Journal of Applied Horticulture, 28(1): 247-251, 2026

https://doi.org/10.37855/jah.2026.v28i01.39

Journal of Applied Horticulture
ISSN: 0972-1045

Comparative analysis of humic acid, fulvic acid, and Eco-WRP combined with nano-NPK on postharvest SOC and NPK availability

I.R. Al-Shahbani[1], A.M. Al-Sultany[2], M.K. Alkhafaji[3] and M.R. Ajeel[4]*

[1]Department of Soil and Water Techniques, Al-Musayyab Technical College, Al-Furat Al-Awsat Technical University, Iraq. [2]Department of Biocontrol Techniques, Al-Musayyab Technical College, Al-Furat Al-Awsat Technical University, Iraq. [3]Department of Plant Protection, College of Agriculture, University of Karbala, Iraq. [4]Department of Soil and Water Techniques, Al-Musayyab Technical College, Al-Furat Al-Awsat Technical University, Iraq.
**E-mail: mohammed.rahim@atu.edu.iq*

Abstract

The study was a field experiment based on a Randomized Complete Block Design (RCBD) with three replications in the autumn growing season of 2023-2024 in loam soil in the Al-Musayyib district, Babylon Governorate, in Iraq. At the test site, the baseline of soil organic carbon (SOC) was 2.72 g kg^{-1}, and, after the harvest, SOC in the control plots dropped to 1.50 g kg^{-1}. The experiment examined the synergistic interactions between humic acid, fulvic acid and Eco-WRP with nano-NPK on post-harvest soil organic carbon and availability of macronutrients in soils under potato cultivation. The treatments were (i) HA (5 g $plant^{-1}$), FA (2 g $plant^{-1}$) and control and (ii) Eco-WRP + nano-NPK at five levels: Eco-WRP only (10 kg ha^{-1}), Eco-WRP + nano-NPK (2 g), Eco-WRP + nano-NPK (4 g), nano-NPK only (2 g) and control. Findings indicated that HA in combination with nano-NPK had a significant effect on the availability of nitrogen in the soil (73.152 mg kg^{-1}). However, a mixture of FA, Eco-WRP (10 kg ha^{-1}) and 4 g nano-NPK led to maximum increases in available phosphorus (31.001 mg kg^{-1}), potassium (318.632mg kg^{-1}) and SOC (3.061g kg^{-1}). The results illustrate the possibility of combined organic and nano-fertilizer management to improve measured soil fertility parameters and nutrient bioavailability in semi-arid soils.

Key words: Eco-WRP, fulvic acid, humic acid, nano-fertilizers, soil organic carbon, potato, available NPK

Introduction

Degradation of agroecosystems, brought about by climate change and the lack of freshwater, resulted in the reduction of organic carbon storage in the soil and the extraction or loss of key nutrients, reducing the nutritional sustainability of agroecosystems worldwide. The initial SOC value was used as the baseline soil carbon status for treatment comparison. Such degradation is fraught with serious problems, such as reduced fertilizer efficiency and soil nutrient depletion, which may be addressed through improved soil management practices to revive its health, the combination of organic compounds - including humic substances- has become a promising approach to augment the nutrient cycle, improve soil structure, and improve soil quality parameters in arid and semi-arid areas(Mahler *et al.,* 2021).

Humic acid (HA), fulvic acid (FA) and humins make up 60-80% of the soil organic matter (SOM), which plays a central role in controlling the biochemical activities of the soil (Mahler *et al.,* 2021). Humic acid is a high-molecular-weight organic substance that increases cation exchange capacity, promotes soil aggregation, and facilitates nutrient retention via complexation and adsorption, particularly in the loam soils in arid and semi-arid environments (de Melo *et al.,* 2016; Akimbekov *et al.,* 2021). In contrast, fulvic acid, due to its lower molecular weight, is characterized by higher solubility and mobility, which facilitates root cell permeability, nutrient translocation, and element mobility within the rhizosphere across various crop species (Azcona *et al.,* 2011; Capstaff *et al.,* 2020). Field trials demonstrated that humic acid and fulvic acid enhanced SOC by 12–18% and nitrogen-use efficiency by 25–30% (Chen *et al.*, 2021).

In spite of these advantages, in semi-arid areas, where more than 40% of arable land has SOC lower than 1.5% (FAO, 2017). Eco-WRP is a commercially available silicon-based hydrogel exhibiting an excellent superabsorbent water-holding capacity (>400%) and nutrient retention (Bakel *et al.,* 2025). Nano-NPK preparations that have high surface-area-to-volume ratios and selective release characteristics have been reported to improve phosphorus availability and reduce leaching losses compared with traditional fertilizers (Chen *et al.,* 2021). Nevertheless, they should be collectively applied with organo-mineral amendments that need to be assessed systematically to achieve the best synergistic impact on the soil-plant complex.

The study seeks to evaluate the effects of important gaps in knowledge by exploring the treatment effects and interactions of HA, FA, and Eco-WRP supplemented with nano-NPK on post-harvest SOC and bioavailability of macronutrients in potato production systems. Using a factorial RCBD design, we measure (I) the differences in effects of HA and FA on soil physicochemical properties, (ii) the effect of Eco-WRP on stabilizing nano-NPK release, and (iii) the nutrient availability dynamics of the interventions in loam soils. Our results will be used to promote accurate soil management systems, which are in line with the UN Sustainable Development Goals (SDGs) that focus on zero hunger and sustainable land use.

Materials and methods

A field study was conducted during the 2023–2024 growing season in a loam soil agricultural field located in Al-Musayyib district, Babylon Governorate, Iraq, to evaluate the synergistic impacts of humic acid (HA), fulvic acid (FA), and Eco-WRP combined with nano-NPK on post-harvest SOC and NPK availability under Solanum tuberosum L. (cv. Spunta) cultivation. Eco-WRP is a commercially available potassium silicate-based hydrogel composed of 20% SiO_2 and 5% K_2O, cross-linked with a synthetic polymer matrix. Its structure allows high water retention (>400%) and controlled nutrient release under field conditions, significantly enhancing soil potassium availability. The elemental composition was derived from the manufacturer's specifications, while its high water-holding capacity aligns perfectly with the superabsorbent behavior of cross-linked polymer hydrogels documented in recent literature (Bakel *et al.*, 2025). The Eco-WRP product was applied according to the manufacturer's instructions and stored at ambient temperature before use. Before trial initiation, composite soil samples (0–30 cm depth) were collected from 10 randomized points across the experimental site, air-dried, homogenized, and sieved (< 2 mm) for baseline physicochemical characterization (Table 1).

The experiment was conducted in a 3 x 5 factorial design within a Randomized Complete Block Design (RCBD) and three replications. Factor A consisted of three organic amendment treatments: 5 g humic acid plant^{-1}, 2 g fulvic acid plant^{-1}, and control without amendment. Factor B consisted of five fertilizer treatments: control (basal DAP and K_2SO_4 only, without HA/FA/Eco-WRP/nano-NPK), Eco-WRP at 10 kg ha^{-1}, Eco-WRP at 10 kg ha^{-1} + nano-NPK at 2 g plant^{-1}, Eco-WRP at 10 kg ha^{-1} + nano-NPK at 4 g plant^{-1}, and nano-NPK at 2 g plant^{-1} only. The experiment was arranged in a 3 × 5 factorial RCBD with three replications, resulting in 15 treatment combinations and 45 experimental units. Plot size was 3 m × 2.5 m with row length of 1 m. Potato tubers were planted on October 5, 2023, with a spacing of 75 cm between rows and 25 cm between plants, resulting in a planting density of approximately 53,333 plants ha^{-1}. All treatments were applied uniformly across plots to minimize spatial variability. Standard agronomic practices were maintained consistently throughout the experiment. Background (basal) fertilization, consisting of 200 kg ha^{-1} of diammonium phosphate (DAP, 18-46-0) and 100 kg ha^{-1} of potassium sulfate (K_2SO_4), was incorporated into the soil during land preparation. The field was irrigated using a surface furrow irrigation system, with watering scheduled every 7–10 days based on crop water requirements and soil moisture levels. Weed and pest management included manual weeding and the preventive application of Imidacloprid to control aphids. To prevent nanoparticle agglomeration and ensure homogeneous distribution, the nano-NPK suspensions were subjected to probe ultrasonication for 20 minutes prior to field application. Nano-NPK was prepared at a concentration of 4 g L^{-1} to deliver the 2 g plant^{-1} dose, and 8 g L^{-1} to deliver the 4 g plant^{-1} dose. The suspensions were applied as a soil drench in the root zone at a uniform volume of 0.5 L plant^{-1} during tuber initiation, targeting the active root zone directly into the planting furrows at a depth of 10 cm and a lateral distance of 15 cm from the plant stem. Based on the configured planting density of 53,333 plants ha^{-1}, the precise quantities of active ingredients administered under each nano-NPK treatment level were calculated as follows: Nano-NPK (2 g plant^{-1} level): Equivalent to a total application rate of 106.67 kg ha^{-1} of the nano-product. This supplied an actual elemental dose of 21.33 kg N ha^{-1}, 21.33 kg P_2O_5 ha^{-1}, and 21.33 kg K_2O ha^{-1} (corresponding to 0.4 g of each macronutrient per individual plant). Eco-WRP + Nano-NPK (4 g plant^{-1} level): Equivalent to a total application rate of 213.33 kg ha^{-1} of the nano-product. This supplied an actual elemental dose of 42.67 kg N ha^{-1}, 42.67 kg P_2O_5 ha^{-1}, and 42.67 kg K_2O ha^{-1} (corresponding to 0.8 g of each macronutrient per individual plant). The commercial nano-NPK formulation was procured from Advanced Nano Technologies Co. (Ankara, Turkey). According to the manufacturer's certified technical specifications, the nano-fertilizer had a total macronutrient composition of 20:20:20 (N: P_2O_5:K_2O). The nanoparticles had an average hydrodynamic particle size of 35–75 nm, a spherical morphology, and a zeta potential of approximately -28 mV, ensuring high colloidal stability in suspension. The product showed high water solubility (>98%) with a controlled-release behavior designed to release nutrients gradually over 35–45 days under standard field temperatures. Organic amendments (HA/FA) and Eco-WRP were applied through subsurface banding in the planting furrows during tuber initiation. Fertilizer placement was standardized at a soil depth of 10 cm and a lateral distance of 15 cm from the plant stem to ensure uniform application and reduce spatial variation. The crop was harvested at physiological maturity on February 12, 2024. Post-harvest sampling was conducted using a zigzag method within each plot, avoiding border effects (>50 cm from plot edges).

Soil organic carbon and matter: Soil organic carbon (SOC) was determined by the Walkley-Black wet oxidation technique, which entails dichromate digestion and subsequent titration by ferrous ammonium sulphate to ascertain oxidizable organic carbon and is reported as g kg^{-1} of soil (Walkley and Black, 1934). Organic matter was then estimated based on the standard relationship:

Organic Matter = SOC × 1.724

Available nitrogen: Fractions of ammonium (NH_4^+) and nitrate (NO_3^-) were extracted in a 2 M KCl solution and magnesium

Table 1. The physical and chemical properties of soil

Measurements	Value	Unit of measurement
Texture	Loam	-
Sand	495	g kg^{-1}
Silt	400	g kg^{-1}
Clay	105	g kg^{-1}
pH	7.54	-
EC	2.9	dS m^{-1}
N	12.04	mg kg^{-1}
P	24.31	mg kg^{-1}
K	199.22	mg kg^{-1}
Organic Carbon (SOC)	2.72	g kg^{-1}
Organic Matter	4.69	g kg^{-1}
Carbonate minerals	318	g kg^{-1}
Dissolved calcium (Ca^{2+})	12.15	me L^{-1}
Dissolved magnesium (Mg^{2+})	10.00	me L^{-1}
Dissolved sodium (Na^+)	5.23	me L^{-1}
Dissolved potassium (K^+)	0.90	me L^{-1}
Dissolved bicarbonate (HCO_3^-)	1.3	me L^{-1}
Dissolved chloride (Cl^-)	15.18	me L^{-1}
Soluble sulfates (SO_4^{2-})	12.52	me L^{-1}
Dissolved carbonate (CO_3^{2-})	Nil	-

The USDA soil texture classification system showed that the soil was loam based on the particle size distribution (49.5% sand, 40% silt, and 10.5% clay).

oxide (MgO) to volatilize NH 3 under an alkali environment. A micro-Kjeldahl apparatus and Devarda alloy were used to perform the distillation to reduce NO_3^- to NH_3, and then titration was conducted to determine the total mineralizable nitrogen (mg kg^{-1}).

Available phosphorus: Phosphorus availability was determined by the Olsen bicarbonate extraction (0.5 M $NaHCO_3$, pH 8.5). The obtained orthophosphate was reacted under acidic conditions with ammonium molybdate and ascorbic acid to form a phosphomolybdenum blue complex, which was measured spectrophotometrically (882 nm). The results were expressed in mg P kg^{-1} soil (Olsen *et al.*, 1954).

Available potassium: Exchangeable potassium was eluted using 1 M ammonium acetate (NH_4OAc, pH 7.0) and measured by flame photometry (Jenway PFP7) in the presence of calibrants made with standard KCl solutions. The concentrations were reported as mg K kg^{-1} soil.

Statistical analysis: The experiment was laid out as a factorial design. Data were subjected to a two-way Analysis of Variance (ANOVA) to assess the significance of the main effects of organic amendments (Factor A), Eco-WRP combined with nano-NPK treatments (Factor B), and their interaction (A × B). Mean separations were performed using Duncan's Multiple Range Test (DMRT) at a significance level of $P < 0.05$. In all data tables, different lowercase letters within the inner data grid represent significant differences among the interaction means, whereas letters in the marginal 'Mean' columns and rows denote significant differences for the respective main effects (Al-Rawi and Khalaf Allah, 1980).

Results and discussion

The factorial ANOVA revealed highly significant effects ($P \leq 0.01$) of organic amendments (Factor A), Eco-WRP/nano-NPK treatments (Factor B), and their interaction (A × B) on SOC and the availability of N, P, and K in soil (Table 2). Therefore, treatment means were compared using Duncan's Multiple Range Test at $P \leq 0.05$.

Table 2. Analysis of variance for the effects of treatments on soil organic carbon and available nutrients in soil

Source of variation	df	SOC (MS)	N (MS)	P (MS)	K (MS)
Replications	2	0.003	2.984	0.357	54.957
Organic amendments (A)	2	0.908**	675.344**	27.037**	4787.661**
Eco-WRP/nano-NPK treatments (B)	4	1.928**	531.818**	79.442**	8873.205**
A × B	8	0.045**	40.559**	1.423**	634.378**
Error	28	0.004	3.510	0.420	64.656
Total	44	10.000	3906.687	395.691	52063.440

Note: Mean squares (MS) obtained from two-way factorial ANOVA under a factorial RCBD. Factor A = organic amendments (control, humic acid, and fulvic acid). Factor B = Eco-WRP and nano-NPK treatments. SE = standard error of the mean. CV = coefficient of variation (%).

Different lowercase letters in Tables 3–6 indicate significant differences among treatment means according to Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$. ** Significant at $P \leq 0.01$.

Table 3 shows that there is a statistically significant change in the soil organic carbon (SOC), with the starting value of 2.72 g kg^{-1}. Humic acid (2.106 g kg^{-1}) and fulvic acid (2.323 g kg^{-1}) treatments outperformed the control (1.832 g kg^{-1}), yielding relative increases of 14.96% and 26.80%, respectively ($p < 0.05$). On the same note, nano-NPK-enriched Eco-WRP showed dose-dependent enhancement of SOC. The incremental additions of nano-NPK (0, 2 and 4 g) to 10 kg ha^{-1} Eco-WRP significantly increased SOC to 1.816, 2.213 and 2.799 g kg^{-1}, respectively, over the control (1.580 g kg^{-1}) by 14.94-77.15%. The nano-NPK treatment alone (2 g) also enhanced SOC to 2.026 g kg^{-1} (+28.23%), indicating a positive short-term post-harvest SOC response.

This indicates that fulvic acid (2 g) in combination with the highest dose of nano-NPK (4 g + 10 kg ha^{-1} Eco-WRP) had a synergistic effect; the highest SOC levels (3.061 g kg^{-1}) were obtained, which increased by 103.66 percent compared to the non-amended control (1.503 g kg^{-1}). The increase in SOC may be associated with improved nutrient retention and organic amendment effects, although microbial and root mechanisms were not directly measured. We hypothesize that their large surface area and controlled-release characteristics might restrict nutrient leaching and temporarily stimulate transient microbial activity, thereby facilitating a short-term accumulation of labile carbon within the soil matrix. This underscores the combinatorial potential of organo-mineral and nanotechnology interventions in accelerating short-term organic carbon accumulation.

Table 3. Effect of humic, fulvic and Eco-WRP fertilizer combined with nano-NPK on soil organic carbon (SOC) (g kg^{-1})

Treatments	Control	Eco-WRP (10 kg ha^{-1})	Eco-WRP (10 kg ha^{-1}) + nano NPK (2 g)	Eco-WRP (10 kg ha^{-1}) + nano NPK (4 g)	nano NPK (2 g)	Mean
Control	1.503c	1.557b	1.842b	2.417a	1.839b	1.832b
Humic acid (5 g)	1.564c	1.772b	2.253a	2.918a	2.021b	2.106a
Fulvic acid (2 g)	1.672c	2.119b	2.543a	3.061a	2.218b	2.323a
Mean	1.580c	1.816b	2.213a	2.799a	2.026b	

Different lowercase letters indicate significant differences at $p \leq 0.05$ according to Duncan's Multiple Range Test (DMRT). Letters within cells represent interaction means (A × B), while marginal row and column mean represent main effects of Factor A and Factor B. Two-way ANOVA showed significant effects of A, B, and A × B interaction

Table 4 data indicate statistically significant increases in the soil mineral nitrogen (N) availability with amendments of the humic and fulvic acids. Humic acid achieved the highest N concentration (63.73 mg kg^{-1}), surpassing the control (50.96 mg kg^{-1}) by 25.05%, while fulvic acid yielded 60.96 mg kg^{-1} (+19.62%) ($p < 0.05$). The presence of nano-NPK synergies also increased soil N availability: Eco-WRP (10 kg ha^{-1}) + 4 g nano-NPK and standalone 2 g nano-NPK increased soil N to 60.16 mg kg^{-1} (+18.09) and 70.94 mg kg^{-1} (+39.26), respectively, compared to the control (50.94 mg kg^{-1}).

The most noticeable interaction was between humic acid and 2 g nano-NPK that synergistically increased soil N to 73.152 mg kg^{-1}, an increase of 87.52% above the non-amended control (39.00 mg kg^{-1}). Interestingly, the nano-NPK dose of 2 g + Humic acid showed a greater N availability in soil as compared to the 4 g dose. This can be suggestive of some threshold effect that the increased dose of 4 g of soil temporarily led to a slight decrease in soil available N. The lower N response at the higher nano-NPK dose suggests a possible threshold effect, but this requires further investigation. The 2 g dose may represent an optimal threshold that supplies adequate N while theoretically supporting positive soil processes, though these speculative mechanistic pathways require further targeted investigations to be confirmed.

This underscores the synergistic potential of organomineral and nanofertilizer approaches to may improve N retention and pools that are reachable by plants under specific soil and crop conditions.

Table 4. Effect of humic acid (HA), fulvic acid (FA) and Eco-WRP fertilizer combined with nano-NPK on the concentration of available nitrogen in the soil (mg kg^{-1})

Treatments	Control	Eco-WRP (10 kg ha^{-1})	Eco-WRP (10 kg ha^{-1}) + nano NPK (2 g)	Eco-WRP (10 kg ha^{-1}) + nano NPK (4 g)	nano NPK (2 g)	Mean
Control	39.01f	47.66d	46.34d	52.16c	69.67a	50.97b
HA (5 g)	56.67c	58.67b	64.01a	66.12a	73.15a	63.73a
FA (2 g)	57.16c	56.65c	58.82b	62.15b	70.00a	60.96a
Mean	50.95c	54.33b	56.39b	60.14a	70.94a	

The results in Table 5 indicate a very strong response of soil-available phosphorus (P) to the amendments of humic and fulvic acids. Fulvic acid produced slightly higher available P than humic acid, although both exceeded the control and both were significantly greater than the control (24.37 mg kg^{-1}). Humic acid had a positive effect on P availability of about 8.85% and fulvic acid had a positive effect on P availability of about 10.11% compared to the control ($p < 0.05$). Further increase in P availability was achieved with nano-NPK fortification: Eco-WRP (10 kg ha^{-1}) with 2 g and 4 g nano-NPK increased soil P to 26.38 mg kg^{-1} and 30.15 mg kg^{-1}, respectively. By comparison, nano-NPK (2 g) alone produced 26.75 mg kg^{-1} compared to the control (22.44 mg kg^{-1}). The findings imply that there is a synergistic interaction between silicon-based Eco-WRP and nano-NPK, which is probably attributed to improved P solubilization and decreased leaching. The evidence also indicates that fulvic acid, having a lower molecular weight and higher mobility, can lead to a higher level of phosphorus availability through root uptake and P cycling through microbes.

Fulvic acid and the maximum nano-NPK dosage (4 g + 10 kg ha^{-1} Eco-WRP) had a synergistic effect with the highest phosphorus bioavailability (31.001 mg kg-1), which was 55.45% greater than that of the non-amended control (19.94 mg kg^{-1}). We hypothesize that this improvement might be partially related to potential localized micro-acidification caused by humic and fulvic acids. Although post-treatment soil pH was not measured in this study to explicitly confirm this effect, literature broadly indicates that such organic acids can theoretically hinder the formation of insoluble calcium phosphates a critical limiting factor in calcareous loam soils (318 g kg^{-1}, Table 1). These conditions likely kept phosphorus in more soluble forms accessible for plant roots.

Table 5. Effect of humic acid (HA), fulvic acid (FA) and Eco-WRP fertilizer combined with nano-NPK on the concentration of available phosphorus in the soil (mg kg^{-1})

Treatments	Control	Eco-WRP (10 kg ha^{-1})	Eco-WRP (10 kg ha^{-1}) + nano NPK (2 g)	Eco-WRP (10 kg ha^{-1}) + nano NPK (4 g)	nano NPK (2 g)	Mean
Control	19.943g	22.172f	25.543c	29.071a	25.132b	24.372b
HA (5 g)	23.581e	24.165d	27.341b	30.382a	27.171b	26.528a
FA (2 g)	23.812e	25.123d	26.273c	31.001a	27.973b	26.836a
Mean	22.445c	23.820c	26.386b	30.151a	26.759b	

Table 6 data show that under the amendments of humic and fulvic acids, the exchangeable potassium (K) of the soil has statistically improved. Humic acid achieved the highest K concentration (284.81 mg kg^{-1}), exceeding the control (249.25 mg kg^{-1}) by 14.26%, while fulvic acid yielded 270.01 mg kg^{-1} (+8.32%) ($p < 0.05$). Nano-NPK-enriched Eco-WRP treatments also improved the K bioavailability: the additions of nano-NPK (0, 2, and 4 g) to 10 kg ha^{-1} Eco-WRP increased the soil K (to 249.01, 280.31 and 305.34 mg kg^{-1}), compared with the control mean of 224.71 mg kg^{-1}. Standalone nano-NPK (2 g) also elevated K to 280.77 mg kg^{-1} (+24.94%).

It is crucial to explicitly acknowledge that this substantial improvement in available K is primarily driven by the enhanced retention and mobilization of the uniform basal potassium sulphate application (100 kg ha^{-1}) and the supplemental K provided by the nano-NPK, rather than the inherent K_2O content (5%) of the Eco-WRP hydrogel itself, which supplies a negligible amount (approx. 0.5 kg K_2O ha^{-1}). The organic amendments and the hydrogel matrix functioned synergistically to reduce the vertical leaching of these applied K sources, thereby preserving a higher plant-available pool in the loam soil.

Table 6. Effect of humic acid (HA), fulvic acid (FA) and Eco-WRP fertilizer combined with nano-NPK on the concentration of available potassium in the soil (mg kg^{-1})

Treatment	Control	Eco-WRP (10 kg ha^{-1})	Eco-WRP (10 kg ha^{-1}) + nano NPK (2 g)	Eco-WRP (10 kg ha^{-1}) + nano NPK (4 g)	nano NPK (2 g)	Mean
Control	185.76e	240.43d	262.03c	292.62b	265.44c	249.26b
HA (5 g)	259.49c	264.31c	306.68a	304.78a	288.85b	284.82a
FA(2 g)	228.88d	242.30d	272.22c	318.63a	288.02b	270.01a
Mean	224.71d	249.01c	280.31b	305.34a	280.77b	

The results indicated that humic and fulvic acids increased the nutrient holding capacity of the soil which is responsible for increasing the nutrient plant available pool. The major humus components include functional groups and bioactive molecules which could play role towards faster degradation of organic matter, liberation of macro- and micronutrients, and improvement of their solubility and overall availability in the soil solution (Abdul Reeza *et al.*, 2009; Mora *et al.*, 2012; Ajeel, 2026). Additionally, they might help improve soil aggregation, porosity, water holding capacity, and nutrient mobility within the soil (Mora *et al.*, 2012).

Humic and fulvic acids may also serve as nutrient reserves, specifically in nitrogen, by reducing ammonia volatilization and improving N-use efficiency (Abdul Reeza *et al.*, 2009; Mora *et al.*, 2012; Aswad *et al.*, 2026). They can enhance cation exchange capacity which might aid in stabilizing ammonium and other cations, mitigate nutrient losses and boost their availability, presumably because of increased microbial activity, enzyme release, mineralization and chelation processes (Ajeel *et al.*, 2025 and Ajeel and Al-Hakeim, 2024). Although root biomass and plant uptake were not measured in this study, the observed increase in available N, P, and K is highly indicative of the nutrient-stabilizing effect of Eco-WRP and the organic amendments, which effectively reduced leaching and immobilized nutrients in the active root zone. This might be the effect of a lower molecular weight, higher mobility and higher ability to solubilize and cycle phosphorus by fulvic acid compared to humic acid. The porous Eco-WRP consists of silicon, which creates a porous network that is able to retain water (more than 400%) and ammonium ions, theorizing to reduce nutrient leaching and offer a more controlled release. The structure may facilitate aeration of soil and provide much more favorable environment for ammonification and nitrification processes, the processes of transformation of organic nitrogen into mineral nitrogen that can be taken up by a plant (Szatanik-Kloc *et al.*, 2021). The improved availability of phosphorus in these treatments could also be associated with the fact that a small acidification caused by the humic and fulvic acid might help prevent the development of insoluble calcium phosphates in the calcareous loam soil (318 g kg-1), and hence, increases plant-accessible phosphorus.

The results corroborate those of Abdul Reeza *et al.* (2009) who reported that both humic and fulvic acids reduced the volatilization of ammonia from urea and resulted in the improvement of nutrient availability. Likewise, positive effect of humic materials on nutrient cycling and soil productivity was highlighted by the stimulating effect on the soil microbial metabolism, and equilibrium between organic and inorganic nutrient pools. The nano-NPK, which was introduced, further increased these effects by providing a slow-release source of nitrogen, phosphorus and potassium and had a very large surface area that presumably amplified the effects of the organic acids, resulting in a greater nutrient retention and availability.

In general, the results of the present study indicate that nano-NPK, humic acid, fulvic acid and Eco-WRP can enhance the fertility of loam soils in arid and semi-arid conditions. The integrated treatments increased the organic carbon in the soil by 103.66%, nitrogen by 87.52%, phosphorus by 55.45%, and potassium by 71.53%. Such improvements were attributed to the chelation of nutrients by organic acids, stimulation of microorganisms, reduction of leaching and improved retention of water. The plots were equally applied with basal DAP and potassium sulphate, therefore the observed differences are indication that the HA, FA and Eco-WRP enhanced nutrient holding and availability above the baseline of the common fertilizer.

In conclusion, the single-season field study shows that the short-term chemical fertility of loam soils under semi-arid conditions can be effectively improved by the synergistic application of humic acid, fulvic acid, and Eco-WRP combined with nano-NPK. Integrated treatments increased SOC, available N, P and K compared to basal fertilization alone by up to 103.66%. The strongest effect was observed with the combination of fulvic acid and the highest nano-NPK dose. But these findings represent short-term post-harvest soil responses only. Further long-term field studies are required to confirm effects on potato productivity, fertilizer-use efficiency and long-term carbon stabilization, as crop phenology and yield were not evaluated.

Acknowledgments

The authors want to thank Al-Furat Al-Awsat Technical University and Al-Musayyab Technical College for supporting this research. The Soil and Water Techniques Department is given special credit to provide the field and laboratory facilities necessary to conduct this study.

References

Abdul Reeza, A., O.H. Ahmed, N.M.N.A. Majid and M.B. Jalloh, 2009. Reducing ammonia loss from urea by mixing with humic and fulvic acids isolated from coal. *Am. J. Environ. Sci.*, 5(3): 420-426. https://doi.org/10.3844/ajessp.2009.420.426

Ajeel, M.R., 2026. Agricultural consideration of the effects of biofertilizers and boron on desertified soils: A sustainable strategy for enhancing soil chemical properties. *J. Jordan Earth Environ. Sci.*, 17(1): 106-110. https://jjees.hu.edu.jo/Vol17.htm

Ajeel, M.R. and M.S. Al-Hakeim, 2024. The influence of biological and organic fertilization and boron spraying in some soil characteristics. *IOP Conf. Ser.: Earth Environ. Sci.*, 1371(8): 082022. https://doi.org/10.1088/1755-1315/1371/8/082022

Ajeel, M.R., M.M.H. Hamid and I.R. Al-Shahbani, 2025. The impact of biofertilizers, organic fertilizers, and foliar application of boron on yield characteristics of maize (*Zea mays* L.). *Basrah J. Agric. Sci.*, 38(1): 312-323. https://doi.org/10.37077/25200860.2024.38.1.24

Akimbekov, N.S., M.T. Kudaibergenov, J. Azcona and R. Bayat, 2021. Low-rank coal as a source of humic substances for soil amendment and fertility management. *Agriculture*, 11(12): 1261. https://doi.org/10.3390/agriculture11121261

Al-Rawi, K.M. and A.M. Khalaf Allah, 1980. *Design and Analysis of Agricultural Experiments*. Dar Al-Kutub, Mosul University, Iraq, p. 487.

Aswad, A.H., M.M. Hamid, M.T.A. Almeekh and M.R. Ajeel, 2026. Phosphorus adsorption and release dynamics in calcareous soil as affected by humic and fulvic acids. *J. Degrad. Min. Lands Manag.*, 13(1): 9463-9472. https://doi.org/10.15243/jdmlm.2026.131.9463

Azcona, I., A. Polo, E. Moyano, T. Hernández and C. García, 2011. Growth and development of pepper are affected by humic substances derived from composted sludge. *J. Plant Nutr. Soil Sci.*, 174(6): 916-924. https://doi.org/10.1002/jpln.201000264

Bakel, T.Y., Y. Berbar, N. Bouslah, M. Díaz-Sánchez, N. Haddadine, S. Gómez-Ruiz and M. Trari, 2025. Sodium-alginate/poly(acrylamide-co-acrylic acid) semi-interpenetrating hydrogels for removal of heavy metals from aqueous solutions. J. Polym. Eng., 45(5): 425-436.

Capstaff, N.M., A.J. Miller and J. Wood, 2020. Fulvic acid increases forage legume growth by inducing preferential up-regulation of nodulation and signalling-related genes. *J. Exp. Bot.*, 71(18): 5689-5704. https://doi.org/10.1093/jxb/eraa305

Chen, Q., X. Li, Y. Zhang and S. Wang, 2021. Coated diammonium phosphate combined with humic acid improves soil phosphorus availability, photosynthesis and yield of maize. *Front. Plant Sci.*, 12: 759929. https://doi.org/10.3389/fpls.2021.759929

de Melo, B.A.G., F.L. Motta and M.H.A. Santana, 2016. Humic acids: Structural properties and multiple functionalities for novel technological developments. *Mater. Sci. Eng. C Mater. Biol. Appl.*, 62: 967-974. https://doi.org/10.1016/j.msec.2016.02.055

FAO, 2017. Soil Organic Carbon: The Hidden Potential. Food and Agriculture Organization of the United Nations, Rome, Italy.

Mahler, C.F., N. Dal Santo Svierzoski and C.A.R. Bernardino, 2021. Chemical characteristics of humic substances in nature. IntechOpen, London. https://doi.org/10.5772/intechopen.97414

Mora, V., J. Dell'Amico and J.M. García-Mina, 2012. The humic acid-induced changes in the root concentration of nitric oxide, IAA and ethylene do not explain the changes in root architecture in cucumber. *Environ. Exp. Bot.*, 76: 24-32. https://doi.org/10.1016/j.envexpbot.2011.10.006

Olsen, S.R., C.V. Cole, F.S. Watanabe and L.A. Dean, 1954. *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate*. USDA Circular 939, Washington, DC.

Szatanik-Kloc, A., A. Nowak and L. Kloc, 2021. Effect of low zeolite doses on plants and soil physicochemical properties. *Materials*, 14(10): 2617. https://doi.org/10.3390/ma14102617

Walkley, A. and I.A. Black, 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.*, 37(1): 29-38.

Received: December, 2025; Revised: December, 2025;
Accepted: January, 2026