International Journal of Design & Nature and Ecodynamics
Vol. 21, No. 2, February, 2026, pp. 417-424
Journal homepage: http://iieta.org/journals/ijdne

Synergistic Effects of Nano-NPK and Organic Fertilization on Potato Yield and Soil Nutrient Availability under Drip Irrigation

Safa Mohammed AlQaisi[1*], Faris A. Al-Wazzan[1], Hussien Albayati[2]

[1] Department of Soil Science and Water Resources, College of Agriculture and Forestry, University of Mosul, Mosul 41002 Iraq
[2] Department of Horticulture and Landscape Engineering, College of Agriculture and Forestry, University of Mosul, Mosul 41002, Iraq

Corresponding Author Email: Safa.agp54@student.uomosul.edu.iq

https://doi.org/10.18280/ijdne.210210

Received: 6 December 2025
Revised: 12 February 2026
Accepted: 19 February 2026
Available online: 28 February 2026

Keywords:
drip irrigation, Nano-NPK, organic fertilization, potato yield, soil nutrient availability, synergistic effects

ABSTRACT

This study evaluated the impact of integrated water and nutrient management on potato (*Solanum tuberosum* L.) yield and soil fertility. A field experiment was conducted using a split-plot design. Drip irrigation was assigned to the main plots, while nano-NPK levels (0, 3, 6, 9 g L^{-1}) and organic fertilizer levels (0, 12, 24 t ha^{-1}) were randomly distributed in the sub-plots. Results showed that the combination (6 g L^{-1} nano × 24 t ha^{-1} organic) significantly maximized nutrient concentrations (NPK) achieving the highest values in leaves (3.14%, 0.69%, 2.52%) and tubers (1.74%, 0.66%, 2.04%) respectively with maximum soil nutrient accumulation (32.74, 8.77, 273 mg kg^{-1}). Interactions demonstrated a strong synergistic effect; drip irrigation maintained stable moisture, preventing nanoparticle aggregation and enhancing organic matter mineralization. This propelled the marketable yield to its peak at 64.93 t ha^{-1}, a 60.28% increase over the control. The Soil Nutrient Index (SNI) revealed improved fertility for P and K (2.33) while N required enhanced management (2.17) to reduce leaching losses. The study concludes that integrating nanotechnology and organic fertilization under drip irrigation is an effective strategy for sustainable productivity in light-textured soils.

1. INTRODUCTION

Potato (*Solanum tuberosum* L.) is one of the most important food crops worldwide, due to its high nutritional value and significant economic role in ensuring food security. It serves as a major source of carbohydrates, in addition to providing essential proteins and mineral nutrients. The productivity and tuber quality of potatoes largely depend on the efficient management of agricultural resources, particularly water and nutrients, especially in arid and semi-arid regions where water scarcity and soil fertility decline are common challenges [1].

Drip irrigation is considered one of the most efficient irrigation systems for optimizing water and nutrient use, as it delivers water and fertilizers directly to the root zone, reducing losses from evaporation and leaching while enhancing fertilizer use efficiency. Recent studies indicate that integrating drip irrigation with precise nutrient management improves nutrient distribution in the soil and increases potato yield compared to conventional irrigation methods [2, 3].

In recent years, multi-element nano-fertilizers (nano-NPK) have emerged as an advanced approach in sustainable agriculture due to their high surface area, which enhances nutrient uptake efficiency and minimizes environmental losses. Studies have demonstrated that nano-fertilizer application improves vegetative growth, increases tuber number and size, and enhances nutrient use efficiency, particularly under modern irrigation systems such as drip irrigation [4-6].

Moreover, organic fertilization remains a fundamental practice for enhancing long-term soil fertility, as it increases soil organic matter and improves physical, chemical, and biological properties, including microbial activity. Recent research has shown that the application of organic fertilizers in potato cultivation improves yield, tuber quality, and soil fertility, particularly in sandy and semi-sandy soils [7, 8].

Furthermore, the Soil Nutrient Index (SNI) serves as a comprehensive quantitative tool for assessing soil fertility. It classifies major nutrients (N, P, K) into low, medium, and high categories and integrates them into a single numerical value representing the overall soil fertility status. Recent studies have demonstrated that SNI provides a more accurate and integrated evaluation of soil fertility changes under different fertilization practices, including organic and nano-fertilization, especially when combined with drip irrigation systems [9-11]. Although previous studies have focused on the individual effects of fertilization or irrigation on soil fertility, the integrated evaluation of their interaction on nutrient translocation efficiency in potato plants and the SNI remains limited. This study was conducted on a loamy sand soil to assess the effects and interactions of nano-NPK fertilizer and organic fertilization under drip irrigation on potato growth and yield, and soil fertility status. Accordingly, the objectives of this study are: (1) to determine the optimum level of nano-NPK fertilizer under drip irrigation, (2) to evaluate the effect of organic fertilization on potato growth and yield and nutrient uptake efficiency, (3) to assess the effect of the interaction between nano-NPK and organic fertilization on nutrient translocation from leaves to tubers, (4) to examine the effect of the interaction between drip irrigation and nano and organic fertilizers on potato growth and yield and identify the most efficient treatment, and to evaluate soil fertility through the SNI.

2. MATERIALS AND METHODS

The field experiment for potato cultivation was conducted at the experimental field of the College of Agriculture and Forestry, University of Mosul, located in Nineveh Governorate at 36.23079° N latitude and 43.07480° E longitude, during the spring season of 2024. The field was equipped with a surface drip irrigation system (Figure 1).

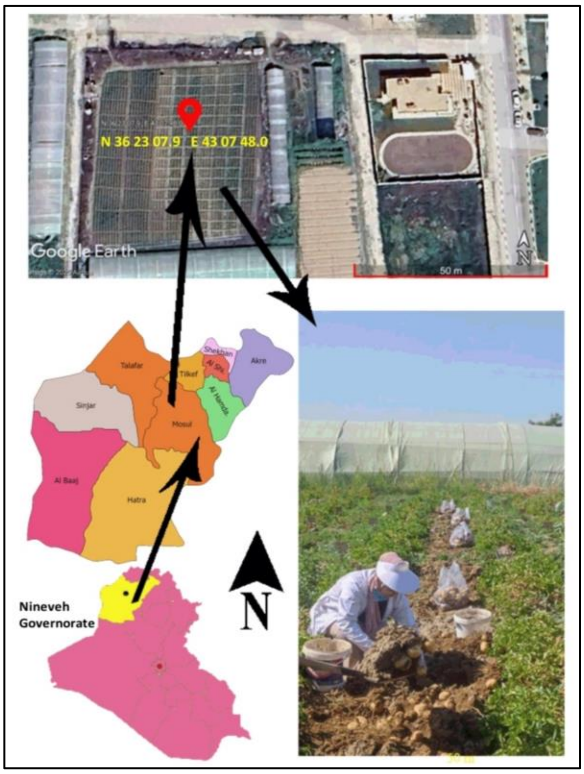

Figure 1. Map showing the study location field

Table 1. Physical and chemical properties of the soil

Soil Characteristics	Quantity	Source
pH	7.4	[12]
Electrical Conductivity, ds m^{-1}	0.7	
Cation Exchange Capacity, cmol kg^{-1}	14.3	[13]
Organic matter, g kg^{-1}	15	[14]
N, mg kg^{-1}	15	[15]
P, mg kg^{-1}	5.2	[16]
K, mg kg^{-1}	120.4	[17]
Sand, g kg^{-1}	794.5	[18]
Silt, g kg^{-1}	143.0	
Clay, g kg^{-1}	62.5	
Texture	Loamy Sand	

The soil samples were randomly collected prior to planting at a depth of 0–30 cm to obtain a composite sample, then air-dried, crushed, and sieved through a 2 mm mesh to ensure homogeneity. Laboratory analyses were conducted at the Soil Science Department Laboratory following the standard analytical methods cited in Table 1.

The experiment was conducted during the 2024 spring season, including land preparation plowing, harrowing, and leveling, and all necessary agronomic practices for potato cultivation. The field was divided into experimental units according to the adopted design, with 3 replicates, totaling 36 experimental units.

The study included three main factors as described: First Factor: Surface drip irrigation system. The system included a main water tank pumping through main and sub-main pipes to lateral lines with a 16 mm diameter and a length of 80 m, equipped with emitters having a discharge rate of 1 L h^{-1} and 25 cm spacing with control valves installed for each treatment to ensure uniform distribution. Crop water requirements were determined based on the soil moisture content to achieve a depth of 42 cm, where soil moisture was measured at 15% of the field capacity for the loamy sand soil.

Second Factor: nano-NPK fertilizer. A commercial chelated nano-NPK with a 20:20:20 nutrient composition from Sodour Ahrar Shargh Company, Iran, was used with particles within the nano-scale range < 100 nm. Four levels (0, 3, 6, and 9 g L^{-1}) were applied by dissolving the required amount in a 15 L fertilizer holder, and the solution was added directly to the soil within the root zone to ensure uniform distribution. Fertilization was carried out in three equal splits: the first 15 days after germination, the second 15 days after the first, and the third 15 days after the second.

Third Factor: Organic fertilizer. Sheep manure prepared on February 2/2024 by pit-placing, moistening, and plastic-covering for decomposition was used with samples collected for laboratory analysis Table 2. The fertilizer was applied at three levels (0, 12, and 24 t ha^{-1}) by incorporating it into the soil to a depth of 15 cm 10 days before planting to allow for interaction and enhance nutrient availability for the plant.

Table 2. Chemical properties of the organic fertilizer (sheep manure)

Fertilizer Properties	Quantity	Source
pH	6.8	Chemical analyses were conducted according to standard methods used for soil analysis.
Electrical Conductivity, ds m^{-1}	1.5	
C/N	19.85	
Organic carbon, g kg^{-1}	321.6	
Organic matter, g kg^{-1}	554.5	
Total N, g kg^{-1}	16.2	
Total P, g kg^{-1}	8.4	
Total K, g kg^{-1}	25.0	

The experiment was conducted according to a split-plot design within a Randomized Complete Block Design (RCBD) with three replicates; the irrigation system was assigned as the main plot, while nano-fertilizer and organic fertilizer treatments were randomly distributed as sub-plots. The data were statistically analyzed using the SAS software [19], and mean comparisons were performed using Duncan's Multiple Range Test at a probability level of 0.05 [20].

Planted potato seed tubers cultivar Riviera *Solanum* *tuberosum* L. were used in the study. Planting was carried out on February 27/2024, at a depth of 10–12 cm in loamy sand soil [21, 22]. The field was divided into 36 experimental units for three replicates with an area of 5.625 m² per unit. Each unit consisted of 3 ridges, 0.25 m wide, 0.75 m apart, and 9 tubers were planted per ridge with 0.25 m spacing between them. A distance of 1 m was maintained between replicates, 0.75 m between treatments, and a 1 m buffer zone between blocks. Harvesting was conducted on June/11/ 2024, and soil and plant samples were collected for analysis.

After the experiment, leaf samples were collected 10 days after the last nano-fertilizer application on May 15, 2024, and oven-dried at 70 ℃ for 48 hours. Samples were ground and digested using sulfuric acid and perchloric acid [23, 24]. Nitrogen was determined by the Kjeldahl method, while phosphorus and potassium were also estimated [24]. Similarly, soil samples were analyzed after harvest to determine nitrogen, phosphorus, and potassium using the same standard methods.

The SNI was calculated to evaluate soil fertility before and after planting based on N, P, and K values for the previously analyzed experimental units and replicates. Nutrient values were classified according to Table 3, and the index was calculated using the following equation [25, 26]:

$$SNI = (NL \times 1) + (NM \times 2) + (NH \times 3) / \, TNS$$

where, *NL* represents the number of samples in the first category, *NM* the second category, and *NH* the third category, while *TNS* represents the total number of analyzed samples.

Table 3. Rating chart of soil nutrient index values

Soil Nutrient Index (SNI)	Value	Description
Low	< 1.67	Less fertility status
Medium	2.33-1.67	Medium fertility status
High	> 2.33	High fertility status

Source: research [27].

3. RESULT AND DISCUSSION

3.1 The effects of nano-fertilizers on plant and soil leaf nutrient content

3.1.1 Leaf nutrient content (NPK)

According to the results presented in (Tables 4, 5, and 6), statistical analysis indicated that the application of nano-fertilizer had a highly significant effect on increasing nutrient concentrations in leaves ($P \leq 0.0003$). The 6 g L^{-1} level recorded the highest averages for nitrogen (3.14%), and potassium (2.52%), for phosphorus content both 3 and 6 g L^{-1} levels achieved the highest results (0.69%), while the control treatment recorded the lowest values. This superiority is attributed to the role of nano-particles in improving the solubility, mobility, and availability of nutrients for root uptake while minimizing their loss in the soil.

Table 4. Effect of nano-fertilization, organic fertilizer, irrigation system, and their interactions on nitrogen concentration in potato leaves (%)

Irrigation Method	Organic Fertilizer (g ha^{-1})	Nano Fertilizer (g L^{-1})				Irrigation × Organic Fertilizer	Average Irrigation
		0	3	6	9		
Drip irrigation	0	1.76 i	3.20 a- c	3.59 a	2.80 d-h	2.84 b	3.02 a
	12	3.52 ab	2.94 c-f	3.33 a-c	2.94 d-f	3.18 a	
	24	2.87 d-h	3.20 a-c	3.07 a-d	3.07 a-d	3.05 ab	
Irrigation × Nano-fertilizer	Drip irrigation	2.72 cd	3.11 ab	3.33 a	2.94 bc	Average organic fertilizer	
Organic fertilizer × Nano fertilizer	0	1.76 e	3.07 a-c	3.29 a	2.67 cd	2.70 a	
	12	2.89 b-d	2.64 d	3.13 ab	2.71 cd	2.84 a	
	24	2.61 d	2.82 b-d	2.98 a-d	2.74 cd	2.79 a	
Average nano fertilizer		2.42 c	2.84 b	3.14 a	2.71 b		

*NPK (F = 18.30, P < 0.0001); I × NPK (F = 8.48, P = 0.0008); I × Org (F = 2.79, P = 0.0726); NPK × Org (F = 0.46, P = 0.7145); I × NPK × Org (F = 5.62, P < 0.0001).

Table 5. Effect of nano-fertilization, organic fertilizer, irrigation system, and their interactions on phosphorus concentration in potato leaves (%)

Irrigation Method	Organic Fertilizer (g ha^{-1})	Nano Fertilizer (g L^{-1})				Irrigation × Organic Fertilizer	Average Irrigation
		0	3	6	9		
Drip irrigation	0	0.62 i	0.70 b-d	0.76 a	0.71 bc	0.70 a	0.69 a
	12	0.65 g h	0.67 e-g	0.69 b-e	0.70 b-d	0.68 b	
	24	0.72 b	0.78 a	0.65 g h	0.67 d-g	0.70 a	
Irrigation × Nano-fertilizer	Drip irrigation	0.66 c	0.71 a	0.71 ab	0.69 b	Average organic fertilizer	
Organic fertilizer × Nano fertilizer	0	0.62 e	0.68 bc	0.72 a	0.68 b-d	0.67 a	
	12	0.67 cd	0.66 cd	0.68 bc	0.68 bc	0.67 a	
	24	0.70 ab	0.71 a	0.66 d	0.66 cd	0.68 a	
Average nano fertilizer		0.66 c	0.69 a	0.69 ab	0.68 b		

*NPK (F = 7.77, P = 0.0003); I × NPK (F = 9.43, P < 0.0001); I × Org (F = 9.69, P = 0.0003); NPK × Org (F=2.60, P = 0.0855); I × NPK × Org (F = 16.79, P < 0.0001).

Table 6. Effect of nano-fertilization, organic fertilizer, irrigation system, and their interactions on potassium concentration in potato leaves (%)

Irrigation Method	Organic Fertilizer (g ha^{-1})	Nano Fertilizer (g L^{-1}) 0	3	6	9	Irrigation × Organic Fertilizer	Average Irrigation
Drip irrigation	0	1.11 h	2.70 ab	2.83 a	2.35 e-g	2.25 c	2.37 a
	12	2.33 e	2.63 a-c	2.51 b-e	2.33 e-g	2.45 a	
	24	2.35 e-g	2.45 c-f	2.38 d-g	2.43 c-g	2.40 ab	
Irrigation × Nano-fertilizer	Drip irrigation	1.93 e	2.60 a	2.57 ab	2.37 cd	Average organic fertilizer	
Organic fertilizer × Nano fertilizer	0	1.15 e	2.52 b	2.71 a	2.28 d	2.16 b	
	12	2.28 d	2.52 b	2.45 bc	2.26 d	2.38 a	
	24	2.35 cd	2.42 b-d	2.39 b-d	2.41 b-d	2.39 a	
Average nano fertilizer		1.92 c	2.49 a	2.52 a	2.32 b		

*NPK (F = 94.63, $P < 0.0001$); I × NPK (F = 2.31, P = 0.0896); I × Org (F = 2.28, P = 0.1144); NPK × Org (F = 27.28, $P < 0.0001$); I × NPK × Org (F = 30.36, $P < 0.0001$).

Table 7. Effect of nano-fertilization, organic fertilizer, irrigation system, and their interactions on nitrogen concentration in potato tubers (%)

Irrigation Method	Organic Fertilizer (g ha^{-1})	Nano Fertilizer (g L^{-1}) 0	3	6	9	Irrigation × Organic Fertilizer	Average Irrigation
Drip irrigation	0	1.24 g	1.79 e	1.63 e-g	1.69 ef	1.59 b	1.63 b
	12	1.56 e-g	1.37 f g	1.69 ef	1.76 ef	1.60 b	
	24	1.24 g	1.69 ef	1.93 de	1.89 de	1.69 b	
Irrigation × Nano-fertilizer	Drip irrigation	1.35 e	1.62 d	1.75 d	1.78 d	Average organic fertilizer	
Organic fertilizer × Nano fertilizer	0	1.31 a	1.45 ab	1.32 ab	1. 43 a-d	1.05 a	
	12	1.53 ce	1.50 f	1.86 d-e	1.91 c-d	1. 53 a	
	24	1.25 ab	1.33 b-e	1.79 e	1.54 ac	1.11 a	
Average Nano fertilizer		1.74 c	1.24 b	1.44 a	1.74 b		

*NPK (F = 23.91, $P < 0.0001$); I × NPK (F = 4.57, P = 0.0072); I × Org (F = 0.52, P = 0.5964); NPK × Org (F = 1.84, P = 0.1130); I × NPK × Org (F = 3.15, P = 0.0026).

Table 8. Effect of nano-fertilization, organic fertilizer, irrigation system, and their interactions on phosphorus concentration in potato tubers (%)

Irrigation Method	Organic Fertilizer (g ha^{-1})	Nano Fertilizer (g L^{-1}) 0	3	6	9	Irrigation × Organic Fertilizer	Average Irrigation
Drip irrigation	0	0.59 h	0.66 a-e	0.68 a	0.68 ab	0.65 ab	0.65 a
	12	0.64 c-f	0.65 a-e	0.65 a-f	0.66 a-d	0.65 a	
	24	0.63 e-g	0.67 a-c	0.62 f-h	0.66 a-e	0.64 ab	
Irrigation × Nano-fertilizer	Drip irrigation	0.62 d	0.66 ab	0.65 a-c	0.66 a	Average organic fertilizer	
Organic fertilizer × Nano fertilizer	0	0.60 d	0.66 ab	0.66 a	0.65 ab	0.64 a	
	12	0.65 a-c	0.66 ab	0.65 ab	0.65 a-c	0.65 a	
	24	0.64 bc	0.67 a	0.63 c	0.65 ab	0.65 a	
Average Nano fertilizer		0.63 c	0.66 a	0.65 b	0.65 b		

*NPK (F = 12.89, $P < 0.0001$); I × NPK (F = 5.79, P = 0.0020); I × Org (F = 2.32, P = 0.1105); NPK × Org (F = 1.45, P = 0.2110); I × NPK × Org (F = 3.88, P = 0.0005).

3.1.2 Tubers nutrient content (NPK)

Statistical results in Tables 7, 8, and 9 indicated a significantly superior effect of nano-fertilizer on increasing nutrient concentrations in tubers ($P < 0.0001$). The 0 and 9 g L^{-1} level achieved the highest averages of Nitrogen (1.74%), at the 3 g L^{-1} level phosphorus (0.66%), and potassium the 6 g L^{-1} level (2.04%). This superiority is attributed to the efficiency of nanotechnology in enhancing physiological activity and photosynthesis, which accelerated the translocation of metabolites from the leaves (Source) to the tubers (Sink), thereby increasing dry matter accumulation and crop quality. This value reflects the exceptional response of potato plants to potassium as a primary quality element. nano-particles doubled their cellular permeability and the speed of their accumulation in storage tissues compared to conventional fertilizers, creating a sharp statistical contrast between treatments [28].

3.1.3 Soil nutrient content (NPK)

The results presented in Tables 10, 11, and 12 demonstrated a fundamental role of nano-fertilizer ($P < 0.0001$) in enhancing the soil nutrient reservoir after harvest.

The 6 g L^{-1} concentration achieved the maximum nutrient accumulation, recording Nitrogen (32.74 mg kg^{-1}), phosphorus (8.77 mg kg^{-1}), and potassium (273 mg kg^{-1}). These findings prove the efficiency of nanotechnology in reducing nutrient waste through leaching or chemical fixation. Nano-particles act as smart reservoirs that release nutrients gradually (Slow-release), ensuring the maintenance of soil fertility and providing sustainable nutrient availability in the rhizosphere that surpasses the capacity of conventional fertilizers [29]. nano-fertilizer treatments (6 g L^{-1}) significantly increased NPK concentrations (Tables 4-12) following a dose-response curve that peaked at this concentration. This improvement is attributed to the high penetration efficiency through stomata and cellular channels, facilitated by the large specific surface area of the nanoparticles. The stabilization or decline in response at 9 g L^{-1} is explained by physical aggregation of the particles, which increases their size beyond the diameters of cellular pores, thereby hindering their permeability into plant tissues [30].

Table 9. Effect of nano-fertilization, organic fertilizer, irrigation system, and their interactions on potassium concentration in potato tubers (%)

Irrigation Method	**Organic Fertilizer (g ha^{-1})**	**Nano Fertilizer (g L^{-1})**				**Irrigation × Organic Fertilizer**	**Average Irrigation**
		0	**3**	**6**	**9**		
	0	1.14 g	1.90 b-e	2.09 a	1.84 d-f	1.75 d	
Drip irrigation	12	1.70 f	1.92 a-e	1.92 a-e	1.86 c-f	1.85 bc	1.84 a
	24	1.83 d-f	1.95 a-d	2.04 a-c	1.84 d-f	1.92 ab	
Irrigation × Nano-fertilizer	Drip irrigation	1.56 c	1.92 b	2.02 a	1.85 b	Average organic fertilizer	
Organic fertilizer × Nano fertilizer	0	1.21 g	1.90 c-e	2.09 a	1.87 de	1.77 c	
	12	1.73 f	1.91 c-e	2.00 a-c	1.85 de	1.87 b	
	24	1.79 ef	1.96 b-d	2.04 ab	1.92 cd	1.93 a	
Average Nano fertilizer		1.57 c	1.92 b	2.04 a	1.88 b		

* NPK (F = 81.54, P < 0.0001); I × NPK (F = 0.37, P = 0.7739); I × Org (F = 0.11, P = 0.8938); NPK × Org (F = 27.28, P < 0.0001); I × NPK × Org (F = 30.36, P < 0.0001).

Table 10. Residual soil available nitrogen (mg kg^{-1}) as influenced by study treatments

Irrigation Method	**Organic Fertilizer (g ha^{-1})**	**Nano Fertilizer (g L^{-1})**				**Irrigation × Organic Fertilizer**	**Average Irrigation**
		0	**3**	**6**	**9**		
	0	20.51 f	21.16 f	31.36 a-c	27.44 cd	25.12 c	
Drip irrigation	12	22.08 f	23.08 ef	33.97 a	28.74 b-d	26.97 ab	26.58 a
	24	21.49 f	23.14 ef	33.97 a	32.01 ab	27.65 a	
Irrigation × Nano-fertilizer	Drip irrigation	21.36 d	22.46 d	33.10 a	29.4 b	Average organic fertilizer	
Organic fertilizer × Nano fertilizer	0	20.35 e	21.62 e	31.36 ab	26.88 d	25.05 b	
	12	21.59 e	22.55 e	33.48 a	28.22 cd	26.46 a	
	24	21.65 e	22.93 e	33.38 a	29.82 bc	26.94 a	
Average Nano fertilizer		21.20 c	22.37 c	32.74 a	28.31 b		

*NPK (F = 114.24, P < 0.0001); I × NPK (F = 0.82, P = 0.4905); I × Org (F = 0.57, P = 0.5713); NPK × Org (F = 1.04, P = 0.3845); I × NPK × Org (F = 0.36, P = 0.9695).

Table 11. Residual soil available phosphorus (mg kg^{-1}) as influenced by study treatments

Irrigation Method	**Organic Fertilizer (g ha^{-1})**	**Nano Fertilizer (g L^{-1})**				**Irrigation × Organic Fertilizer**	**Average Irrigation**
		0	**3**	**6**	**9**		
	0	3.28 m	6.53 j	8.09 fg	7.38 hi	6.32 d	
Drip irrigation	12	5.51 k	8.91 bc	8.80 cd	8.18 e-g	7.85 b	7.09 b
	24	4.67 L	7.76 gh	8.65 c-e	7.30 hi	7.09 c	
Irrigation × Nano-fertilizer	Drip irrigation	4.49 f	7.73 d	8.51 c	7.62 d	Average organic fertilizer	
Organic fertilizer × Nano fertilizer	0	3.31 f	7.43 c	8.22 b	8.08 b	6.76 c	
	12	6.46 d	8.87 a	9.05 a	8.42 b	8.20 a	
	24	5.91 e	8.25 b	9.04 a	8.19 b	7.85 b	
Average Nano fertilizer		5.23 c	8.18 b	8.77 a	8.23 b		

*NPK (F = 616.21, P < 0.0001); I × NPK (F = 10.76, P<.0001); I × Org (F = 14.05, P < 0.0001); NPK × Org (F = 1.12, P = 0.3204); I × NPK × Org (F = 25.57, P < 0.0001).

Table 12. Residual soil available potassium (mg kg^{-1}) as influenced by study treatments

Irrigation Method	Organic Fertilizer (g ha^{-1})	Nano Fertilizer (g L^{-1})				Irrigation × Organic Fertilizer	Average Irrigation
		0	3	6	9		
Drip irrigation	0	105 e	223 c	274 ab	232 bc	208 b	225 a
	12	156 d	240 a-c	286 a	253 a-c	234 a	
	24	164 d	257 a-c	270 a-c	244 a-c	234 a	
Irrigation × Nano-fertilizer	Drip irrigation	142 c	240 b	277 a	243 b	Average organic fertilizer	
Organic fertilizer × Nano fertilizer	0	101 c	234 b	270 a	242 ab	212 b	
	12	156 c	248 ab	276 a	251 ab	233 a	
	24	160 c	255 ab	274 a	236 b	231 a	
Average Nano fertilizer		139 c	246 b	273 a	243 b		

*NPK (F = 96.76, $P < 0.0001$); I × NPK (F = 0.48, P = 0.6987); I × Org (F = 0.33, P = 0.7196); NPK × Org (F = 0.98, P = 0.4210); I × NPK × Org (F = 1.35, P = 0.2248).

3.2 Effects of organic fertilization

The addition of organic fertilizer led to a significant improvement in the availability of macronutrients for both the plant and the soil (Tables 4, 10). The level of 24 t ha^{-1} recorded the maximum nutrient concentrations compared to the lowest values in the control treatment (0 t ha^{-1}). This is attributed to the ability of organic matter to enhance the physicochemical properties of the soil by increasing the Cation Exchange Capacity (CEC) and forming chelated complexes that prevent phosphorus fixation and protect potassium from leaching. For the plant, it contributes to the secretion of organic acids and growth hormones that stimulate the root system, thereby increasing uptake efficiency. Furthermore, its role in interactions stands out as a natural dispersing agent that improves the stability of nanoparticles and prevents their aggregation, ensuring a continuous flow of nutrients throughout the growing season [31].

3.3 Effects of drip irrigation

The drip irrigation system significantly improved nutrient uptake and accumulation in the tubers (Tables 7, 8, 9). The importance of this system is particularly evident in the study's soil, which has a loamy sand texture. Drip irrigation addresses the low water-holding capacity of such soils by providing continuous and regulated moisture in the rhizosphere, thereby limiting nutrient loss through deep leaching—a common characteristic of coarse-textured soils. This mechanism creates an ideal hydraulic environment that ensures nutrients remain in a soluble state, facilitating their movement via "mass flow" toward the roots and maximizing the utilization of applied fertilizers under the soil's permeable conditions [32].

3.4 Two-way interactions

The two-way interactions between (drip irrigation × nano) and (nano × organic) exhibited a highly significant synergistic effect ($P < 0.0001$) on enhancing nutrient content (Tables 5, 8, 11) with the combination of (6 g L^{-1} nano × 24 t ha^{-1} organic) achieving the highest values. This effectiveness is explained by the ability of organic matter to function as a "stabilizing agent" that protects nanoparticles from precipitation or side reactions within the soil, maintaining them in a technically active state. In turn, these particles act as biocatalysts that stimulate the microbial communities responsible for organic matter mineralization, thereby accelerating the release of nutrients within the rhizosphere. This integration, supported by the uniform moisture distribution of drip irrigation, ensures a balanced nutrient supply that bridges nutritional gaps during critical growth stages [33].

3.5 Three-way interactions

The three-way combination (drip irrigation + 6 g L^{-1} nano + 24 t ha^{-1} organic) achieved the highest recorded nutrient concentrations across all plant parts and the soil (Tables 6, 9, 12). The success of this interaction is attributed to the creation of an integrated ecosystem that enhances Fertilizer Use Efficiency (FUE). The biological synchronization between stable moisture levels and organic matter works to reduce sorption forces within the soil, allowing nanoparticles to move more freely toward the root absorption zone. This harmony minimizes the chemical and physical loss of nutrients and ensures a continuous stream of available elements that aligns with the plant's increasing demands during the tuber formation stage, making it the most efficient system for nutrient management under field conditions [34].

3.6 Potato yield and components

The increase in crop productivity was closely linked to the improved nutritional and water status of the plant, where the synergy between drip irrigation nano-fertilizers and organic fertilizers maximized yield characteristics (Table 13). This integration contributed to reaching a tuber weight of 128.7 g tuber^{-1} achieved with the combined treatment of drip irrigation + 6 g L^{-1} nano + 24 t ha^{-1} organic, and a marketable yield peak of 64.93 t ha^{-1} of drip irrigation + 9 g L^{-1} nano + 24 t ha^{-1} This superiority is attributed to the role of drip irrigation in creating a hydraulic balance that reduced water stress, allowing the plant to efficiently direct photosynthesis products (Assimilates) toward the tubers. Furthermore, the sustained supply of elements from nano and organic fertilization enhanced dry matter accumulation, confirming that reaching maximum crop productive capacity depends on the integrated management of water and fertilizer resources [35].

3.7 Soil Nutrient Index

According to the SNI results calculated after harvest (Table 14), the soil exhibited a significant improvement in overall fertility status. Phosphorus and potassium levels rose to the (medium–high) fertility category with a value of (SNI = 2.33) while nitrogen recorded a (medium) fertility level with a value of (SNI = 2.17). The superiority of phosphorus and potassium values is attributed to the effectiveness of integrated fertilization and the soil's capacity to retain them. Conversely, nitrogen remained relatively lower due to the loamy sand texture, which increases the loss of mobile nutrients through leaching. It is worth noting that the initial soil properties recorded before planting (Table 1), such as the ideal pH (7.4) and low salinity (0.7 dS m^{-1}), established a chemical environment that enhanced nutrient availability and uptake efficiency. This reflects the positive impact of water and fertilizer management practices in improving the soil's nutrient reservoir by the end of the season [36, 37].

Table 13. Effect of nano-NPK and organic fertilization on tuber weight and marketable yield under drip irrigation

Parameter	Organic (t ha^{-1})	Nano Fertilizer (g L^{-1})				Mean Organic
		0	3	6	9	
Tuber Weight (g $tuber^{-1}$)	0	119.3 c-e	118.3 c-e	135.7 ab	112.7 e-g	121.5 a
	12	106.7 fg	113.3 d-f	116.7 c-f	123.7 b-d	115.1 ab
	24	115.7 c-f	109.7 f-g	128.7 a-c	120.0 c-e	118.1 ab
Mean (Nano) Weight		113.9 bc	113.8 bc	127.0 a	118.8 b	Drip irrigation 118.4
Marketable Yield (t ha^{-1})	0	40.51 e-g	46.85 c-f	54.44 a-d	51.35 a-e	45.57 b
	12	44.55 d-g	48.28 b-f	55.43 a-c	53.47 a-d	50.10 ab
	24	52.86 a-d	53.51 a-d	55.82 a-c	64.93 a	56.12 a
Mean (Nano) Yield		45.97 b	49.55 b	55.23 a	56.58 a	Drip irrigation 51.84

*Tuber Weight: NPK: F = 38.15, $P < 0.0001$; Organic: F = 12.44, P = 0.0015; NPK × Organic: F = 9.28, P = 0.0008, Marketable Yield: NPK: F = 42.67, $P < 0.0001$; Organic: F = 25.31, $P < 0.0001$; NPK × Organic: F = 11.54, $P < 0.0001$.

Table 14. Soil Nutrient Index (SNI)

Nutrient	No. of Low Samples	No. of Medium Samples	No. of High Samples	Index Value	Fertility Level
N	1	8	3	2.17	Medium
P	1	6	5	2.33	M–High
K	1	6	5	2.33	M–High

*Status of Nutrient, as per the calculation by the author.

4. CONCLUSIONS

From the above results, it can be concluded: 1) Soil application of nano-NPK at a concentration of 6 g L^{-1} which is confirmed to be more effective and balanced in providing plant nutrients than other concentrations; 2) The combination of the two is most effective with the optimal combination being (24 t ha^{-1} of organic fertilizer in soil + 6 g L^{-1} in soil nano-application), showing the highest synergistic effect on nutrient translocation to tubers; 3) Nano and organic fertilizers mainly work by improving soil fertility (SNI), although enhanced nitrogen management is still required in light-textured (loamy sand) soils to reduce leaching losses; 4) This integrated program achieved the highest marketable yield (64.93 t ha^{-1}), representing a (60.28%) increase over the control; therefore, we recommend its adoption for sustainable production and high resource-use efficiency.

ACKNOWLEDGMENT

The authors would like to express their gratitude to the University of Mosul and the Dean of the College of Agriculture and Forestry at the University of Mosul.

REFERENCES

[1] Chen, X., Zhang, H., Li, H. (2025). Optimizing deficit irrigation management to improve potato yield, quality and water use efficiency: A review. GBP Proceedings Series, 4: 39-44.

[2] Fan, J., Lu, X., Gu, S., Guo, X. (2020). Improving nutrient and water use efficiencies using water-drip irrigation and fertilization technology in Northeast China. Agricultural Water Management, 241: 106352. https://doi.org/10.1016/j.agwat.2020.106352

[3] Badr, M.A., Ali, E., Salman, S.R. (2023). Effects of nitrogen application and fertigation scheduling on potato yield performance under drip irrigation system. Gesunde Pflanzen, 75: 2909-2918. https://doi.org/10.1007/s10343-023-00871-y

[4] Kah, M., Kookana, R.S., Gogos, A., Bucheli, T.D. (2020). A critical evaluation of nanopesticides and nano-fertilizers against their conventional analogues. Nature Nanotechnology, 13(8): 677-684. https://doi.org/10.1038/s41565-018-0131-1

[5] Mostafa, A.S., Hegazi, M.M., Farghali, A.A., Salama, M.A.E. (2025). Managing a drip irrigation system to maximize potato crop productivity using nano-phosphate in sandy soil. Arab Universities Journal of Agricultural Sciences, 33(1): 7-20.

[6] Abdel-Aziz, H.M.M., Hasaneen, M.N.A., Omer, A.M. Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil. Spanish Journal of Agricultural Research, 14(1): e0902. https://doi.org/10.5424/sjar/2016141-8205

[7] Zhang, H., Li, X., Zhou, J., Wang, J., et al. (2024). Combined application of chemical fertilizer and organic amendment improved soil quality in a wheat–sweet potato rotation system. Agronomy, 14(9): 2160. https://doi.org/10.3390/agronomy14092160

[8] Sánchez-Navarro, A., Sánchez-Martínez, J., Barba-Corbalán, E.M., Valverde-Pérez, M., Girona-Ruiz, A., Delgado-Iniesta, M.J. (2021). Long-term effects of the use of organic amendments and crop rotation on soil properties in Southeast Spain. Agronomy, 11(12): 2363. https://doi.org/10.3390/agronomy11112363

[9] Abdehvand, Z.Z., Karimi, D., Rangzan, K., Mousavi, S.R. (2024). Assessment of soil fertility and nutrient management strategies in calcareous soils of Khuzestan province: A case study using the Nutrient Index Value

method. Environmental Monitoring and Assessment, 196: 503. https://doi.org/10.1007/s10661-024-12665-4

[10] Singh, S.P., Singh, S., Kumar, A., Kumar, R. (2018). Soil fertility evaluation for macronutrients using parkers nutrient index approach in some soils of Varanasi district of eastern Utter Pradesh, India. International Journal of Pure and Applied Bioscience, 6(5): 542-548.

[11] Malo, S.K., Saha, S. (2023). Assessment of the soil fertility index (SFI) for sustainable nutrient management in rice-based cropping systems of Barind tract of West Bengal, India. Discover Soil, *2*(1): 96. https://doi.org/10.1007/s44378-025-00130-8

[12] Richards, L.A. (1954). Diagnosis and Improvement of Saline and Alkali Soils (No. 60). US Government Printing Office.

[13] Gupta, S.C., Singh, P.N. (1999). Soil physical properties and their management. In Soil Science: An Introduction, pp. 125-158. https://www.worldcat.org/title/soil-science-an-introduction/oclc/46886470.

[14] Jackson, M.L. (1958). Soil chemical analysis. Journal of Plant Nutrition and Soil Science, 85(3): 251-252. https://doi.org/10.1002/jpln.19590850311

[15] Gupta, S.C., Larson, W.E. (1999). Estimating soil water retention characteristics from particle size distribution, organic matter percent, and bulk density. Water Resources Research, 15(6): 1633-1635. https://doi.org/10.1029/WR015i006p01633

[16] Olsen, S.R., Sommers, L.E. (1982). Phosphorus. In Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties, pp. 403-430. https://doi.org/10.2134/agronmonogr9.2.2ed.c24

[17] Page, A.L., Miller, R.H., Keeney, D.R. (1982). Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties. American Society of Agronomy, Madison, 1088. https://doi.org/10.2134/agronmonogr9.2

[18] Gee, G.W., Bauder, J.W. (1986). Particle-size Analysis. In Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, pp. 383-411. https://doi.org/10.2136/sssabookser5.1.2ed.c15

[19] SAS Institute Inc. (2001). Statistical Analysis System (SAS) User's Guide: Statistics (Version 8.2). SAS Institute Inc., Cary, NC, USA. https://www.sas.com/en_us/software/stat.html.

[20] Al-Rawi, K.M., Khalafallah, A.A. (2000). Design and analysis of agricultural experiments. Ministry of Higher Education and Scientific Research, University of Mosul, Iraq. https://www.researchgate.net/publication/Design_and_Analysis_of_Agricultural_Experiments.

[21] Muharram, H.J., Al-Bayati (1987). Principles of Potato Production. University of Mosul Press, Iraq.

[22] Alva, A., Fan, M., Qing, C., Rosen, C., Ren, H. (2011) Improving nutrient-use efficiency in Chinese potato production: Experiences from the United States. Journal of Crop Improvement, 25(1): 46-85. https://doi.org/10.1080/15427528.2011.538465

[23] Schuffelen, A.C., Muller, A., Van Schouwenburg, J.C. (1961). Quick-tests for-soil and plant analysis used by small laboratories. Netherlands Journal of Agricultural Science, 9(1): 2-16.

[24] Jones, J.B. (2012). Plant Nutrition and Soil Fertility Manual (2nd ed.). CRC Press, USA.

[25] Ahamad, A., Gupta, A.K., Kumar, D. (2021). Soil fertility evaluation using nutrient index approach. Journal of Krishi Vigyan, 10(1): 276-282. https://doi.org/10.5958/2349-4433.2021.00106.9

[26] Sachan, H.K., Krishna, D. (2022). Assessment of soil fertility status using nutrient index approach in cassava farms of Rewa Province, Fiji. Indian Journal of Agricultural Research, 56(5): 594-598. https://doi.org/10.18805/IJARe.AF-680

[27] Parker, F.W., Nelson, W.L., Winters, E., Miles, I.E. (1951). The broad interpretation and application of soil test information. Agronomy Journal, 43(3): 105-112. https://doi.org/10.2134/agronj1951.00021962004300030001x

[28] Al-Juthery, H.W.A., Al-Shami, Q.M.N. (2019). The effect of fertigation with nano NPK fertilizers on some parameters of growth and yield of potato (Solanum tuberosum L.). QJAS Al-Qadisiyah Journal for Agriculture Sciences, 9(2): 225-232.

[29] Seleiman, M.F., Almutairi, K.F., Alotaibi, M., Shami, A., Alhammad, B.A., Battaglia, M.L. (2021). Nano-fertilization as an emerging fertilization technique: Why can modern agriculture benefit from its use? Plants, 10(1): 2. https://doi.org/10.3390/plants10010002

[30] Rajput, V.D., Singh, A., Minkina, T., Rawat, S., et al. (2021). Nano-enabled products: Challenges and opportunities for sustainable agriculture. Plants, 10(12): 2727. https://doi.org/10.3390/plants10122727

[31] Shaji, H., Chandran, V., Mathew, L. (2021). Organic fertilizers as a route to controlled release of nutrients. In Controlled release fertilizers for sustainable agriculture, pp. 231-245 https://doi.org/10.1016/B978-0-12-819555-0.00013-3

[32] Al-Saigh, N.N., Al-Wazzan, F.A. (2025). The effect of water stress under drip irrigation system on different textured soils in the values of available water (TAW and RAW) on yellow corn crop Zea mays L. Euphrates Journal of Agricultural Science, 17(2): 842-859.

[33] Mahato, M., Dutta, D., Krishna, V.V.S.J., Paul, A. (2026). Integrated effects of irrigation scheduling and nano-fertilizers on potato yield, soil enzymes, and residual fertility. Potato Research, 69: 61. https://doi.org/10.1007/s11540-026-10024-z

[34] Niu, Y., Wang, L., Luo, Z., Fudjoe, S.K., Palta, J.A., Li, L., Li, S. (2025). Effects of irrigation practices on potato yield and water productivity: A global meta-analysis. Agronomy, 15(8): 1942. https://doi.org/10.3390/agronomy15081942

[35] Mijwel, A.K., Ali, G.M. (2020). Organic and nano fertilizers on qualitative and quantitative traits of potatoes. Biochemical and Cellular Archives, 20(1): 1887-1893.

[36] Choudhury, D., Thomas, T., Kumar, T. (2021). Fertility status and evaluation of nutrient index using available nitrogen, phosphorous and potassium of soils of Deomali hill-range valley zone, Odisha. The Pharma Innovation Journal, 10(7): 121-126.

[37] Al-Wazzan, F.A., Muhammad, S.A. (2022). Effects of conservation and conventional tillage on some soil hydraulic properties. IOP Conference Series: Earth and Environmental Science, 1060(1): 012002. https://doi.org/10.1088/1755-1315/1060/1/012002