain weight (g)	228.86 B	244.79 A	229.01 B	
	Biological yield (t ha^{-1})	9.16	9.47	9.98	
	Grain yield (t ha^{-1})	3.83	4.33	4.23	
	Harvest index (%)	38.08	39.9	37.55	
Q Value	Number of grains per cob	A = 8.108 T = 9.485 A × T = 10.585			
	1000 grain weight (g)	A = 4.8466 T = 6.3902 A ×T = 15.003			
	Biological yield (t ha^{-1})	A = 0.4187 T = 0.4059 A × T = 0.9278			
	Grain yield (t ha^{-1})	A = 0.1195 T = 0.1672 A×T = 0.3821			
	Harvest index (%)	A = 1.8447 T = 1.8981 A × T = 4.3384			

Means not sharing the same letter differ significantly ($p \leq 0.05$) by Tukey HSD test
T_1 = Control (no urea-phosphate), T_2 = 50% urea-phosphate, T_3 = 75% urea-phosphate, T_4 = Recommended rate, A_1 = Common practice (Soil application), A_2 = Practice by progressive farmer (Soil application + fertigation), A_3 = Integrated approach (Soil application + fertigation + foliar application)

Biological yield (t ha^{-1})

Results showed significant effect of urea-phosphate and its application methods on biological yield (*Table 2*). Among the urea-phosphate application methods, Soil application gave highest biological yield 9.98 t ha^{-1} followed by fertigation 9.47 tha^{-1}

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and foliar application 9.16 tha^{-1} on average regardless of application rates. Regardless of application methods, 75% of recommended rate of urea-phosphate gave highest average biological yield followed by recommended rate and 50% of recommended rate. However, treatment without urea-phosphate (i.e., control) showed least biological yield. When considering biological yield, soil application of urea-phosphate demonstrated the highest average yield of 9.98 tha^{-1}, followed by fertigation at 9.47 tha^{-1} and foliar application at 9.16 tha^{-1}, irrespective of the application rates. Among the application methods, regardless of the rates, the highest average biological yield was achieved with 75% of the recommended rate of urea-phosphate, followed by the recommended rate and 50% of the recommended rate (Thind et al., 2011; Ting-Hui et al., 2006). The control group, without urea-phosphate application, displayed the lowest biological yield.

Grain yield (t ha^{-1})

Maximum grain yield was shown by recommended rate of urea-phosphate applied as fertigation 4.92 t ha^{-1} followed by recommended rate of urea-phosphate applied via soil application 4.85 t ha^{-1} and 75% of recommended urea-phosphate applied by fertigation 4.73 t ha^{-1}. Non-significant results were observed for 50% of recommended rate of urea-phosphate among all application methods. Control showed least and non-significant results in all application methods. In foliar application grain yield was decreased with increase in the rate of urea-phosphate (*Table 2*). In terms of grain yield, the recommended rate of urea-phosphate applied through fertigation resulted in the maximum yield of 4.92 t ha^{-1}, followed by the recommended rate applied via soil application at 4.85 t ha^{-1}, and 75% of the recommended urea-phosphate applied through fertigation at 4.73 tha^{-1} (Wu et al., 2022). Non-significant differences were observed for the 50% reduced rate of urea-phosphate among all application methods. The control group exhibited the lowest and non-significant results across all application methods. Interestingly, in foliar application, grain yield decreased as the rate of urea-phosphate increased (Iqbal et al., 2003; Kaiser and Rubin, 2013; Kandil, 2013).

Harvest index (%)

In the present study, *Table 2* described that minimum harvest index was observed in control where no urea-phosphate was applied followed by 50% of recommended rate of urea-phosphate with foliar and soil application. While in fertigation minimum harvest index was indicated in 75% of recommended rate of urea-phosphate i.e. 40.5%. Maximum harvest index 43.27% was observed with recommended rate of urea-phosphate applied via fertigation technique. While minimum harvest index was observed in foliar application method for urea-phosphate application. The harvest index, which indicates the proportion of harvested grain to the total biological yield, varied depending on the application methods (Iqbal et al., 2003; Yang et al., 2020). The control group showed the minimum harvest index, followed by the 50% reduced rate of urea-phosphate with foliar and soil application. Among the fertigation methods, the minimum harvest index was observed with 75% of the recommended rate of urea-phosphate at 40.5%. The maximum harvest index of 43.27% was observed with the recommended rate of urea-phosphate applied through fertigation. The foliar application method generally resulted in the lowest harvest index for urea-phosphate application (Iqbal et al., 2003).

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Protein, starch content of maize and urea-phosphate efficiency

Effect of urea-phosphate and its application methods on protein, starch content of maize and urea-phosphate efficiency is depicted in *Figures 4, 5* and *6*, respectively. Results revealed that maximum protein and starch contents were observed where urea-phosphate was applied at the rate of 75% of urea-phosphate whereas, minimum were observed in control treatment followed by 50% recommended rate of urea-phosphate application. Among the application methods highest protein and starch content were recorded in fertigation application method and minimum in foliar application. Data on urea-phosphate efficiency also depicted a similar trend, as maximum efficiency was observed by 75% of recommended rate of urea-phosphate with all application methods followed by recommended rate. Minimum efficiency was given by 50% of recommended rate of urea-phosphate. Among application methods, highest efficiency was given by fertigation technique followed by soil application. However, the performance of foliar application was minimal (Hammad et al., 2012; Iqbal et al., 2003). When analyzing protein and starch content, it was evident that applying urea-phosphate at a rate of 75% of the recommended amount led to the maximum protein and starch contents, while the minimum contents were observed in the control treatment, followed by the 50% recommended rate of urea-phosphate application (Gheysari et al., 2015). Among the application methods, fertigation yielded the highest protein and starch content, while foliar application had the lowest. The data on urea-phosphate efficiency followed a similar trend, with the maximum efficiency achieved by applying 75% of the recommended rate of urea-phosphate through all application methods, followed by the recommended rate. The minimum efficiency was observed with 50% of the recommended rate of urea-phosphate (Gheysari et al., 2009; Yaseen et al., 2021). Among the application methods, fertigation demonstrated the highest efficiency, followed by soil application, while foliar application showed the lowest performance.

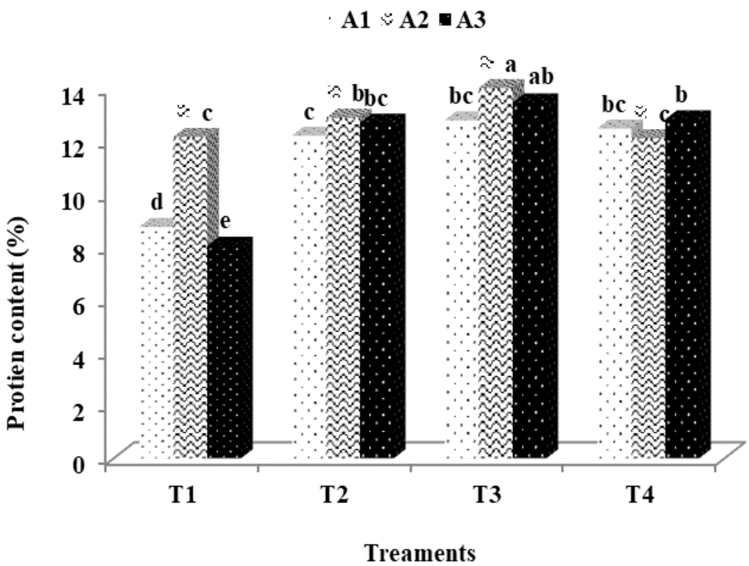

Figure 4. *Effect of urea-phosphate and its application methods on protein content (%) of maize. T_1 = Control (no urea-phosphate), T_2 = 50% urea-phosphate, T_3 = 75% urea-phosphate, T_4 = Recommended rate, A_1 = Common practice (Soil application), A_2 = Practice by progressive farmer (Soil application + fertigation), A_3 = Integrated approach (Soil application + fertigation + foliar application)*

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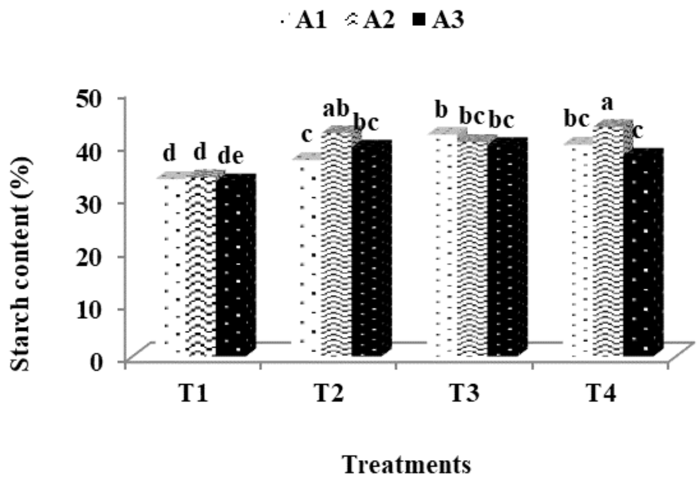

Figure 5. *Effect of urea-phosphate and its application methods on starch content (%) of maize. T_1 = Control (no urea-phosphate), T_2 = 50% urea-phosphate, T_3 = 75% urea-phosphate, T_4 = Recommended rate, A_1 = Common practice (Soil application), A_2 = Practice by progressive farmer (Soil application + fertigation), A_3 = Integrated approach (Soil application + fertigation + foliar application)*

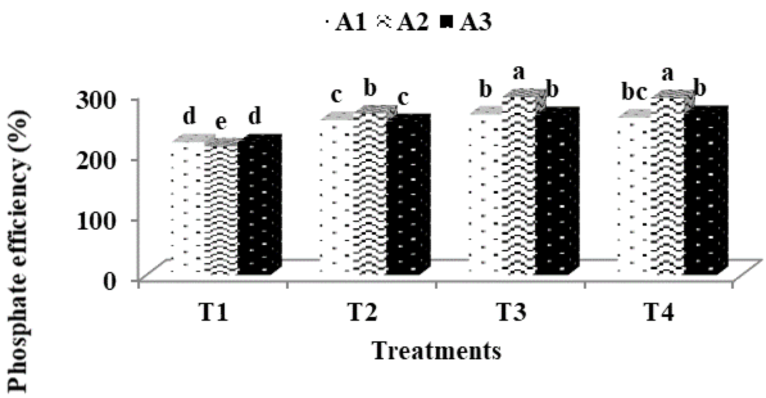

Figure 6. *Effect of urea-phosphate and its application methods on urea-phosphate efficiency (ug g^{-1}). T_1 = Control (no urea-phosphate), T_2 = 50% urea-phosphate, T_3 = 75% urea-phosphate, T_4 = Recommended rate, A_1 = Common practice (Soil application), A_2 = Practice by progressive farmer (Soil application + fertigation), A_3 = Integrated approach (Soil application + fertigation + foliar application)*

These findings underscore the importance of urea-phosphate rates and application methods in influencing biological yield, grain yield, harvest index, protein content, starch content, and urea-phosphate efficiency in maize cultivation. It is suggested that applying urea-phosphate at the recommended rate through fertigation or soil application can maximize yield and improve crop quality. Furthermore, fertigation appears to be more effective than foliar application in terms of nutrient uptake and utilization, resulting in higher protein and starch content (Gheysari et al., 2015, 2009). Overall, fertigation and soil application of urea-phosphate at the recommended rate showed the most favorable outcomes for maize growth and yield, indicating the importance of optimizing fertilizer application strategies for maximizing crop productivity.

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Conclusion

The study revealed a significant impact of urea-phosphate rates and application methods on the growth and productivity of maize plants. Fertigation application, along with the recommended rate of urea-phosphate, consistently produced the best outcomes across various parameters, including plant height, number of leaves per plant, cob length, number of grain lines per cob, number of grains per cob, photosynthetic rate, transpiration rate, and sub-stomatal CO_2 levels. Soil application also showed promising results in terms of plant height and growth rate. On the other hand, foliar application exhibited comparatively lower effectiveness. These findings offer valuable insights into optimizing fertilizer application strategies for maize cultivation, leading to higher yields and improved crop quality.

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