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Managing a Drip Irrigation System to Maximize Potato Crop Productivity Using Nano-Phosphate in Sandy Soil

Amina, MS[1*], MM Hegazi[2], KhF El-Bagoury[2], AA Farghali[3], MA Salama[1]

1- Soil and Water Research Department, Nuclear Research Center, Egyptian Atomic Energy Authority, Inshas, Egypt
2- Agricultural Engineering Dept, Fac of Agric, Ain Shams Univ, P.O. Box 68, Hadayek Shubra 11241, Cairo, Egypt
3- Materials Science and Nanotechnology Dept, Fac of Postgraduate Studies for Advanced Science, Beni-Suef University, Egypt

*Corresponding author: amina_mostafa@agr.asu.edu.eg

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Abstract: Phosphorus is essential for plant growth, but its low availability in sandy soils limits agricultural productivity. Therefore, an open-field experiment was conducted on sandy soil under drip irrigation to compare the effects of nano and traditional phosphate fertilizers on potato yield and water use efficiency (WUE). Irrigation was maintained at 100% field capacity (FC), with the system showing an emission uniformity of 96.42% and emitter clogging at 14.4%. The reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c) were 512.1 and 498.5 mm season^{-1}, respectively, with adjusted crop coefficients ($K_{c\ adj}$) of 0.46, 0.82, 1.22, and 0.99 for the initial, development, mid-season, and late-season growth stages. The results revealed that tuber yield was slightly higher with nano-phosphate (10.47 ton ha^{-1}) than with conventional phosphate (10.34 ton ha-1), while water use efficiency (WUE) was recorded at 2.10 and 2.07 kg m^{-3}, respectively. As a result of the crop coefficient adjustment, the water requirements of 7.15 and 31.00 m³ ha¹ during the initial and development stages were reduced, and the nano phosphate achieved an 80% reduction in the recommended phosphorus fertilizer dose. Combining nano-phosphate and optimal irrigation enhances water and phosphorus use efficiency, creating an eco-friendly strategy for potato cultivation in sandy soils.

1 Introduction

In recent years, it was documented that fertilization management is considered one of the most challenging tasks under field management. Despite the necessity of mineral fertilizers for developing plant growth and yields, their prolonged and excessive application caused environmental and health risks (Poudel et al 2023).

Nano fertilizers are emerging as a transformative innovation in agriculture, addressing challenges associated with conventional fertilizers such as low nutrient use efficiency, high environmental losses and soil degradation (Mahesha et al 2023, Syaifudin et al 2024). Due to their nanoscale size, high surface area, and increased reactivity, nano fertilizers enhance nutrient availability and uptake by plants, improving crop productivity and resource use efficiency

(Pudhuvai et al 2025). These features make nano fertilizers a promising tool for sustainable agriculture, particularly in regions facing water scarcity, nutrient-poor soils, and climate change pressures (Kah et al 2018, Tang et al 2023). Studies have demonstrated that nano phosphate fertilizers improve crop yield and reduce the required dosage compared to conventional phosphorus fertilizers, thus lowering production costs and minimizing environmental pollution (Solanki et al 2015, Malhotra et al 2016).

Drip irrigation has revolutionized agriculture in sandy soils by addressing the unique challenges these soils pose, such as poor water retention, low nutrient-holding capacity, and high infiltration rates (Yang et al 2023, Dou and Sun 2024), by ensuring uniform moisture distribution. Drip irrigation optimizes the use of available water resources and enhances the solubility and uptake of fertilizers, improving crop yield and quality (Yang et al 2023). For potato crops, which have high water and nutrient demands, drip irrigation plays a pivotal role in maximizing WUE and fertilizer use efficiency (FUE) (Akkamis and Caliskan 2023, Cheng et al 2023). Adjusting irrigation schedules according to the potato crop's specific K_c values during different growth stages (e.g., initial, development, mid-season, and late season) ensures that water requirements are met without over-irrigation, thus enhancing both WUE and FUE (Cheng et al 2023, Gonzalez et al 2023).

Given the global importance of this crop, ensuring optimal water use without shortages or excess is crucial for achieving sustainable and efficient production (Jama-Rodzenska et al 2021). Therefore, phosphorus (P), one of the most essential nutrients for potato growth, is pivotal in achieving high yields and tuber quality. However, limited phosphorus availability often poses a major challenge, particularly in soils where it is naturally deficient. This challenge is further exacerbated by the fact that phosphorus in soil is not readily water-soluble, making it difficult for plants to absorb it efficiently. Consequently, farmers rely heavily on phosphate fertilizers to meet crop nutrient requirements (Shen et al 2011, Koch et al 2020); thus, nano fertilizers (NFs) offer a promising solution to address these challenges. Innovative approaches, such as integrating nano-phosphate fertilizers with precision irrigation systems, offer significant potential to overcome these barriers. Therefore, the current research aims to utilize mathematical modeling to adjust the crop coefficient (K_c) and optimize irrigation water requirements, thereby increasing potato yield. Additionally, Investigate the use of nano-phosphate fertilizers to enhance phosphorus use efficiency, minimize nutrient losses, and improve fertilization efficiency in sandy soils.

2 Materials and Methods

2.1 Study area

A field experiment was conducted at the Soil and Water Research Department farm, Nuclear Research Center, Egyptian Atomic Energy Authority, Inshas, Egypt. The experimental site is geographically positioned at 30° 17' N latitude and 31° 23' E longitude, with an altitude of 22 meters above sea level. The soil at the site is classified as sandy and irrigated by a drip irrigation system during the winter growing season 2023.

2.2 Soil and water analysis

The physical and chemical characteristics of the experimental soil, under the application of both traditional and nano-P fertilizers, were analyzed. Additionally, the chemical characteristics of irrigation water were estimated following the standard procedures detailed in Carter and Gregorich (2007). The supplementary materials include a detailed description of the soil and water analysis methods, and the results are presented in **Tables (1, 2, 3)**.

2.3 Climatic data during potato growing season

Weather data for the experimental period were obtained from the Automated Weather Station (iMETOS 3.3, by Pessl Instruments GmbH, Austria), located approximately 100 meters away from the experimental site. Climatic parameters, including precipitation, relative humidity, maximum and minimum temperatures, wind speed, and solar radiation, were recorded and are presented in **Table 4.** These parameters were used to calculate the daily reference evapotranspiration (ET_o) following the FAO Penman-Monteith method.

2.4 Drip irrigation system

A solar energy system powered the drip irrigation system used for watering the potato crop. The water supply was sourced from a well-equipped submersible pump (5 hp) and an AC motor. The solar power setup included photovoltaic (PV) panels, each providing 8.95 A of current and 31.3 V of voltage. The array consisted

Table 1. Some physical characteristics of the soil in the experiment under traditional and nano-phosphate fertilizers

Soil characteristics	Items	Traditional P	Nano-P
Physical			
Practical size distribution (%)	Clay	2.20	2.75
	Silt	1.65	0.84
	Sand	96.15	96.41
Soil texture		Sand	Sand
Bulk density (g cm^{-3})		1.72	1.72
Moisture content by volume (%)	FC	9.30	9.25
	WP	1.97	1.95
	AW	7.33	7.30

Table 2. Some chemical characteristics of the soil in the experiment under traditional and nano-phosphate fertilizers

Soil characteristics	Items	Traditional P	Nano-P
pH (1:2.5)		7.99	8.10
EC_e (dSm^{-1})		1.15	1.20
Anions (meq l^{-1})	Cl^-	3.91	3.85
	HCO_3^-	2.28	2.25
	CO_3^-	-	-
	SO_4^{--}	5.17	5.88
Cations (meq l^{-1})	Ca^{++}	3.48	3.10
	Mg^{++}	3.41	4.76
	Na^+	3.70	3.36
	K^+	0.77	0.76
$CaCO_3$ (g kg^{-1})		0.00	0.00
Macronutrients contents (%)	N	0.048	0.032
	P	0.032	0.029
	K	0.044	0.036

Table 3. Some chemical properties of the irrigation water

Item	pH	EC	Soluble anions (meq l^{-1})				Soluble cations (meq l^{-1})			
		(dS m^{-1})	Cl^-	HCO_3^-	CO_3^-	SO_4^{--}	Ca^{++}	Mg^{++}	Na^+	K^+
Irrigation water	7.82	1.46	5.00	2.50	-	7.00	5.80	5.30	1.16	2.24

Table 4. Automated weather station data from an average every 10 days for the experimental area during the growing season 2023.

Duration	Decade	Air Temperature		Relative Humidity		Precipitation	Sunshine hours	Wind speed
		T_{max}	T_{min}	RH_{max}	RH_{min}	P	n	u_2
(Month)	**(day)**	**(°C)**	**(°C)**	**(%)**	**(%)**	**(mm)**	**(hr)**	**(m sec^{-1})**
Jan	15-25	20.60	8.78	93.89	39.25	0.00	7.55	2.32
	26-31	21.76	9.94	85.32	27.88	0.00	7.60	2.80
Feb	1-10	17.12	8.46	79.12	39.00	0.00	7.80	3.00
	11-20	18.01	6.99	92.98	41.42	0.00	8.10	2.52
	21-28	22.28	9.97	93.32	36.04	0.00	8.40	1.84
Mar	1-10	27.18	12.24	86.78	22.19	0.00	8.70	2.61
	11-20	23.71	12.92	83.68	30.25	0.20	9.10	3.48
	21-31	24.24	12.70	86.13	30.31	2.60	9.40	2.71
Apr	1-10	28.98	13.41	81.88	21.74	0.00	9.80	2.83
	11-20	28.21	14.59	80.43	24.33	0.00	10.20	2.77
	21-30	27.97	14.56	82.21	24.33	0.00	10.60	2.88
May	1-6	29.97	14.93	80.54	19.31	0.00	11.00	3.28

of 18 polycrystalline modules, each with a capacity of 280 W, a module efficiency of 21.5%, and a tilt angle of 30°, producing 5 kWh/array. These panels were connected in series to meet the maximum power requirements of the AC motor.

The irrigation system comprises main and sub-main lines. The main line was constructed from PVC pipe with an outer diameter of 75 mm, a pressure capacity of 600 kPa, and a length of 25 m. The sub-main line was made from polyethylene (PE) pipes with an outer diameter of 32 mm and a pressure capacity of 200 kPa. The lateral lines consisted of polyethylene tubes with an outer diameter of 16 mm, featuring built-in emitters spaced 30 cm apart. Each emitter discharged 4 liters per hour at an operating pressure of 100 kPa.

2.5 Experiment conditions

The experiment was conducted using various phosphate fertilizer treatments, including traditional phosphorus and nano-P fertilizers. Two treatments were tested with three replicates and six plots. The experimental plot area was 7 m^2 with length and width (3.5 m × 2 m) under a drip irrigation system. The potato (*Solanum tuberosum L.*) cultivar Sponta was planted on January 15, 2023, and harvesting occurred 112 days later, on May 6, 2023. Plant spacing was 20 cm within rows and 70 cm between rows, resulting in five rows per plot.

Chemical fertilizers were delivered through the irrigation system to supply essential nutrients during the different growth stages. Nitrogen (N) and potassium (K) were applied at rates of 1082 kg ha^{-1} as ammonium nitrate (33% N) and 476 kg ha^{-1} as potassium sulfate (48% K_2O). Ammonium nitrate was divided into six applications, with 20% applied during soil preparation. Potassium sulfate was applied in two equal doses, one before and one during flowering.

Phosphorus fertilizers were provided in two forms: traditional phosphate fertilizer (single superphosphate, 15% P_2O_5) and nano-phosphate fertilizers. Single superphosphate was incorporated into the soil before planting at a rate of 1112 kg ha^{-1}, while nano-phosphate fertilizers were injected into the irrigation system at 20% of the recommended phosphate fertilizer rate. Additionally, organic matter (compost) was incorporated at a rate of 70 m^3 ha^{-1} before planting.

2.6 Preparation and characterization of superphosphate calcium nanoparticles

Superphosphate nanoparticles were synthesized using a top-down method involving the size reduction of bulk materials through ball milling. The ball milling process was carried out for 10 hours at Beni-Suef University, Egypt, following the protocols mentioned by Farghali et al (2007), Shahien et al (2015), and Mahmoud et al (2017). After that, the synthesized nanoparticles were then characterized to evaluate their physical and chemical properties. The following techniques were utilized: A) X-ray Diffraction (XRD): To determine the crystalline structure and phase composition of the nanoparticles; B) Fourier Transform Infrared (FTIR) Spectroscopy: To identify functional groups and chemical bonds in the material; C) Transmission Electron Microscopy (TEM): To examine the morphology, particle size, and distribution of the nanoparticles at the nanoscale. These preparation and characterization steps ensured the production of high-quality superphosphate calcium nanoparticles, suitable for agricultural applications.

The size of the crystallites was estimated by Scherrer's equation:

$$T = \frac{K\lambda}{\beta \cos\theta} \qquad (1)$$

where
T = mean size of the ordered (crystalline) domain.
K = non-dimensional factor = 0.9 but changes with the shape.
λ = X-ray wavelength.
β = is the line broadening at the intensity at half the maximum, after subtracting the instrumental broadening line's, in radians.
θ = is Bragg angle.

2.7 Water requirements and calculations

2.7.1 Reference evapotranspiration (ET_o)

The daily reference evapotranspiration (ET_o) was calculated using the Penman-Monteith equation, as recommended by Allen et al (1998). This calculation relied on the weather parameters recorded during the potato-growing season.

2.7.2 Crop evapotranspiration (ET_c)

Irrigation for potato crops was managed by applying water at 100% field capacity (FC), with a depletion fraction of total available soil water (TAW) set at p = 0.35. Scheduling was based on root zone depletion (D_r) and readily available water (RAW), integrated with the soil water balance equation. The crop evapotranspiration (ET_c) under non-stress conditions was calculated in **Equation 2**. However, the ET_c was estimated using the crop coefficient (K_c) values specific to the growth stages of the potato crop. Whilst the adjusted crop coefficient ($K_{c\ adj}$) was calculated using **Equation 3** according to Allen et al (1998), considering arid region factors such as minimum relative humidity (RH_{min}), wind speed (u_2), and plant height. The adjusted K_c was then used to refine the ET_c calculation. The standard K_c values and their corresponding growth stages are presented in **Table 5**.

$$ET_c = K_c ET_o \quad (2)$$

$$K_{c,i} = K_{cprev} + \left[\frac{i-\Sigma(L_{prev})}{L_{stage}}\right]\left(K_{cnext} - K_{cprev}\right) \quad (3)$$

where:

I, Day of the year during the growing season [ranging from 1 to the duration cultivation season],
$K_{c,\,I}$, Crop. coefficient for that day I,
$K_{c\,prev}$, Crop. coefficient during the previous. stage,
$K_{c\ next}$, Crop coefficient at the start of the next. stage,
L_{stage}, Duration of the stage being considered [days], and
$\Sigma(L_{prev})$, The total length of all previous. Stages combined [days].

Table 5. Parameters for potato crops during standard demand conditions

Growth stages	Duration 2023	Stage length (days)	$K_{c\ FAO}$ (-)
Initial	15/01-08/02	25	0.5
Development	09/02-10/03	30	0.83
Mid-season	11/03-14/04	35	1.15
Late-season	15/04-06/05	22	0.75
Total	-	112	-

2.7.3 Water use efficiency (WUE) and irrigation water use efficiency (IWUE)

At the end of the growing season, WUE (kg m^{-3}) and IWUE (kg m^{-3}) were determined following the formula provided by Kanani et al (2016):

$$WUE = Y_d/ET_c \quad (4)$$

$$IWUE = Y_d/I \quad (5)$$

where:

Y_d, Yield (kg ha^{-1}),
ET_c, Seasonal crop evapotranspiration (m^3 ha^{-1}), and
I, Irrigation obtained seasonally (m^3 ha^{-1}).

2.8 Percentage of emitter clogging for irrigation system

The ratio of emitter clogging is calculated using the equation below (Aboamera et al 2022):

$$P_{colg} = 100\left(1 - \frac{q_n}{q_c}\right) \quad (6)$$

where:

(P_{clog}), The percentage of clogging emitters (%),
(q_n), The least flow output of the emitters in the sampling group (l hr^{-1}) and
(q_c), The standard flow rate for each emitter type (l hr^{-1}).

The emission uniformity (EU) was assessed by measuring the water released from each emitter over a specified time. EU represents the percentage ratio of the average discharge from the lowest 25% of emitters to the over-average discharge across all emitters evaluated. The EU was calculated using the following equation, as described by Keller and Karmeli (1974):

$$EU = 100(Q_n/Q_a) \quad (7)$$

where:

Q_n, The mean flow rate of the bottom 25% of the chosen emitters. (l hr^{-1}), and
Q_a, The overall average discharge rate from the emitters (l hr^{-1}).

The coefficient. of variation (C.V) of the emitters applied in the treatments is determined by the equation presented below (ASAE 1988):

$$C.V = \frac{SD}{\bar{X}} \quad (8)$$

$$SD = \sqrt{\frac{\sum_{i-1}^{n}(xi-\bar{x})^2}{n-1}} \quad (9)$$

where:

SD: Standard deviation. of discharge value of emitter,
$\bar{X}$: Average emission rate of emitters (l hr^{-1}),
Xi: Discharge of emitters (l hr^{-1}), and
n: The quantity of emitters.

2.9 Potato measurements and analyses

The plant height was measured at the end of each growth stage, and at harvest (112 days after planting). At harvest, the fresh weight (FW) of the shoot, root, and tuber was recorded. These samples were then dried in a laboratory oven at 70°C for 72 hours to determine their dry weights (DW). Phosphorus (P) content in various plant parts was analyzed using the colorimetric method, with phosphorus absorption quantified through a UV spectrophotometer, following the protocols outlined by Estefan et al (2013) and Rana et al (2020). phosphorus use efficiency (PUE), phosphorus uptake efficiency (PUTE), and total phosphorus uptake were calculated using the methods described by Valle et al (2011) and Soratto et al (2015).

2.10. Statistical analysis

The experiment was conducted using a completely randomized block design (CRBD) with three replications to evaluate the water requirements of potato crops using two methods: the crop coefficient approach ($K_{c\,FAO}$) and the adjusted crop coefficients ($K_{c\ adj}$). Statistical analysis was performed using one-way analysis of variance (ANOVA) to assess the significance of differences among treatments. Means were compared using the Tukey test at a 5% significance level. All statistical analyses were carried out using the Origin software.

3 Results and Discussions

3.1 Hydraulic evaluation of the irrigation system

The hydraulic performance of the drip irrigation system was evaluated by measuring the EU and C.V on site. At the beginning of the growing season, the average total flow rate of the system was recorded as 4.72 l hr^{-1}, with the lowest quarter mean discharge at 4.55 l hr^{-1} and a standard deviation of 0.139. By the end of the season, the average total flow rate had decreased to 4.04 l hr^{-1}, while the average discharge of the lowest 25% dropped to 3.48 l hr^{-1} with. a higher standard deviation of 0.477. The percentage of emitter clogging was calculated as 14.4%. Initially, the irrigation system exhibited an emission uniformity of 96.42% with a manufacturer coefficient of variation of 0.029, categorizing its performance as "excellent" based on Merriam and Keller (1978) and ASAE (1988) standards. By the end of the season, the EU dropped to 86.06%, with a C.V of 0.118, which is considered "high" This decline reflects a slight reduction in system efficiency, attributed to minor emitter clogging during the growing season. This indicates the distribution of water throughout the layers of the soil was uniform, and the ratio of emitter clogging was low. The water distribution pattern was observed during a one-hour operational test **(Fig 1)**, which was conducted to evaluate the system emission uniformity. The system pressure was maintained at 1 bar, theoretically ensuring optimal performance throughout the test period. These results emphasize the importance of regular maintenance to sustain high emission uniformity and system efficiency, particularly in long-term agricultural applications.

3.2 Water requirements of the potato crop

The total ET_o varied across the growth stages, measuring 74.86, 109.44, 184.16, and 143.63 mm during the initial, development, mid-season, and late stages, respectively. These values reflect the varying water demand of the potato crop at different growth stages, driven by factors such as canopy development, root expansion, and environmental conditions. Furthermore, the average annual precipitation during the potato growth stage was minimal, recorded at approximately 0.025 mm $season^{-1}$, emphasizing the reliance on supplemental irrigation to meet crop water needs. The cumulative reference evapotranspiration (ET_o) for the growing season was 512.10 mm, as depicted in **Fig 2**.

In the early growth stage, 43.20 mm of water was applied, which decreased to 42.69 mm after adjusting the crop coefficient ($K_{c\,adj}$), resulting in a 1.19% reduction in water consumption. This modest reduction indicates the potential for fine-tuned irrigation management to conserve water without affecting crop performance.

Meanwhile, during the development stage, water application totaled 101.23 mm $stage^{-1}$, with an average daily ET_c of 3.29 mm. After modifying the K_c values, water application was reduced to 99.01 mm $stage^{-1}$, achieving a 2.20% reduction in water consumption. This stage saw an increase in ET_c as the crop canopy expanded and root systems developed, emphasizing the importance of precise irrigation to avoid water stress. However, the mid-season stage exhibited the highest water demand. The ET_c reached a total of 212.85 mm $stage^{-1}$, averaging 6.36 mm day^{-1}. After adjusting the K_c values, water applications increased slightly to 221.98 mm at stage 1. The higher $ET_{c\,adj}$ reflects the crop's peak water requirements during this stage to support optimal growth and productivity under full canopy conditions.

This increase highlights the necessity of providing sufficient water to avoid yielding losses during critical growth phases. In the late stage, the ET_c decreased to a mean daily value of 5.35 mm, with a total water use of 124.52 mm. After modifying K_c values, the adjusted ET_c ($ET_{c\ adj}$) increased to a mean daily value of 6.47 mm, totaling 136.37 mm. The increase in $ET_{c\ adj}$ is associated with the plant's physiological response to declining growth conditions, including higher net radiation, soil moisture depletion, and drier leaves, resulting in elevated reference evapotranspiration (ET_o) (Kadam et al 2021). Therefore, across the entire 112-day growing period, the total ET_c was 474.30 mm. After applying the adjusted crop coefficient ($K_{c\ adj}$), the total ET_c increased to 498.50 mm. The peak $ET_{c\ adj}$ occurred during the late stage, coinciding with the highest net radiation and declining soil moisture content.

The standard K_c values provided by FAO-56 (Allen et al 1998) were 0.5, 0.83, 1.15, and 0.75 for the initial ($K_{c\ ini}$), development ($K_{c\ dev}$), mid-season ($K_{c\ mid}$), and late-season ($K_{c\ end}$) growth stages, respectively. These coefficients were established for a sub-humid climate characterized by a mean of daytime minimum relative humidity (RH_{min}) of approximately 45%, an average wind speed of 2 m s^{-1}, and a plant height of about one meter during the relevant growth stages.

Adjustments to these K_c values are essential to account for variations in local climate, such as differing humidity levels, windy conditions, and other environmental factors (Modified K_c).

The results shown in **Fig 3** revealed that the determined K_c values were slightly lower during the initial (0.46) and development (0.82) stages, with reductions of approximately 8% and 1.2%, respectively. Conversely, the K_c values were higher during the mid-season (1.22) and late-season (0.99) stages, with increases of 6.1% and 32%, respectively. These variations can be attributed mainly to specific crop types, changes in the local climate and variations in seasonal crop growth patterns. These findings are consistent with the results reported by Salama et al (2015).

3.3 Characterization of superphosphate calcium nanoparticles

The XRD pattern of superphosphate calcium nanoparticles presented in **Fig 4** exhibits strong reflections and excellent crystallinity. The diffraction peaks were indexed against the ICDD card 04-023-8930 for the hydrogen calcium phosphate, confirming an anorthic structure (space group C-1(2)) with triclinic symmetry, highlighting their potential applications in materials science. This crystalline structure highlights the potential applications of nanoparticles in materials science. The average particle size of the prepared superphosphate calcium nanoparticles was calculated to be approximately 57.77 nm. Selected area electron diffraction (SAED) analysis from TEM, shown in **Fig 5A**, corroborates the excellent crystallinity observed in the XRD pattern. The SAED concentric rings correspond well with the monoclinic pattern identified in the XRD data. High-resolution TEM images further reveal that the nanoparticles form thin, stacked sheets a few hundred nanometers wide, with no evident preferred orientation, as seen in **Fig 5B**. In addition to that, FTIR spectroscopy analysis **Fig 6** and **Table 6** identified key surface functional groups in the superphosphate calcium nanoparticles. These include phosphate groups (HPO_4^{-2} and PO_4^{-3}), hydroxyl groups (^-OH), and water (H_2O). The observed functional groups are consistent with those reported by Singh et al (2010) and Maity et al (2011), further validating the structural and chemical composition of the nanoparticles.

3.4 Response of potato's growth traits to phosphate fertigation

Table 7 presents the yield of potatoes cultivated under a drip irrigation system using traditional and nano superphosphate calcium fertilizers. The results reveal comparable potato yields, ranging from 10.34 to 10.47 tons ha^{-1} under traditional, nano, and superphosphate fertilizer treatments. However, the nano fertilizer treatment demonstrated a 1.25% increase in tuber yield and a 6.53% rise in dry weight (DW), indicating enhanced carbohydrate allocation and biomass accumulation. These outcomes align with the findings of Wichrowska et al (2021), who also highlighted the benefits of drip irrigation systems. The improvement in tuber yield from nano phosphate (Nano-P) fertilizer aligns with previous studies, which report that nano-fertilizers enhance potato tuber yield by improving yield components and, to a lesser extent, other measured traits. Similar effects have been observed in other crops (Liu and Lal 2014). Nano phosphate fertilizer increased root fresh weight (FW) by 10% and root dry weight (DW) by 11.36%, suggesting that its smaller particle size facilitates better nutrient absorption and root biomass accumulation. In contrast, traditional phosphate fertilizer was more effective in enhancing shoot fresh weight, shoot dry weight and plant height. These results are consistent with earlier findings by Al-Juthery and Al-Shami (2019).

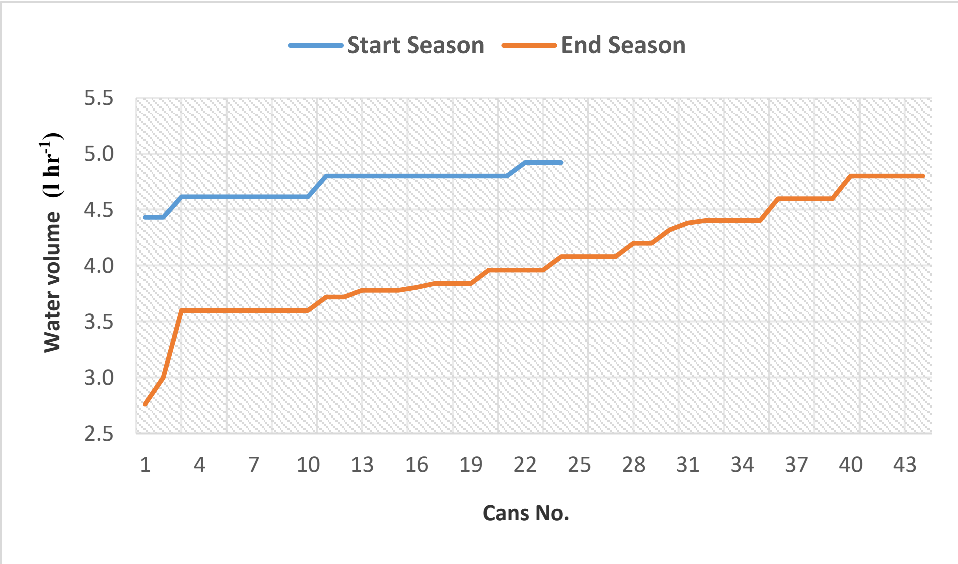


Fig 1. Discharge from emitters assessed for calculating the EU of the drip irrigation system at the beginning and at the end of season

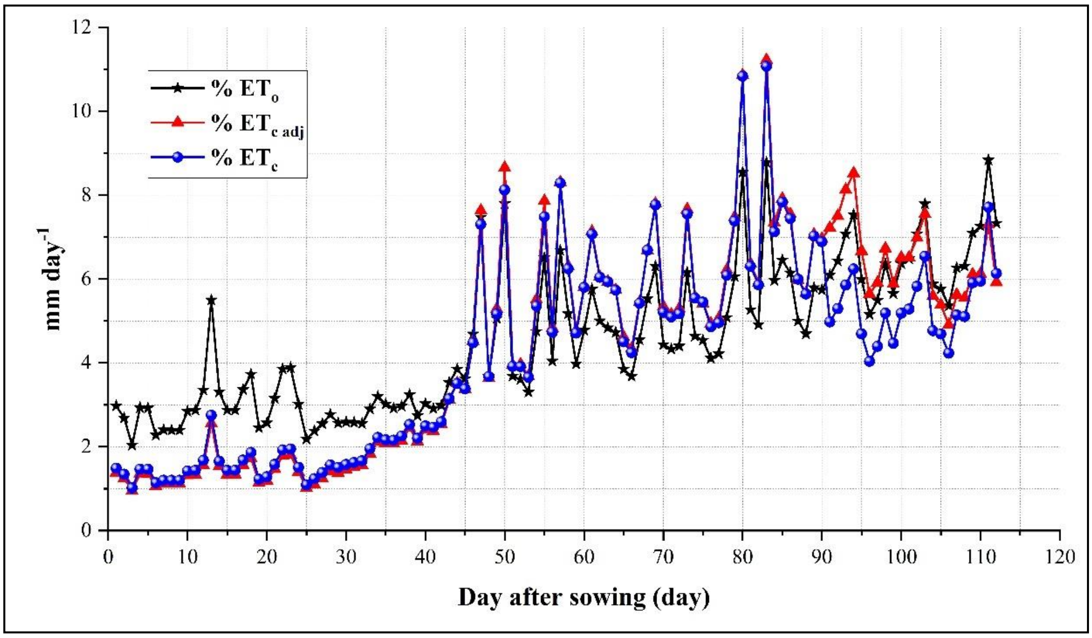


Fig 2. The ET_o, ET_c and $ET_{c\ adj}$ estimation through during the growing season (2023)

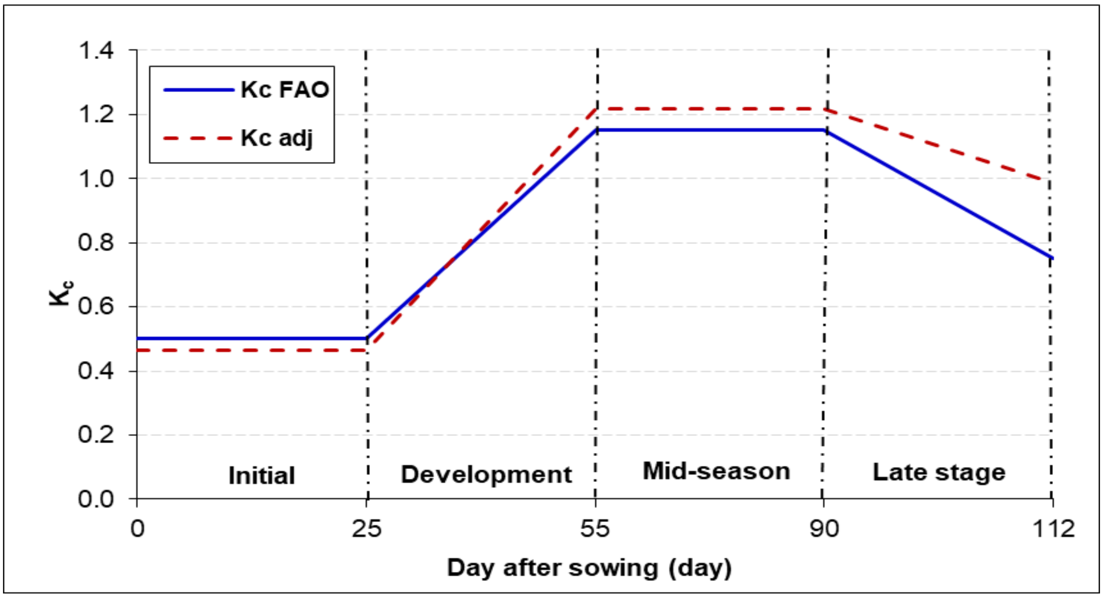


Fig 3. $K_{c\ FAO}$ and $K_{c\ adj}$ under different growth stages for potato crop

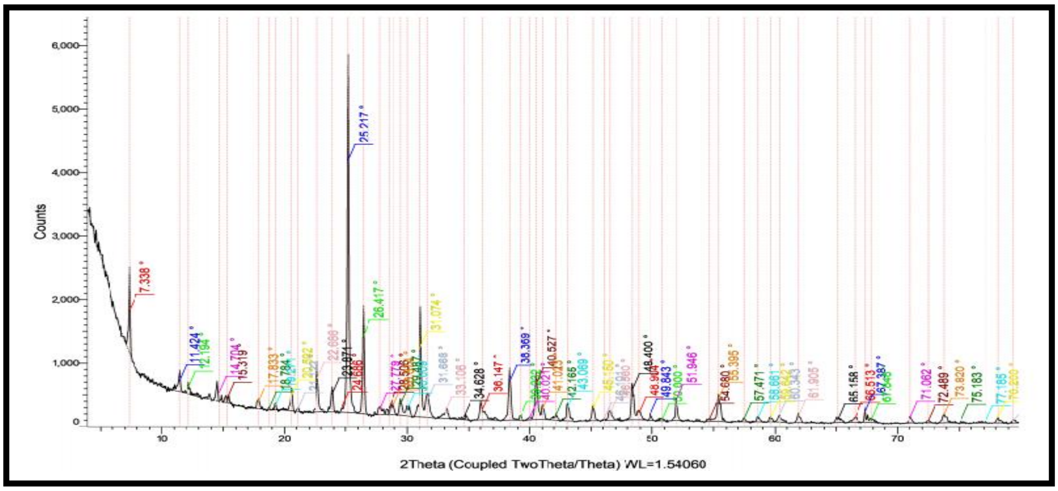
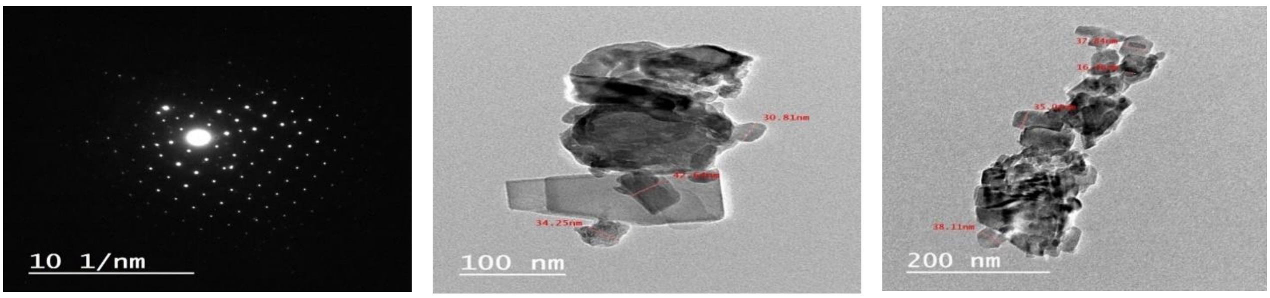


Fig 4. X-Ray pattern of superphosphate calcium nanoparticles



(A) (B) (C)

Fig 5. Selected area electron diffraction of super phosphate calcium nanoparticles (A), (B and C) are High-Resolution Transmission electron micrographs at two different magnifications of super phosphate calcium nanoparticles

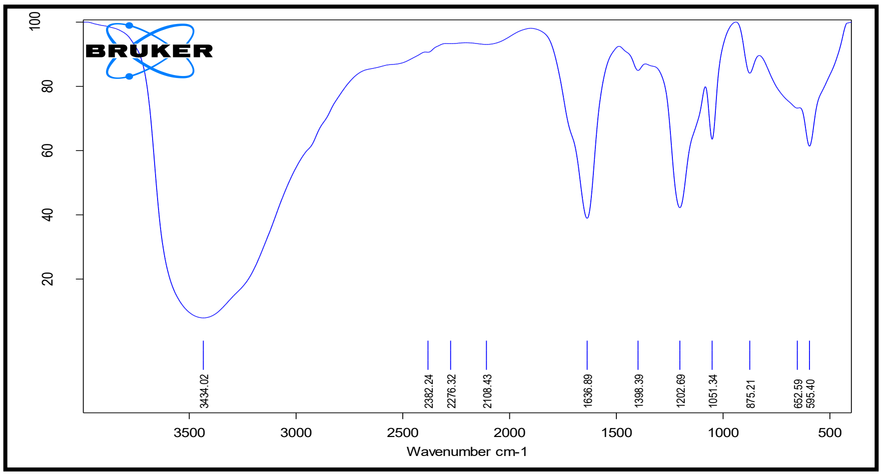


Fig 6. Fourier Transformer Infrared (FTIR) spectrum of nano superphosphate calcium

Table 6. Characteristic transmittance infrared bands of brushite

Wave number (cm^{-1})	Assignment	Wave number (cm^{-1})	Assignment
595.40	Stretching of the P_2PO^{-4} & PO_2^{-4} groups of calcium phosphate	1398.39	Blending vibration of (C-H) and carbonate groups
652.59	Stretching of the calcium pyrophosphate ($Ca_2P_2O_7$) and $CaCo_3$ groups	1636.89	Bending mode of H_2O and C=O highly conjugated
875.21	Stretching mode of (HPO_2^{-4})	2108.43, 2276.32 and 2382.24	Overtone or combination band (CH_2-CH_3) groups
1051.34	V_3 (P–O) Stretching of the PO_3^{-4} group	3434.02	stretching of the NH_2, $CaSo_4$ and (v_s (O-H) of water) groups
1202.69	Stretching of the (C-O) group		

The differences between nano and traditional phosphate fertilizers can be attributed to their mechanisms of nutrient release and absorption. Traditional phosphorus fertilizer may provide nutrients more readily to the shoots, leading to increased shoot biomass. Nano-P fertilizers, with their slower release rates and improved nutrient efficiency, favor root biomass development. While traditional phosphorus fertilizers may promote faster initial root elongation, nano-P fertilizers enhance overall biomass accumulation, particularly in tubers, which are the primary economic yield in potato cultivation (El-Ghany et al 2021). Therefore, this comparison highlights the potential of nano-phosphate fertilizers to reduce nutrient runoff and environmental impact due to their efficient utilization, while traditional fertilizers may still be advantageous for shoot growth. Specific growth objectives and environmental considerations should guide the choice between these fertilizers. Differences observed in this study compared to prior research (e.g., Quasem et al 2009, Sahayaraj et al 2016, Al-Juthery et al 2018) may be attributed to varying experimental conditions. The increase in dry plant yield achieved through fertigation could be linked to more efficient utilization of nitrogen, phosphorus, and potassium delivered alongside irrigation water. This approach ensures a more targeted nutrient supply, enhancing plant growth and development.

WUE and IWUE under traditional and nano superphosphate calcium fertilizers. No significant differences were observed in WUE, which ranged from 2.07 to 2.10 kg m^{-3} between treatments **(Table 7)**. However, nano fertilizers improved nutrient availability and phosphorus uptake, resulting in more effective water use. Nano fertilizers also demonstrated a greater IWUE, suggesting that they enable plants to use irrigation water more efficiently, likely due to improved nutrient uptake and reduced water stress. Enhanced root development with nano fertilizers may allow for better crop growth with the same or even less irrigation water. These findings are consistent with studies showing that fertigation through the surface (Kim and Rho 2023) or subsurface (Badr et al 2010) drip irrigation systems can significantly improve potato yields.

Table 7. Comparison of potato crop production under traditional phosphate fertilizers and nano-phosphate fertilizers at post-harvest

Parameters	Unit	Traditional P fertilizer	Nano-P fertilizer
Shoot (FW)	(ton ha^{-1})	3.08±0.81 a	2.45±0.13 a
Shoot (DW)	(ton ha^{-1})	0.45±0.08 a	0.38±0.06 a
Plant height	(cm)	28.70±1.53 a	26.70±0.58 a
Root (FW)	(ton ha^{-1})	0.30±0.04 a	0.33±0.04 a
Root (DW)	(ton ha^{-1})	0.044±0.01 a	0.049±0.01 a
Root length	(cm)	36.70±2.52 a	34.00±2.00 a
Tuber (FW)	(ton ha^{-1})	10.34±0.79 a	10.47±0.87 a
Tuber (DW)	(ton ha^{-1})	1.53±0.22 a	1.63±0.07 a
WUE	(kg m^{-3})	2.07±0.16 a	2.10±0.17 a
IWUE	(kg m^{-3})	1.49±0.11 a	1.50±0.12 a

Note: Means followed by the same letter are not significantly different but the different letters indicate significant differences at $P \leq 0.05$ (Tukey test).

3.5 Phosphorus content, uptake, and utilization by potato crop

Table 8 highlights the effects of traditional and nano phosphate fertilizers on various growth and productivity parameters of potato crops. Nano phosphate fertilizer demonstrated a 6.64% increase in tuber dry matter yield, a 9.2% improvement in phosphorus utilization efficiency (PUE), and a 6.55% increase in overall efficiency compared to traditional phosphate fertilizer.

These results underline the superior ability of nano phosphate fertilizers to enhance biomass production, particularly in tubers.

In contrast, traditional phosphate fertilizer was more effective in promoting shoot dry matter yield and phosphorus uptake. Despite these differences, the total phosphorus uptake was similar for both fertilizer types, suggesting that the choice of fertilizer should be based on specific production goals, with the priority being either maximizing tuber or shoot productivity. Experiments on phosphorus fertilization indicated that the total phosphorus accumulated in potato plants often exceeds the amount required for optimal dry matter accumulation and tuber yield (Soratto and Fernandes 2016). This phenomenon might be attributed to the faster dissolution rate of nano fertilizers, which enhances nutrient availability and utilization. The benefits of nano phosphate fertilizers were particularly evident when applied through fertigation, where phosphorus was more efficiently delivered to the crop, resulting in improved tuber yield. The advantages of nanotechnology, as demonstrated by nano phosphate fertilizers, lie in improving fertilizer use efficiency and boosting crop yields. These benefits are further amplified when the fertilizer is administered via irrigation water, as reported by Carmona et al (2022). This method ensures precise nutrient delivery, reducing losses and optimizing plant nutrient uptake, making it a promising approach for sustainable agricultural practices.

Table 8. Impacts of traditional and nano phosphate fertilizers on various agricultural characteristics of potato crops

Parameters	Unit	Traditional P fertilizer	Nano P fertilizer
Tuber P concentration	(%)	0.06±0.00 b	0.08±0.01 a
Shoot P concentration	(%)	0.40±0.08 a	0.34±0.13 a
Tuber P uptake	(kg ha^{-1})	0.89±0.13 b	1.37±0.09 a
Shoot P uptake	(kg ha^{-1})	1.79±0.17 a	1.25±0.35 a
Total P uptake	(kg ha^{-1})	2.68±0.05 a	2.62±0.30 a
PUTE (P utilization efficiency)		568.80±91.37 a	621.13±101.33 a
PUPE (P uptake efficiency)		0.016±0.00 a	0.016±0.00 a
PUE (P use efficiency)		9.16±1.31 a	9.76±0.44 a

Note: Means followed by the same letter are not significantly different but the different letters indicate significant differences at $P \leq 0.05$ (Tukey test).

4 Conclusion

Nano fertilizers outperformed traditional fertilizers in improving tuber dry matter yield, phosphorus use efficiency (PUE), and overall nutrient efficiency. While traditional phosphate fertilizers promoted greater shoot biomass and phosphorus uptake, nano fertilizers proved more effective in root and tuber development, highlighting their advantage in carbohydrate allocation and biomass production. Therefore, the integration of nanotechnology in fertilizers, particularly when applied through fertigation, not only enhances nutrient availability and uptake but also reduces nutrient runoff, thereby mitigating environmental impacts. Nano fertilizers were shown to enhance root biomass by improving phosphorus absorption and utilization, resulting in improved water use efficiency (WUE). These findings suggest that nano phosphate fertilizers enable crops to optimize water and nutrient use, achieving comparable or higher yields with reduced resource inputs. Moreover, the results underline the role of fertigation as a sustainable practice for maximizing fertilizer efficiency and improving crop productivity. Future research should investigate the long-term effects of nano fertilizers on soil health and crop performance across diverse environmental conditions to further validate and optimize their use.

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