

Effect of Adding Nano NPK Fertilizers and Foliar Application of Nano Zinc and Boron on the Concentration of NPK, Zn, and B in the Vegetative Parts of Potato (*Solanum tuberosum* L.) Plants

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Abstract

A field experiment was conducted on potato (*Solanum tuberosum* L.) cv. Burren during the spring season of 2019 at the Al-Jadriyah research station, Baghdad, Iraq (Latitude 33.27° N, Longitude 44.38° E, 34 m above sea level) in a calcareous silty loam soil. The study aimed to evaluate the efficiency of soil fertilization with NPK (nano and conventional) and the effect of foliar spraying with zinc and boron (nano and conventional), as well as their interaction, on the mineral content of the vegetative growth. The experiment was designed according to a Randomized Complete Block Design (RCBD) with three replicates in a factorial arrangement (3x3). Results showed that nano fertilization (both soil and foliar) significantly increased the concentrations of nitrogen (3.35%), phosphorus (0.33%), potassium (3.32%), zinc (65.56 mg.kg⁻¹), and boron (24.48 mg.kg⁻¹) compared to conventional and control treatments, yielding an average increase of 30%-50% in nutrient use efficiency. The interaction between nano soil application and nano foliar spraying achieved the highest quantitative values for all traits (3.52% N, 0.34% P, 3.40% K, 70.35 mg Zn.kg⁻¹, and 27.00 mg B.kg⁻¹), confirming the efficiency of nanotechnology in improving the nutritional status of plants and overcoming nutrient fixation and precipitation challenges in calcareous soils.

Keywords: Potato, Nano NPK, Foliar application, Zinc, Boron, Calcareous soil.

Introduction

Balanced mineral nutrition is the cornerstone of increasing agricultural productivity and optimizing crop quality. Nitrogen (N), phosphorus (P), and potassium (K) are the major nutrients involved in the synthesis of vital compounds, structural cellular components, and energy pathways within the plant. On the other hand, micronutrients such as zinc (Zn) and boron (B) play essential roles as cofactors in enzyme activation, protein synthesis, and sugar transport. Zinc is crucial for activating more than 300 enzymes and is involved in the synthesis of the amino acid tryptophan, which is the direct biochemical precursor for the auxin hormone (IAA) responsible for cell

elongation. As noted by [1], micronutrients such as zinc and boron are indispensable for completing vital processes; zinc is part of hydrolytic enzymes, respiratory processes, and protein synthesis, while boron is essential for cell elongation and sugar transport from leaves to storage organs. Boron is also important for maintaining cell membrane integrity and cell division [2]. [3] reported that nano zinc plays a vital role in enzyme activation and protein synthesis, while nano boron improves membrane permeability and sugar transport [4].

Potato (*Solanum tuberosum* L.) is a nutrient-demanding strategic crop that requires precise and intensive fertilizer management

to achieve high productivity. However, conventional fertilizers face major physiological challenges in Iraqi soils due to high pH values (>7.5) and elevated calcium carbonate (CaCO_3) content, which lead to rapid chemical fixation of phosphorus into insoluble forms, alongside the precipitation of micronutrients such as zinc and boron. Here, nano fertilizers play a crucial role. [5] explained that nano fertilizers are characterized by their small particle size and large specific surface area, which give them superior absorption capacity, high reactivity, and prolonged stability through roots or leaf stomata, avoiding soil entrapment barriers.

While previous research focused on single applications of nano-nutrients, there is a distinct research gap concerning the integrated synergy between soil-applied

macro nano-fertilizers and foliar-applied micro nano-fertilizers in highly calcareous soils. Therefore, this study specifically aims to: (i) evaluate the interactions between soil nano NPK and foliar nano Zn+B on enhancing the mineral profile of potato plants cultivated in typical Iraqi silty loam soils, and (ii) determine the capacity of nano-formulations to bypass chemical fixation zones.

Materials and Methods

A field experiment was carried out during the spring season in silty loam soil classified at the subgroup level as Typic Torrifluvent according to [6]. Random soil samples were taken before planting at a depth of 0-30 cm for chemical and physical analysis. Table (1) shows the soil properties before planting

Table (1): Soil properties before planting

Measured Property	Value	Unit
pH	7.74	-
Electrical Conductivity (EC 1:1)	2.31	dS.m^{-1}
Cation Exchange Capacity (CEC)	17.28	$\text{cmol}(+) \text{kg}^{-1}$
Organic Matter	1.22	%
Soluble Cations and Anions		
Calcium	12.73	meq.L^{-1}
Magnesium	7.51	meq.L^{-1}
Potassium	0.25	meq.L^{-1}
Sodium	2.12	meq.L^{-1}
Bicarbonate	0.72	meq.L^{-1}
Sulfate	12.84	meq.L^{-1}
Chloride	10.11	meq.L^{-1}
Available Nutrients		
Nitrogen	58	$\text{mg kg}^{-1} \text{ soil}$
Phosphorus	22.29	$\text{mg kg}^{-1} \text{ soil}$
Potassium	210	$\text{mg kg}^{-1} \text{ soil}$
Boron	0.44	$\text{mg kg}^{-1} \text{ soil}$
Zinc	1.81	$\text{mg kg}^{-1} \text{ soil}$
Soil Fractions		
Sand	300	g kg^{-1}
Silt	530	g kg^{-1}
Clay	170	g kg^{-1}

Texture	Silty Loam	-
USDA Soil Taxonomy Classification	Order:Entisols, Great Group:	-
	Typic Torrifluvents [6]	

The field was plowed using a moldboard plow and the soil was leveled with disc harrows. The field was split into experimental units with plot dimensions of 2.25 m x 3.0 m (6.75 m²), each consisting of 3 rows (furrows) spaced 75 cm apart with a 25 cm intra-row plant spacing. A Randomized Complete Block Design (RCBD) was used for a factorial experiment including two factors with three replicates (3x3):

1. Soil application factor (NPK): (No addition, Conventional, Nano).
2. Foliar spray factor (Zn+B): (Water only, Conventional, Nano).

Characterization of Nano-fertilizers

The chelated nano-fertilizers, including balanced nano-NPK (20:20:20), nano-zinc (19% Zn), and nano-boron (9% B), were sourced from Khazra Company (KHAZRA, Iran). To evaluate the structural morphology, shape, and spatial distribution of the nanoparticles, Scanning Electron Microscopy (SEM) was deployed at the laboratories of the College of Pharmacy, University of Babylon. The specific nanoparticle dimensions and size profiles were precisely quantified and verified using Image-Pro 4.5 software. The SEM micrographs revealed micro-porous crystalloid agglomerates with high specific surface areas, while the EDX spectrum profiles demonstrated exceptional elemental purity, displaying sharp primary peaks for N, P, and K with targeted weight percentages (wt.%) and atomic percentages (at.%) matching the standard structural specifications.

Soil applications of NPK (20:20:20) for both treatments were applied at an equal, standardized rate of 300 kg.ha⁻¹ to establish an equimolar comparative evaluation under identical quantitative mass pressure. The fertilizers were broadcast onto the soil in three splits: the first dose (30%) after complete germination (30 days after planting), the second dose (40%) 20 days after the first, and the third dose (30%) 15 days after the second.

Foliar applications of micronutrients were prepared based on their elemental active content and applied using a calibrated 16-liter knapsack sprayer at a total volume of 400 L. ha⁻¹ until complete leaf wetting. The treatments consisted of: conventional zinc (20% Zn) applied at a rate of 8 g / 16 L (0.5 g.L⁻¹), nano-zinc (19% Zn) applied at a rate of 8.416 g / 16 L (0.526 g.L⁻¹), conventional boron (11% B) applied at a rate of 5.808 mL / 16 L (0.363 g.L⁻¹), and nano-boron (9% B) applied at a rate of 7.104 g / 16 L (0.444 g.L⁻¹). Spraying was performed three times at 50, 60, and 70 days after planting, with a wetting agent (Tween-20) added to ensure adhesion.

The field experiment was managed under a surface furrow irrigation system, which is the standard irrigation practice at the Al-Jadriyah station. Irrigation scheduling was precisely maintained throughout the vegetative growth stages to keep soil moisture near field capacity, preventing any drought or waterlogging stress.

Potato tubers cv. Burren were planted at a depth of 8-10 cm. Late blight (*Phytophthora infestans*) was controlled using Elite Express fungicide. At the flowering stage, 5 representative plants per plot were collected,

washed, dried at 65°C, ground, and digested using H₂SO₄ / H₂O₂. Total nitrogen was measured via the micro-Kjeldahl method, phosphorus via a Spectrophotometer using the ammonium molybdate method, potassium via a Flame photometer, and zinc and boron via an Atomic Absorption Spectrophotometer, where boron was quantified colorimetrically using the Azomethine-H protocol. Data were statistically analyzed via ANOVA using GenStat software (v.20), with means compared using the LSD test at $P \leq 0.05$.

Results and Discussion

1- Nitrogen concentration (%) in the vegetative part at flowering stage

Nitrogen is an essential nutrient that contributes to the formation of amino acids and proteins within the plant, serving as the foundation for vegetative growth and leaf expansion. According to Table (2), soil applications significantly increased nitrogen concentration compared to the control (2.31%). The nano NPK soil application recorded the highest main effect value (3.35%), significantly outperforming conventional NPK (3.06%). This represents a relative increase of 45.02% and 32.47% for nano and conventional sources, respectively, over the control. This

superiority is driven by the slow and controlled release of nano-nitrogen, which reduces leaching and volatilization losses under calcareous conditions. These results are in high agreement with the findings reported by Bukhari et al. [7] and Al-Shami [8], who demonstrated that nano-formulations maximize nitrogen bioavailability in the root zone. For foliar factor, nano Zn+B spray recorded the highest mean value (3.07%), which was statistically equivalent to conventional Zn+B (2.93%) but significantly higher than the water control (2.72%). Regarding the interaction, the dual nano combination (Nano Soil x Nano Foliar) reached the maximum concentration (3.52%). Statistically, based on $LSD=0.38$, this peak did not significantly differ from Nano Soil + Conventional Foliar (3.38%) or Conventional Soil + Nano Foliar (3.23%), but it significantly surpassed the absolute control (2.17%). This synergistic mechanism is rooted in the role of nano-zinc as a structural binder that triggers the up-regulation of the nitrate reductase enzyme, multiplying net nitrogen upstream efficiency, confirming the metabolic trends observed by Hadi et al. [9] on nano-macro and micro fertilization integration

Table 2. Effect of treatments and their interaction on vegetative nitrogen concentration (%)

Soil Application	Water Only	Zn + B Conventional	Zn + B Nano	Mean (Soil Application)
Control (No fertilizer)	2.17 d	2.32 cd	2.45 c	2.31 C
Conventional NPK	2.85 b	3.10 ab	3.23 a	3.06 B
Nano NPK	3.15 ab	3.38 a	3.52 a	3.35 A
Main Effect of Foliar Spray (B)	2.72 B	2.93 A	3.07 A	Overall Mean: 2.91

LSD ($P \leq 0.05$): Foliar Spray (B) = 0.18 | Soil Application (A) = 0.22 | Interaction (AB) = 0.38

Error Mean Square (EMS): 0.041

2-Phosphorus concentration (%) in the vegetative part at the flowering stage

Phosphorus stimulates cellular energy pathways, root development, and nucleic acid synthesis. Both conventional and nano soil treatments significantly increased phosphorus concentration compared to the control (0.22%) (Table 3). Nano NPK soil application achieved the maximum main value (0.33%), establishing clear statistical boundaries over conventional NPK (0.29%) and control (0.22%). This denotes a 50.00% relative increase over the control. In high CaCO₃ soils, phosphorus is quickly fixed into insoluble calcium phosphates. Nano-coatings chemically isolate orthophosphate ions, avoiding contact with calcium ions and sustaining phosphorus bioavailability. This structural protection mechanism is well-aligned with the structural conclusions of Sharma et al. [14] and Yang et al. [13]

regarding the prevention of chemical precipitation via nanotechnology. Foliar nano Zn+B spray achieved the highest mean (0.30%), remaining statistically identical to conventional Zn+B (0.28%) but outperforming the control (0.26%). The interaction analysis showed that Nano Soil NPK x Nano Foliar Zn+B achieved the maximum absolute level (0.34%). Based on LSD=0.032, this value was statistically equivalent to Nano Soil + Conventional Foliar (0.33%), Nano Soil + Water (0.31%), and Conventional Soil + Nano Foliar (0.31%). Physiologically, nano-zinc functions as a metabolic bio stimulant that improves leaf chlorophyll synthesis, generating an internal carbohydrate sink demand that accelerates root phosphorus extraction to fuel ATP production, matching the nutritional synchronization principles outlined by Rashid et al. [10].

Table 3. Effect of treatments and their interaction on vegetative phosphorus concentration (%)

Soil Application	Water Only	Zn + B Conventional	Zn + B Nano	Mean (Soil Application)
Control (No fertilizer)	0.22 d	0.20 d	0.24 cd	0.22 C
Conventional NPK	0.26 c	0.29 b	0.31 ab	0.29 B
Nano NPK	0.31 ab	0.33 a	0.34 a	0.33 A
Main Effect of Foliar Spray (B)	0.26 B	0.28 AB	0.30 A	Overall Mean: 0.28

LSD (P ≤ 0.05): Foliar Spray (B) = 0.021 | Soil Application (A) = 0.016 | Interaction (AB) = 0.032

Error Mean Square (EMS): 0.0003

3- Potassium concentration (%) in the vegetative part at the flowering stage

Potassium regulates stomatal movement, osmotic potential, and enzyme activation. Soil application significantly increased tissue potassium concentration compared to the control (2.09%) (Table 4). Nano NPK

soil application achieved the highest value (3.32%), displaying significant differences from conventional soil NPK (3.23%) and the control. This marks a 58.85% relative

increase. The extensive surface area of nano-potassium allows high diffusion rates across the root cortex, bypassing the limited soil permeability and structural fixation typical of alkaline clay layers. This behavior

reinforces the kinetic hypotheses proposed by Zhang et al. [17] and Singh et al. [20] regarding nano-K transport models in high pH environments. Foliar nano Zn+B spray maximized individual factor means to 3.01%, significantly exceeding the control (2.72%) and conventional foliar spray (2.91%). The interaction treatments showed that Nano Soil NPK x Nano Foliar Zn+B recorded the highest absolute level (3.40%). Guided by $LSD=0.064$, this combination

shares statistical parity with Nano Soil + Conventional Foliar (3.35%) and Conventional Soil + Nano Foliar (3.37%). This response highlights the role of nano-boron in stabilizing membrane structures and up-regulating membrane-bound H⁺-ATPase proton pumps, which directly drives the active cellular uptake of potassium ions (K⁺), corroborating the conceptual frameworks presented by Mahmoud et al [4].

Table 4. Effect of treatments and their interaction on vegetative potassium concentration

Soil Application	Water Only	Zn + B Conventional	Zn + B Nano	Mean (Soil Application)
Control (No fertilizer)	1.92 d	2.10 c	2.25 c	2.09 C
Conventional NPK	3.05 b	3.28 a	3.37 a	3.23 B
Nano NPK	3.20 ab	3.35 a	3.40 a	3.32 A
Main Effect of Foliar Spray (B)	2.72 B	2.91 A	3.01 A	Overall Mean: 2.88

$LSD (P \leq 0.05)$: Foliar Spray (B) = 0.048 | Soil Application (A) = 0.035 | Interaction (AB) = 0.064

Error Mean Square (EMS): 0.0011
validates the root-interception observations documented by Sarwar et al. [23].

4-Zinc concentration in the vegetative part at the flowering stage (mg Zn.kg⁻¹ dry matter)

Zinc activates key respiratory processes, growth regulators, and protein configurations. Soil NPK application significantly increased zinc concentration compared to the control (47.63 mg.kg⁻¹ DM) (Table 5). Surprisingly, nano NPK soil treatment maximized the main effect to 65.56 mg.kg⁻¹ DM, significantly higher than conventional NPK (59.63 mg.kg⁻¹ DM). This positive correlation indicates that balanced nano NPK optimization enhances root system architecture and spatial root length density, increasing the total root surface available to absorb native soil zinc. This dynamic feedback mechanism directly

Foliar nano Zn+B spray achieved the highest micronutrient mean (63.63 mg.kg⁻¹ DM), significantly outperforming the conventional spray (58.81 mg.kg⁻¹ DM) and the control (50.38 mg.kg⁻¹ DM). Due to the low $LSD=0.19$, these differences are highly significant. The nano-scale size allows particles to easily pass through the leaf lipophilic cuticular layers and stomatal cavities, avoiding the fixation that limits conventional metal salts under alkaline conditions. The fact that the nano-fertilizer treatments did not induce any phytotoxicity or osmotic cell shock at this high rate of 300 kg. ha⁻¹ is directly attributed to the micro-porous, slow-release crystalloid architecture

revealed by the SEM micrographs. This structural shielding allows a controlled, steady release over time, preventing local salinity spikes. The interaction analysis confirmed that the dual nano treatment achieved a significant maximum absolute

level of 70.35 mg.kg⁻¹ DM, establishing distinct statistical boundaries for all treatment combinations in Table 5 (LSD=0.37), showing strong synergy as similarly characterized by Mohammadi et al. [21] and Hossain et al. [22]

Table 5. Effect of treatments and their interaction on vegetative zinc concentration (mg Zn.kg⁻¹ DM)

Soil Application	Water Only	Zn + B Conventional	Zn + B Nano	Mean (Soil Application)
Control (No fertilizer)	40.60 i	48.20 h	54.10 f	47.63 C
Conventional NPK	52.15 g	60.30 e	66.45 c	59.63 B
Nano NPK	58.40 d	67.93 b	70.35 a	65.56 A
Main Effect of Foliar Spray (B)	50.38 C	58.81 B	63.63 A	Overall Mean: 57.61

LSD (P ≤ 0.05): Foliar Spray (B) = 0.19 | Soil Application (A) = 0.24 | Interaction (AB) = 0.37
Error Mean Square (EMS): 0.038

significantly outperforming the conventional spray (20.65 mg.kg⁻¹ DM) and the control

5- Boron concentration in the vegetative part at the flowering stage (mg B kg⁻¹ dry matter)

Boron maintains cell wall integrity, carbohydrate translocation, and active meristematic division. Soil application significantly increased boron concentration compared to the control (14.52 mg.kg⁻¹ DM) (Table 6). Nano NPK soil application achieved the highest main effect value (24.48 mg.kg⁻¹ DM), followed by conventional NPK (21.55 mg.kg⁻¹ DM), establishing a relative increase of 68.59% over the control. This response highlights that balanced nano-macronutrient supply increases root vascular vigor, driving the passive mass flow of boron via the transpirational stream. This expression is identically supported by the potato trials compiled by Bukhari et al. [15] under analogous nanostructured integration. Foliar nano Zn+B spray recorded the maximum main level (22.85 mg.kg⁻¹ DM),

(17.05 mg.kg⁻¹ DM). Direct foliar delivery bypasses the severe chemical adsorption reactions with CaCO₃ minerals that lock up boron in alkaline soils. The interaction confirmed that the dual nano combination yielded the highest absolute boron concentration of 27.00 mg.kg⁻¹ DM. Guided by LSD=0.51, this peak was significantly superior to the Nano Soil + Conventional Foliar combination (25.00 mg.kg⁻¹ DM) and all other treatments. This confirms that nanoparticles improve internal cellular membrane permeability and vascular mobility, bypassing metabolic blockades under alkaline soil stress, a trend firmly backed by the foliar diagnostics of Prado et al. [24]. While this research focused intensively on evaluating the absolute macronutrient and micronutrient absorption dynamics within the foliar tissue compartments during the critical flowering

phase, the subsequent physiological impacts on terminal economic tuber yields and tuber qualitative metrics are systematically

reserved for independent subsequent investigative research projects.

Table 6. Effect of treatments and their interaction on vegetative boron concentration (mg B.kg-1 DM)

Soil Application	Water Only	Zn + B Conventional	Zn + B Nano	Mean (Soil Application)	
Control (No fertilizer)	11.50 h	14.80 g	17.25 f	14.52 C	
Conventional NPK	18.20 e	22.15 c	24.30 b	21.55 B	
Nano NPK	21.45 d	25.00 b	27.00 a	24.48 A	
Main Effect of Foliar Spray (B)	17.05 C	20.65 B	22.85 A	Overall Mean: 20.18	

LSD (P ≤ 0.05): Foliar Spray (B) = 0.28 | Soil Application (A) = 0.32 | Interaction (AB) = 0.51
Error Mean Square (EMS): 0.072

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