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Interactive Effects of Mineral Fertilizer and Irrigation Method on Nutrient Uptake and Use Efficiency in Quinoa

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I. ABSTRACT

Native to the Andes Mountains of South America, quinoa (Chenopodium quinoa Willd.) is a pseudocereal crop. Quinoa seeds are suitable for human and animal consumption due to their high nutritional value. Many factors affect a plant's ability to uptake nutrients, including inadequate or improper irrigation. The current study was aimed at analyzing the effect of mineral fertilization under different irrigation systems (drip and surface). The mineral fertilizer levels applied included 3 levels (0, 50, and 100% of the recommended fertilizer rate of (120 kg ha^{-1} N + 50 kg ha^{-1} P + 80 kg ha^{-1} K). Treatments that received the full dose of mineral fertilizer resulted in greater nutrient uptake values compared to 50% of the dose and the unfertilized control. The drip irrigation system resulted in the highest positive response of nutrient uptake compared to surface irrigation. The highest nutrient use efficiency values were obtained under drip irrigation at the 50% fertilizer rate for nitrogen (34.16%) and potassium (34.75%), whereas phosphorus use efficiency was highest at the full (100%) fertilizer rate under drip irrigation (17.80%). The findings suggest that employing drip irrigation allows for a 50% reduction in the recommended nitrogen and potassium fertilizers, a benefit not observed for phosphorus.

***Keywords**: **Chenopodium quinoa**; **drip irrigation**; **fertilizer use efficiency; inorganic fertilizer**; **nutrient availability**.*

II. INTRODUCTION

In the pursuit of meeting global food demand, agricultural intensification has frequently resulted in the excessive use of chemical fertilizers, with insufficient regard for their economic and environmental impacts (Bhowmik *et al*., 2019). This practice has contributed to environmental degradation through nutrient runoff and leaching, while simultaneously increasing production costs.

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Irrigation method plays a critical role in determining both water use efficiency and the efficiency with which crops utilize applied fertilizers.

Recent efforts to address these challenges have focused on improving agricultural practices through precision technologies and integrated nutrient management. Modern irrigation methods, particularly drip irrigation, enable frequent application of small water volumes, maintaining optimal soil moisture with high uniformity while minimizing water and nutrient losses below the root zone. This approach has been shown to enhance crop yield per unit area (Al-Yasiry, 2022)..

Nutrient uptake by plants is governed by root system effectiveness and soil nutrient availability. Nutrient losses through leaching, volatilization, and fixation represent major constraints to crop productivity globally, resulting from low fertilizer use efficiency (Sharma *et al*., 2012). Fertilizer use efficiency (FUE)—defined as the capacity of a plant to acquire and utilize nutrients for biomass production—remains a critical challenge in global agriculture. Numerous factors influence FUE, including climate, soil properties, crop biology, and critically, irrigation management practices (González-Fontes *et al*., 2017).

Therefore, the objective of this study was to investigate the effects of irrigation method (drip vs. surface) and mineral fertilizer rate (0, 50, and 100% of recommended NPK) on nutrient uptake and nutrient use efficiency in quinoa (Chenopodium quinoa Willd.) grown under field conditions in southern Iraq.

III. MATERIALS AND METHODS

The experiment was conducted at the College of Agriculture and Marshlands, University of Thi-Qar, Iraq, during the 2021-2022 growing season. The soil, classified as silty clay (Table 1), was used to evaluate quinoa (Chenopodium quinoa Willd.) responses to mineral fertilizer application and irrigation methods, with particular emphasis on nutrient uptake and use efficiency. Nitrogen (120 kg ha^{-1} as urea, 46% N), phosphorus (50 kg ha^{-1} as triple superphosphate, 46% P_2O_5), and potassium (80 kg ha^{-1} as potassium sulfate, 50% K_2O) were applied at three rates: 0% (control), 50%, and 100% of the recommended rates. Fertilizers were applied at sowing for phosphorus and potassium, while nitrogen was applied in two equal splits: at sowing and 30 days after sowing. Two irrigation methods were compared: (1) drip irrigation using inline drip tapes with 4 L h^{-1} emitters spaced at 30 cm intervals, and (2) conventional surface (furrow) irrigation. For drip irrigation, water is applied every (3 days) to maintain soil moisture near field capacity. For surface irrigation, water is applied at (10 day interval) based on local practice. The experiment was arranged in a split-plot design with three replications.

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Irrigation method (drip vs. surface) was assigned to main plots, and mineral fertilizer rate (0%, 50%, 100%) was assigned to sub-plots. Each sub-plot measured (3 m × 4 m = 12 m²). Rows were spaced (50 cm) apart, with (20 cm) between plants within rows, resulting in a plant population of (100,000 plants ha^{-1}).

Table 1. Some chemical and physical Properties of the soil before cultivation.

Traits		Value	Unit
pH		7.76	
ECe		4.63	Dms. m^{-1}
O.M		2.92	g. kg^{-1}
Available Nitrogen		14.35	mg kg^{-1}
Available Phosphorus		11.9	mg kg^{-1}
Available Potassium		97.91	mg kg^{-1}
Calcium carbonate		198	g. kg^{-1}
Texture (Silty Clay)	Sand	173	g. kg^{-1}
	Silt	422	g. kg^{-1}
	Clay	405	g. kg^{-1}

At physiological maturity, plant samples were collected from a (1 m²) quadrat in the center of each sub-plot, excluding border rows. Plants were separated into grain and straw (stems and leaves), dried at 70°C to constant weight, and ground to pass a 1 mm sieve. Nitrogen concentration was determined by the Micro-Kjeldahl digestion and distillation method. Phosphorus concentration was determined by vanado-molybdate colorimetry using a spectrophotometer. Potassium concentration was determined by flame photometry (Haynes, 1980). All analyses were performed in duplicate, and mean values were used for calculations. The formula below was used to calculate the total nutrient uptake by multiplying the percent of nutrient content with dry matter accumulation (Sharma *et al*., 2012**).**

$$\text{Nutrient uptake (kg ha}^{-1}) = \frac{\text{Nutrient content (\%)}}{100} \times \text{dry matter (kg ha}^{-1})$$

The following formula was used to calculate nutrient use efficiency (Baligar *et al*., 2001).

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$$\text{Nutrient use efficiency(\%)} = \frac{\text{Nutrient uptake(Fertilization)kg - Nutrient uptake(Control)kg}}{\text{Quantity of nutrient applied (kg)}} \times 100$$

Statistical Analysis:

The data was analyzed using Analysis of Variance (ANOVA) with Genstat version 10.0, the means of treatment were compared using the least significant difference (LSD) at a significance level of 5%.

IV. RESULTS AND DISCUSSION

Both mineral fertilizer rate and irrigation method significantly ($P < 0.05$) influenced nitrogen (N), phosphorus (P), and potassium (K) concentrations in quinoa straw (Table 2). The highest straw N concentration (0.87%) was observed with the 100% fertilizer rate, followed by the 50% rate (0.72%), while the unfertilized control (0%) resulted in the lowest N concentration (0.52%). Compared to the control, the 50% and 100% fertilizer rates increased straw N concentration by 38.5% and 67.3%, respectively. Phosphorus concentration in straw followed a similar pattern, with the 100% fertilizer rate producing the highest P concentration (0.22%), which was not statistically different from the 50% rate (0.20%) but significantly higher than the control (0.14%). Potassium concentration in straw was also significantly affected by fertilizer rate, with the 100% rate yielding the highest K concentration (0.78%), followed by the 50% rate (0.67%), and the control (0.45%). The 50% and 100% rates increased straw K concentration by 48.9% and 73.3%, respectively, compared to the control. These increases can be attributed to greater nutrient availability in the soil solution with higher fertilizer application rates, facilitating root uptake. These findings are consistent with Sobh *et al*. (2021) and Abdolahpour *et al*. (2021), who reported positive relationships between mineral fertilizer application and nutrient accumulation in quinoa.

Irrigation method significantly influenced nutrient concentrations in straw, with drip irrigation consistently outperforming surface irrigation (Table 2). Averaged across fertilizer rates, drip irrigation increased straw N, P, and K concentrations by 20.3%, 25.0%, and 25.0%, respectively, compared to surface irrigation. This improvement likely reflects more favorable soil moisture conditions under drip irrigation, which enhance nutrient diffusion and mass flow to roots, as well as reduced nutrient losses through leaching and runoff. These results align with findings by Nie *et al*. (2021) and Al-Yasiry

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(2022), who reported enhanced nutrient uptake under drip irrigation in various crops, including quinoa.

Table 2. Effect of mineral fertilizer and irrigation method on NPK uptake in straw.

Mineral Fertilizer	%N			%P			%K		
	Irrigation method			Irrigation method			Irrigation method		
	surface	drip	average	surface	drip	average	surface	drip	average
%0	0.49	0.56	0.52	0.11	0.16	0.14	0.35	0.54	0.45
%50	0.59	0.86	0.72	0.18	0.21	0.20	0.61	0.73	0.67
%100	0.86	0.89	0.87	0.19	0.25	0.22	0.74	0.82	0.78
Average	0.64	0.77		0.16	0.20		0.56	0.70	
LSD	M= 0.027	IR= 0.037	M*IR= 0.036	M = 0.053	IR= 0.043	M*IR= N.S	M= 0.066	IR= 0.116	M*IR= N.S

Note: *M = Mineral Fertilizer, IR = Irrigation, N = Nitrogen, P = phosphorus, K = Potassium, LSD = Least Significant Difference*

Data in (Table 3) indicate that the irrigation method and uptake of N, P, and K (%) in quinoa grains at the harvest stage, increased significantly with increasing mineral fertilizer rate. Fertilization had a positive effect on nutrient uptake compared with the control. In particular, the whole fertilizer dose recorded the highest uptake rates of N, P, and K in quinoa grains: 3.08%, 0.55%, and 1.74%, respectively, followed by the 50% dose, which resulted in 2.49%, 0.48%, and 1.49%, respectively. The uptake of N, P, and K also increased by 46.47 to 81.17, 50 to 71.87, and 49 to 74% when 50% and 100% of the fertilizer dose were added, respectively, compared to the unfertilized control. This result might be because quinoa responds well to mineral fertilization and can accumulate nutrients in grains. The above results agree with results obtained by (Razzaghi *et al*., 2012; Fawy *et al*., 2017; Kakabouki *et al*., 2018; Van Minh *et al*., 2022) as reported by that as the rate of fertilizer application increased, quinoa's total uptake of nutrients increased. Table (3) shows that the uptake of N, P, and K in grains under drip Irrigation was higher than that of the surface irrigation treatment. The N, P, and K uptake under drip irrigation increased by 23.04%, 33.33%, and 23.80%, respectively, compared with surface Irrigation treatment. This increase in nutrient uptake is due to reduced nutrient loss by leaching under drip irrigation compared to surface irrigation. The data recorded in the current investigation agree with those obtained by (Wu *et al*., 2019; Nie *et al*., 2021; Fghire *et al*., 2022; Yan *et al*., 2022).

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Table 3. Effect of mineral fertilizer, irrigation method on NPK uptake in grains.

Mineral Fertilizer	%N			%P			%K		
	Irrigation method			Irrigation method			Irrigation method		
	surface	drip	average	surface	drip	average	surface	drip	average
%0	1.55	1.85	1.70	0.23	0.41	0.32	0.79	1.21	1.00
%50	1.94	3.04	2.49	0.45	0.52	0.48	1.36	1.63	1.49
%100	3.03	3.14	3.08	0.48	0.62	0.55	1.65	1.84	1.74
Average	2.17	2.67		0.39	0.52		1.26	1.56	
LSD	M= 0.116	IR= 0.133	M*IR= 0.147	M= 0.098	IR= 0.086	M*IR= N.S	M= 0.149	IR= 0.251	M*IR= N.S

Note: *M = Mineral Fertilizer, IR = Irrigation, N = Nitrogen, P = phosphorus, K = Potassium, LSD = Least Significant Difference*

Mineral fertilizer and irrigation methods had a significant effect on the total uptake of N, P, and K concentrations in all treatments. Figure 1 shows the fertilization treatments significantly affected the total uptake of N, P, and K by plants, the higher nutrient concentrations with an application of 100 % treatments of mineral fertilizer were, 69.9 kg ha^{-1} for N, 17.55 kg ha^{-1} for P, and 49.60 kg ha^{-1} for K than for the 50 % and control. Generally, the total uptake of N, P, and K by plants with the application of 50% mineral fertilizer was low as a result of high nutrient loss by leaching, fixation, and volatilization. However, the application of 100 % of mineral fertilizer used in this study increased nutrient availability in soil solution and their uptake by plant roots. Total nutrient uptake has been observed to increase as the fertilizer application rate has increased (Hasan and Saad, 2020; Abdolahpour *et al*., 2021; Van Minh *et al*., 2022).

Figure 2 shows that the total uptake of N, P, and K was substantially lower under surface irrigation compared to drip irrigation. Drip irrigation significantly increased the average plant uptake of N (from 42.6 to 62.00 kg ha^{-1}), P (from 8.6 to 15.53 kg ha^{-1}), and K (from 26.88 to 46.79 kg ha^{-1}). This represents an increase of 45.53% for N, 80.58% for P, and 74.06% for K under drip irrigation. This is likely because surface irrigation conditions counteract the effectiveness of mineral fertilizer in facilitating nutrient uptake by roots. This result is consistent with findings reported by Sampathkumar and Pandian (2011), Al-Yasiry (2022), and Yan et al. (2022).

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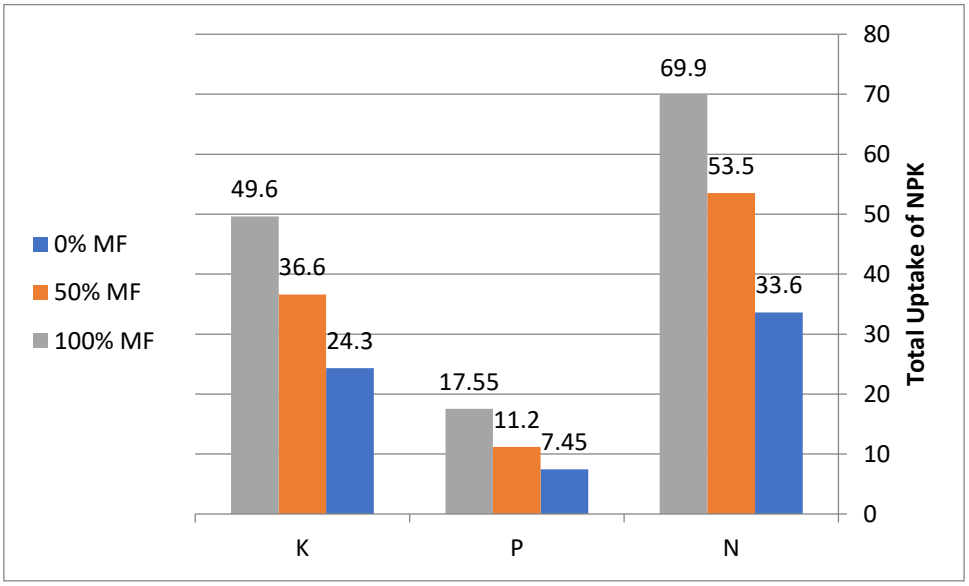

Figure 1. Effect of mineral fertilizer on total uptake of NPK (kg ha^{-1}) in quinoa

Note: MF = Mineral Fertilizer, N = Nitrogen, P = phosphorus, K = Potassium

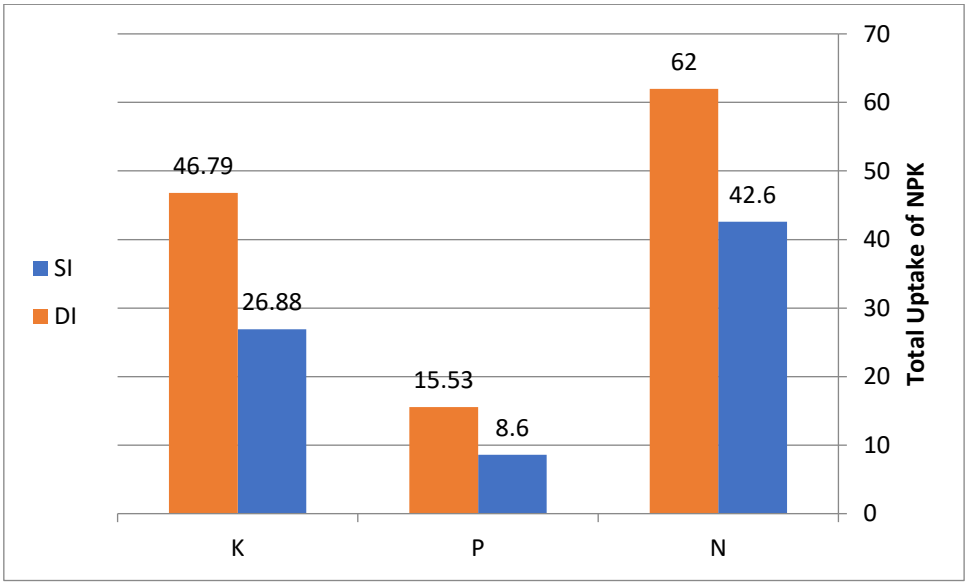

Figure 2. Effect of irrigation method on total uptake of NPK (kg ha^{-1}) in quinoa

Note: SI = Surface Irrigation, DI= Drip Irrigation, N = Nitrogen, P = phosphorus, K = Potassium

Table 4. shows the effect of mineral fertilizer and irrigation methods on nutrient use efficiency. The highest rate of nitrogen use efficiency (34.16%) was noted with the application of 50% nitrogen fertilizer under drip irrigation. An increase in fertilizer concentration to 100% was accompanied by a decrease in the efficiency of nitrogen use. When 100% nitrogen fertilizer was applied, the lowest efficiency of nitrogen use (28.33%) was noted under surface irrigation. It appears that the lower

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concentration of nitrogen fertilizer enhanced the efficiency of nitrogen use. The highest efficiency of potassium use (34.75%) was observed when 50% potash fertilizer was applied followed by 100% (32.12 %) under drip irrigation, an increase in fertilizer concentration led to a decrease in the efficiency of potassium use in quinoa. This might be due to the importance of drip irrigation in saving water, increasing nutrient uptake, and thus improving the efficiency of nutrient use for the same amount of fertilizer added compared to the surface irrigation method (Cabangon *et al*., 2004). It has been reported that drip irrigation saved 50% of water, facilitated nutrient uptake and improved efficiency of nutrient use by (Kumar and Dey, 2011; Kakabouki *et al*., 2018; Al-Naggar *et al*., 2021).

While in case of phosphorous, higher use efficiency (21.40 %) was recorded with application of 100% of phosphate fertilizer followed by 50% (18.80 %) under drip irrigation, this is due to the fact that a pH above 7, Phosphorus precipitates with calcium ions (Johan *et al.,* 2021).

Table 4. Effect of Mineral Fertilizer and Irrigation Method on Nutrient Use Efficiency.

Nutrient Use Efficiency (%)	Fertilization Treatment (%)	Irrigation Method	
		surface	drip
Nitrogen Use Efficiency	100	28.33	32.16
	50	00.32	34.16
Phosphorous Use Efficiency	100	17.80	21.40
	50	11.20	18.80
Potassium Use Efficiency	100	31.12	32.12
	50	26.75	34.75

V. CONCLUSION

This study demonstrates that increasing mineral fertilization rates significantly enhanced the uptake of N, P, and K in quinoa straw and grains, consequently affecting total plant nutrient accumulation. Furthermore, total nutrient uptake was consistently higher under the drip irrigation system compared to surface irrigation. Maximum nutrient use efficiency, with the exception of phosphorus, was achieved by applying 50% of the recommended mineral fertilizer under drip irrigation. These findings suggest that adopting drip irrigation is a beneficial strategy not only for water conservation but also for improving nutrient uptake and use efficiency. This approach could potentially reduce fertilizer application by 50% compared to surface irrigation, leading to higher yields and improved economic feasibility.

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