Impact of Humic Acid, Silicon and Mycorrhizal Inoculation on Soil and Potato Phosphorus Availability, Growth and Productivity

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Summary

The potato (*Solanum tuberosum* L.) is a heavy nutrient-demanding crop that responds strongly to fertiliser applications. Appropriate rates and timing of nutrient supply are critical for achieving high potato yields. This study evaluated the effects of humic acid, silicon and mycorrhizal inoculation (*Glomus mosseae* sp.) on soil phosphorus availability, potato growth and tuber yield. A factorial experiment was conducted using a randomised complete block design (RCBD). Three rates of humic acid (0, 100, and 200 kg·ha^{-1}) and two rates of silicon (0 and 150 mg Si·kg^{-1} soil) were applied, with or without mycorrhizal inoculation. Although marketable yield did not differ significantly among treatments, unmarketable tuber yield showed clear differences. Treatments T4 and T8 resulted in the highest soil test phosphorus at flowering and at harvest, with values of 6.78 mg P·kg^{-1} soil and 7.39 mg P·kg^{-1} soil, respectively. The lowest soil pH (7.70) was also observed in T8. The highest phosphorus uptake in tubers (15.53 kg·ha^{-1}) occurred in treatment T12, whereas phosphorus uptake in leaflets did not differ significantly among treatments. The highest net return was recorded for T6, which combined humic acid and mycorrhiza without silicon. Principal component analysis (PCA) indicated that soil test phosphorus at harvest, phosphorus concentration in tubers and phosphorus concentration in leaflets were the variables contributing most strongly to overall variability. Overall, treatments combining humic acid and silicon, with or without mycorrhiza, improved soil and plant phosphorus status, while humic acid plus mycorrhiza without silicon (T6) provided the best economic benefit.

Key words

potato crop, humic acid, mycorrhizal fungi, phosphorus uptake, soil pH

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Introduction

The potato crop (*Solanum tuberosum* L.) is a major vegetable worldwide, ranking after maize, wheat and rice in terms of nutritional value and consumption (Jasim et al., 2020a; Man-hong et al., 2020; Maruthi et al., 2024). In Iraq, potato cultivation covers 12,645 ha with a total production of 270,591 t, corresponding to an average yield of 21,339.1 kg·ha^{-1} (FAOSTAT, 2025). Owing to its high yield potential and rich vitamin and mineral content, potato has emerged as a crucial food source for combating malnutrition and improving diets, particularly in low-income countries (Hadi and Abdulrasool, 2019; Jasim et al., 2020b; Naser et al., 2020). However, achieving economically viable yields while maintaining environmental sustainability remains a major challenge in potato production systems (Baruah et al., 2024).

Humic acid is widely used in agricultural production (Abdelqader et al., 2022; Ierna and Distefano, 2024; Maruthi et al., 2024; Zhang et al., 2024). It improves soil physical, chemical and biological properties, as well as soil fertility (Abdellatef et al., 2023; Mahmood et al., 2019). Humic acid positively affects soil properties by enhancing plant growth, mineral availability and nutrient uptake. Accordingly, applications of humic acid have improved the yield of vegetables, including tomatoes, potatoes, onions, peppers, peas and various leafy crops (Juma et al., 2024; Wyszkowski and Kordala, 2024). Due to its phenolic and carboxylic acid functional groups, humic acid is a substance known for its potential to enhance soil characteristics and crop yields (Abdel-Sattar et al., 2024; Naser et al., 2020; Shyaa and Kisko, 2024). The application of humic acid boosts crop growth and development through multiple mechanisms. Humic acid compounds contain numerous photodegradable components that would enhance light energy capture and conversion in the shoot system, thereby increasing photosynthesis (Zhou et al., 2024; Maruthi et al., 2024).

Silicon (Si) is the second most abundant element in soils (Mohamed et al., 2024). Even though silicon is considered a non-essential element for plants, some authors have suggested that it should be considered a beneficial or quasi-essential nutrient for plant growth (Kurt and Ateş, 2024; Saleh et al., 2024; G. Wang et al., 2024). Thus, Si is widely used as a soil amendment or fertiliser, enhancing crop growth and reducing both biotic and abiotic stresses (Ahmad et al., 2024; Khilji et al., 2024; Sarma et al., 2024). Si contributes significantly to mitigating damage caused by water deficit (Wang et al., 2024). Plant development recognizes Si as a positive influence, strengthening resistance to crop diseases, pests, and external environmental stresses such as salinity, drought, mineral toxicity, and sodicity (Sharma et al., 2024). Notably, farm studies on Si fertilization of potato crops were implemented only in minor scholarly investigations, which were primarily limited to the foliar applications of Si in arid and semi-arid areas (Huang et al., 2024; Puppe et al., 2024; Torres-Hernández et al., 2023; Xu et al., 2024).

Furthermore, earlier studies mainly focused on the effects of foliar and soil applications of silicon on crops (Ahmad et al., 2024; Gonzalez-Porras et al., 2024; Thakral et al., 2024). However, some studies have demonstrated a synergistic interaction between silicon and phosphorus, which enhances crop yields. These experiments show the effectiveness of silicate supplementation in boosting crop yields, even in conditions of phosphorus deficiency, indicating that silicon may either replace some phosphorus or increase phosphorus levels in the soil. A study was implemented by A. J. Al-rubaie and A. Abdulkareem (2025) who stated that applying silicon to the calcareous soils in Iraq can increase soil phosphorus availability in the incubated soils at three of the incubation intervals. The field study resulted in soil test phosphorus, grain phosphorus concentration, and uptake being improved as a result of silicon levels (Al-Rubie and Abdulkareem, 2024)

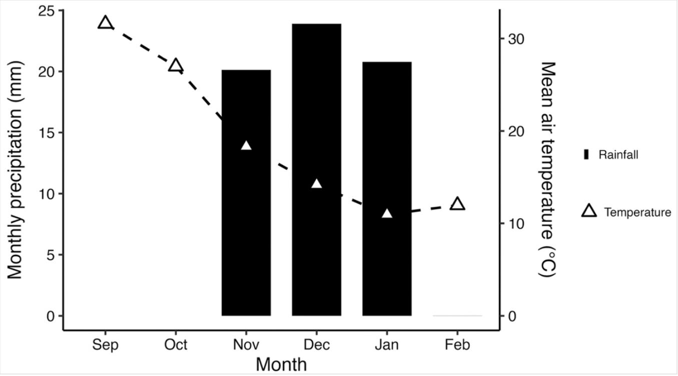
The Arbuscular Mycorrhizal Fungi (AMF) inoculation is mainly relevant to nutrient acquisition, which basically depends on the physicochemical characteristics of the soil, especially phosphorus levels (Mahmood et al., 2024). However, recent studies on various crops indicate that soils with low soil test phosphorus in Iraq can be responsive due to mycorrhiza inoculation (Mahmood, 2025; Mahmood et al., 2025; Hamid, 2025). Researchers have noted that biological applications enhance potato growth and crop yield(Chen et al., 2024; Nahuelcura et al., 2024; Steidinger, 2024). Moreover, it is essential to reduce the overuse of mineral fertilizers to improve environmental sustainability and remove contaminants from their excessive application in the field(Sun and Shahrajabian, 2023).

This study hypothesized that utilizing the integrated fertilizer strategy of humic acid, silicon, and AMF simultaneously would decrease soil pH, improve soil P availability and P uptake, in turn enhancing potato growth and yield more advantageously than individual applications or no fertilisation.

Materials and methods

Description of study site

A one-year field experiment was conducted during the 2022–2023 season at the University of Baghdad, College of Agricultural Engineering Sciences Station, located in Al-Jaderyaa, Baghdad Province, Iraq (33°16'10"N, 44°22'44" E), and 36.58 meters in elevation. The study area has a semi-arid climate. Meteorological data, including mean monthly air temperature and rainfall for the study period, are shown in Fig. 1. The physicochemical properties of the soil are outlined in Table 1.



Source: Agricultural Meteorological Center, 2025

Figure 1. Climate data for the potato-growing season of 2022–2023, covering the period from September to February. It presents the mean monthly air temperature (°C) and monthly rainfall (precipitation) (mm).

Table 1. Physical and chemical characteristics and fertility attributes of soil

Soil characteristic	Unit	Values
pH (1:1)		7.75
Ec (1:1)	$dS\cdot m^{-1}$	4.9
Organic matter	%	1.8
Cl^{-}	$Meq\cdot L^{-1}$	22.98
Ca^{++}		20.92
Mg^{++}		18.85
Na^{+}		11.1
Soluble K^{+}		6.33
HCO_3		1.9
Nitrogen $NO_3^{-} + NH_4^{+}$	$mg\ nutrient\cdot kg^{-1}$ soil	20
Phosphorus (P)		6.13
Available Potassium (K)		195.92
Available Silicon (Si)		0.11
	Soil texture	
Sand	$g\cdot kg\cdot soil^{-1}$	572
Silt		380
Clay		48
Soil texture type	Sandy loam	

Experimental design

The experiment consisted of three replications, each employing the randomized complete block design (RCBD). Humic acid was the first factor and was applied once on the potato seed-tuber planting day at three different rates: 0 kg humic acid·ha^{-1}, 100 kg humic acid·ha^{-1}, and 200 kg humic acid·ha^{-1}. The second factor involved the application of silicon fertilizer, which was added at once on the planting day as a replacement mixed with the other fertilizer sources into the soil at two rates: 0 and 150 mg Si·kg^{-1} of soil. The silicon fertilizer was derived from silicic acid (H_4SiO_4), which contains 29% silicon. The third factor entailed mycorrhizal inoculation, with or without *Glomus mosseae* sp. applications, which provides 50 spores g^{-1} in a mixture of spores, peat moss, and root fragments and was applied once. Two grams of the mixture were spread under the potato seed tuber to ensure that each tuber obtained 100 spores, then covered with soil. After covering mycorrhizae and the part of the tuber seed with soil, all other fertilizers were applied as a replacement, and then the entire seed tuber was covered with soil. Urea was applied at 300 kg N·ha^{-1}, while diammonium phosphate (DAP) (18-46-0) was used at 60 kg P·ha^{-1} for fertilization. Potassium was applied at 200 kg K·ha^{-1} using potassium sulfate fertilizer (41.5% K_2O). However, nitrogen, phosphorus, and potassium fertilizers, humic acid, silicon, and mycorrhizal inoculation were applied as replacements in the soil on the planting day as a one-time application, except the nitrogen applications were divided into three stages: the first nitrogen application occurred on the planting date, followed by additional applications at 30 and 45 days after planting. The study treatments were conducted from September 30, 2022, to February 4, 2023. Potato seed tubers of the cultivar Riviera were planted, imported from the Netherlands, in sizes ranging from 28 to 55 mm. The potatoes were planted in three rows, retaining a distance of 70 cm between rows and 40 cm between plants within each row. The plot area for each treatment was 2 m in length and 2.10 m in width, and the entire plot was 4.20 m in total plot area. For the field treatments set, a one-meter distance was maintained between replicates and treatments to prevent nutrient translocation. The hilling method took place 45 days after the date of potato planting. UNIVERSAL CO established a drip irrigation pipe manufacturing system for potato crops, specifying a thickness of MIL (7) and MM (0.175), a flow rate of 2.25 LPH, and a spacing value of 10 cm. Potato plants were irrigated as required. Weeds were removed manually. The insect and disease control was applied as a foliar application on the potato leaves after 45 and 75 days from the planting day using Crosade EC™ (Acetamiprid10% + Abamectin1%EC), recommended dose of 200 mL·100 L^{-1} of water, manufactured by Sineria (industries) Ltd, Cyprus. The settings for the experimental treatments are detailed in Table 2.

Soil sample analysis

Before planting potatoes, soil samples were collected at the study site at a depth of 0–25 cm, and continued to be collected for 60 days after the date of potato planting and harvest. The soil samples were placed, air-dried, crushed, and then passed through a sieve with a mesh size of 2 mm. Soil pH and EC (electrical conductivity) were measured using a 1:1 solution (100 ml distilled water: 100 g soil), then filtered using filter paper type Whatman filter papers. The combined concentration of nitrogen in the forms of nitrate ($N\text{-}NO_3^{-}$) and ammonium ($N\text{-}NH_4^{+}$) was determined as available nitrogen using the Kjeldahl method. Potassium (K) was quantified as a macronutrient using a flame photometer. Phosphorus was determined by the Olsen method, applying a 0.5 M sodium bicarbonate ($NaHCO_3$) solution. The coloration of the samples was enhanced by using ammonium molybdate and ascorbic acid, and the absorbance was measured using a spectrophotometer employing a wavelength of 882 nm.

Plant and potato tubers sampling and analysis

At 60 days after the planting day, ten plant leaflets were collected, and potato tubers were harvested at the end of the growing season on February 4, 2023, for each phosphorus treatment (P analysis). The leaflets and tubers were rinsed with distilled water to eliminate dust or impurities that could compromise the study's accuracy. Ammonium molybdate and ascorbic acid were integrated to analyze the phosphorus concentration in the chemically digested potato leaflets and tubers (using H_2SO_4 and $HClO_4$); the absorbance was measured using a spectrophotometer utilizing a wavelength of 882 nm.

Table 2. Experimental treatment details

Treatments	Description
T1	Control (0 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil without mycorrhizal inoculation)
T2	(0 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil with mycorrhizal inoculation)
T3	(0 kg humic acid·ha^{-1} + 150 mg silicon·kg^{-1} soil without mycorrhizal inoculation)
T4	(0 kg humic acid·ha^{-1} +150 mg silicon·kg^{-1} soil with mycorrhizal inoculation)
T5	(100 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil without mycorrhizal inoculation)
T6	(100 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil with mycorrhizal inoculation)
T7	(100 kg humic acid·ha^{-1} + 150 mg silicon·kg^{-1} soil without mycorrhizal inoculation)
T8	(100 kg humic acid·ha^{-1} + 150 mg silicon·kg^{-1} soil with mycorrhizal inoculation)
T9	(200 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil without mycorrhizal inoculation)
T10	(200 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil with mycorrhizal inoculation)
T11	(200 kg humic acid·ha^{-1} + 150 mg silicon·kg^{-1} soil without mycorrhizal inoculation)
T12	(200 kg humic acid·ha^{-1} + 150 mg silicon·kg^{-1} soil with mycorrhizal inoculation)

Phosphorus uptake was calculated using the following formula:

$$\text{Phosphorus uptake in leaflets and tubers} = ((\text{potato leaflets (or tubers) dry matter kg·ha}^{-1}) * \text{leaflets (or tubers) phosphorus concentration (\%)})/100 \quad (1)$$

Potato yield determination

The yield of potato tubers was randomly selected from six plants in each treatment. The yield of potato tubers per hectare was measured by weighing the harvested potatoes from each experimental plot, then calculated to the area in hectares, and then it converted to Mg·ha^{-1}. Marketable tuber yield was defined as tubers weighing over 65 grams, while those weighing less than 65 grams were classified as unmarketable tuber yield (i.e. undesired potato tubers).

Leaf area determination

The leaf area parameter was measured according to the standards performed by (Fleisher and Timlin, 2006), which was measured at 60 days after the planting date, which is at the tuber initiation stage. The leaf area parameter was calculated using the following formula:

$$LA = 0.872 \times L \times W \quad (2)$$

where

LA is the leaf area,

L indicates the terminal leaflet length (cm),

W denotes the width of the compound leaf (cm).

SPAD index determination

The fully expanded potato plant leaves were selected on 65 days from planting tuber seeds to assess the SPAD index (chlorophyll meter). The SPAD index was calculated by averaging ten readings for each plot using a calibrated chlorophyll meter (SPAD–502 Plus, KONICA MINOLTA).

Number of leaves and stems per plant

The number of leaves and stems for each potato plant was measured at 70 days after the planting date, which is considered the tuber bulking (fully canopy) stage. Ten plants were randomly selected from each treatment, and then the respective values were subsequently calculated for each plant.

Economic analysis

The economic assessment undertaken in this investigation was carried out to evaluate the profitability of humic acid, silicon and mycorrhizal inoculation in potato production. The economic evaluation is expressed in U.S. dollars, applying the Iraqi currency exchange rate of 1 USD = 1320 IQD. The employed formulas depict the approach that was utilized to calculate the total input cost, gross return, net return, benefit-cost ratio, and economic gains related to the control treatment sources from (CIMMYT, 1988). The marketable potato yield was used for calculations, and the updated price was taken from ('Ministry of Agriculture- Iraq', 2025). The other factors were calculated as the retail market price. The economic criteria are illustrated below:

$$\text{Total variable cost} = (\text{humic rate} \times \text{humic price}) + (\text{silicon rate} \times \text{silicon price}) + (\text{mycorrhiza rate} \times \text{mycorrhiza price}) \quad (3)$$

where:

Total variable cost (USD) = Total factor cost ha^{-1}, humic rate = kg humic acid ha^{-1}, humic price= \$ 1.53 per kg of humic acid, silicon rate = kg silicon ha^{-1}, silicon price = \$ 0.95 kg^{-1}, mycorrhiza rate = kg mycorrhiza ha^{-1} (0.036 kg·ha^{-1} for each inoculated treatment), mycorrhiza price = \$1.91 kg^{-1}.

Gross return = marketable potato yield (Mg) × 1000 × potato price (\$ 0.38 per kg^{-1} *potato)* (4)

where:

Gross return (\$) = total revenue ha^{-1}, marketable potato yield (Mg ha^{-1}), 1000 (to convert Mg to kg, potato price (\$0.38 per kg of potato).

Net return (\$) = Gross return (\$) – Total variable cost (\$) (5)

where:

Net return (\$) is the profit after factor cost is subtracted.

Yield Gain = Marketable potato yield of fertilised plot - Marketable potato yield of non-fertilised plot (T1 control) (6)

where:

Measure the marketable potato yield increase compared to the control.

Revenue Gain (\$) = Yield Gain (Mg) × 1000 × marketable potato yield price (\$) (7)

where:

Revenue Gain (\$) = Additional income above the control

Net economic gain against control (\$) = (gross return of fertilized plot – gross return of unfertilised plot (control)) – (total cost of fertilized plot – total cost of unfertilised plot (control)) (8)

Statistical analysis

A three-factor factorial ANOVA (humic acid × silicon × mycorrhiza) in a randomised complete block design (RCBD) was carried out using RStudio software, version 2024.04.0+735 (Boston, MA, USA), with the R packages diffobj and doebioresearch. When ANOVA indicated significant treatment effects ($P < 0.05$), treatment means were separated using Tukey's HSD test ($P < 0.05$). Multivariate relationships among variables were explored using principal component analysis (PCA) with the FactoMineR package and the PCA() function, and visualised with the factoextra package using the fviz_pca_var() function.

Results

Total tuber yield and yield components

The analysis of variance (ANOVA) in Table 3 showed no significant differences among treatments for total potato tuber yield. However, the highest total potato yield (16.35 Mg·ha^{-1}) was obtained in T11 (200 kg humic acid ha^{-1} + 150 mg silicon kg^{-1} soil without mycorrhizal inoculation), representing an increase of about 46.50% compared with the control treatment T1 (0 kg humic acid ha^{-1} + 0 mg silicon kg^{-1}soil without mycorrhizal inoculation). In contrast, unmarketable tuber yield differed significantly among treatments. The lowest value was recorded in T12 (200 kg humic acid ha^{-1} + 150 mg silicon kg^{-1} soil with mycorrhiza inoculation), which amounted to about 0.97 Mg·ha^{-1}, reflecting a decrease of

Table 3. Total potato yield and some yield components were impacted by the study's treatments

Treatments	Total potato tuber yield (Mg·ha^{-1})	Unmarketable Tubers yield (Mg·ha^{-1})	Marketable tubers yield (Mg·ha^{-1})	Number of Unmarketable Tubers per plant	Number of marketable tubers per plant
T1	11.16 a	1.05cd	10.11a	2.01a	3.10a
T2	11.65 a	1.70ab	9.94a	2.66a	2.98a
T3	13.51 a	1.13cd	12.38a	2.34a	3.97a
T4	11.04 a	1.42abcd	9.63a	2.60a	3.49a
T5	14.28 a	1.56abc	12.72a	2.42a	3.46a
T6	14.86 a	1.37abcd	13.49a	2.04a	4.11a
T7	12.35 a	1.39abcd	10.96a	2.43a	3.51a
T8	12.29 a	1.29abcd	11.00a	1.95a	3.41a
T9	13.50a	1.82a	11.67a	2.74a	3.26a
T10	14.54a	1.55abc	12.99a	2.26a	3.57a
T11	16.35a	1.17bcd	15.18a	2.24a	4.03a
T12	12.39a	0.97d	11.42a	1.82a	2.82a

Note: The different letters denote significant differences among the mean values of treatments at $P < 0.05$ according to Tukey HSD test; T1-T12 – experimental treatments (details are given in Table 1)

8.25 % compared to the control treatment. The highest value was recorded in the T9 treatment (200 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil without mycorrhizal inoculation) at 1.82 Mg·ha^{-1}. The ANOVA indicates that the application of humic acid, silicon, and mycorrhiza did not significantly impact the marketable tuber yield. However, the highest marketable tuber yield was recorded in the T11 treatment, reaching approximately 15.18 Mg·ha^{-1}, which represents an increase of about 50.15% compared to the control treatment, which yielded 10.11 Mg·ha^{-1}. Similar trends were noted in the number of unmarketable and marketable tubers per plant. The count of unmarketable and marketable tubers per plant did not exhibit significant differences across treatments. Nonetheless, for the number of unmarketable tubers per plant, the lowest values were recorded in T12, which had about 1.82 unmarketable tubers per plant, while the highest value was found in T9, yielding 2.74 unmarketable tubers per plant. The values for the number of marketable tubers per plant did not show significant differences between treatments; however, results indicated that the highest count occurred in the T6 treatment (100 kg humic acid·ha^{-1} + 0 mg silicon kg^{-1} soil with mycorrhizal inoculation), achieving approximately 4.11 marketable tubers per plant. The lowest value was observed in the T12 treatment, recording a mean of about 2.82 marketable tubers per plant.

Economic analysis of marketable tuber yield

Table 4 illustrates that the gross return obtained the highest value at T11, which achieved a gross return value of \$5750.00·ha^{-1}, exceeding the unfertilised plot (control treatment), which recorded a gross return value of \$3829.55 ha^{-1}, representing a difference of \$ 1920.45 ha^{-1}. Conversely, the lowest value was recorded at T4 treatment, which achieved a value of \$3647.73 ha^{-1}. However, the maximum profitability of net return was recorded at treatments T6 (100 kg humic acid ha^{-1} + 0 mg silicon·kg^{-1} soil with mycorrhizal inoculation) and T11 (200 kg humic acid ha-^{1} + 150 mg silicon·kg^{-1} soil without mycorrhizal inoculation), exhibiting the maximum net return values of \$4958.27·ha^{-1} and \$ 4892.99·ha^{-1}, respectively. However, the net gain against the unfertilized treatment (control) recorded the greatest value, which was achieved at the T6 treatment (\$ 1128.72·ha^{-1}). Other treatments with the negative values resulted in lower values than the unfertilised plot (control treatment).

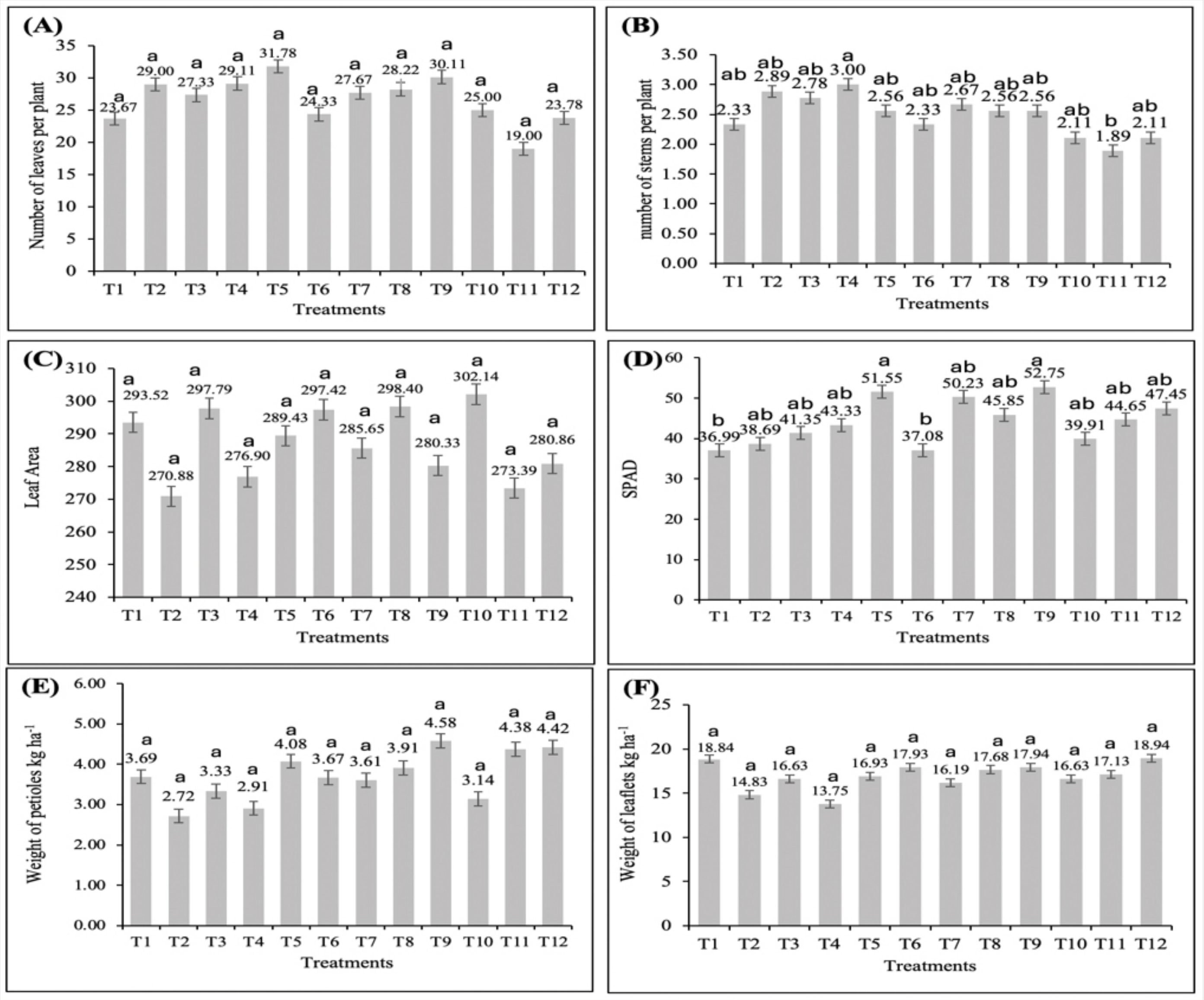
Vegetative growth and leaf biomass

The number of leaves per plant was determined (Fig. 2A). The highest value was recorded in the T5 treatment (100 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil without mycorrhizal inoculation), recording approximately 31.78 leaves per plant, which represents an increase of about 34.26% compared to the control treatment T1 (0 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil without mycorrhizal inoculation), which achieved a value of about 23.67 leaves per plant. The lowest value was observed in the T11 treatment (200 kg humic acid·ha^{-1} + 50 mg silicon·kg^{-1} soil without mycorrhizal inoculation), which had a value of 19.00 leaves per plant. However, the impact of the study's treatments did not reveal significant differences in the number of leaves per plant. The number of stems reflects the strength of the vegetation system, which would increase the number of leaves and consequently enhance the size and quality of potato tubers due to the photosynthesis process occurring in the leaflets. Nonetheless, the statistical analysis indicated that applications of humic acid, silicon, and mycorrhizal inoculation affected the number of stems per plant (Fig. 2 B).

Table 4. The experimental factors economic analysis

Treatments	Marketable potato Yield (Mg·ha^{-1})	Total cost (\$·ha^{-1})	Gross return (\$·ha^{-1})	Net return (\$·ha^{-1})	Net gain vs Control Treatment (\$·ha^{-1})
T1	10.11	0.0	3829.55	3829.55	0.0
T2	9.94	0.07	3765.15	3765.08	-64.46
T3	12.38	553.98	4689.39	4135.42	305.87
T4	9.63	554.05	3647.73	3093.68	-735.86
T5	12.72	151.52	4818.18	4666.67	837.12
T6	13.49	151.58	5109.85	4958.27	1128.72
T7	10.96	705.49	4151.52	3446.02	-383.52
T8	11.0	705.56	4166.67	3461.11	-368.44
T9	11.67	303.03	4420.45	4117.42	287.88
T10	12.99	303.1	4920.45	4617.36	787.81
T11	15.18	857.01	5750.0	4892.99	1063.45
T12	11.42	857.08	4325.76	3468.68	-360.86

Note: T1-T12 – experimental treatments (details are given in Table 1)



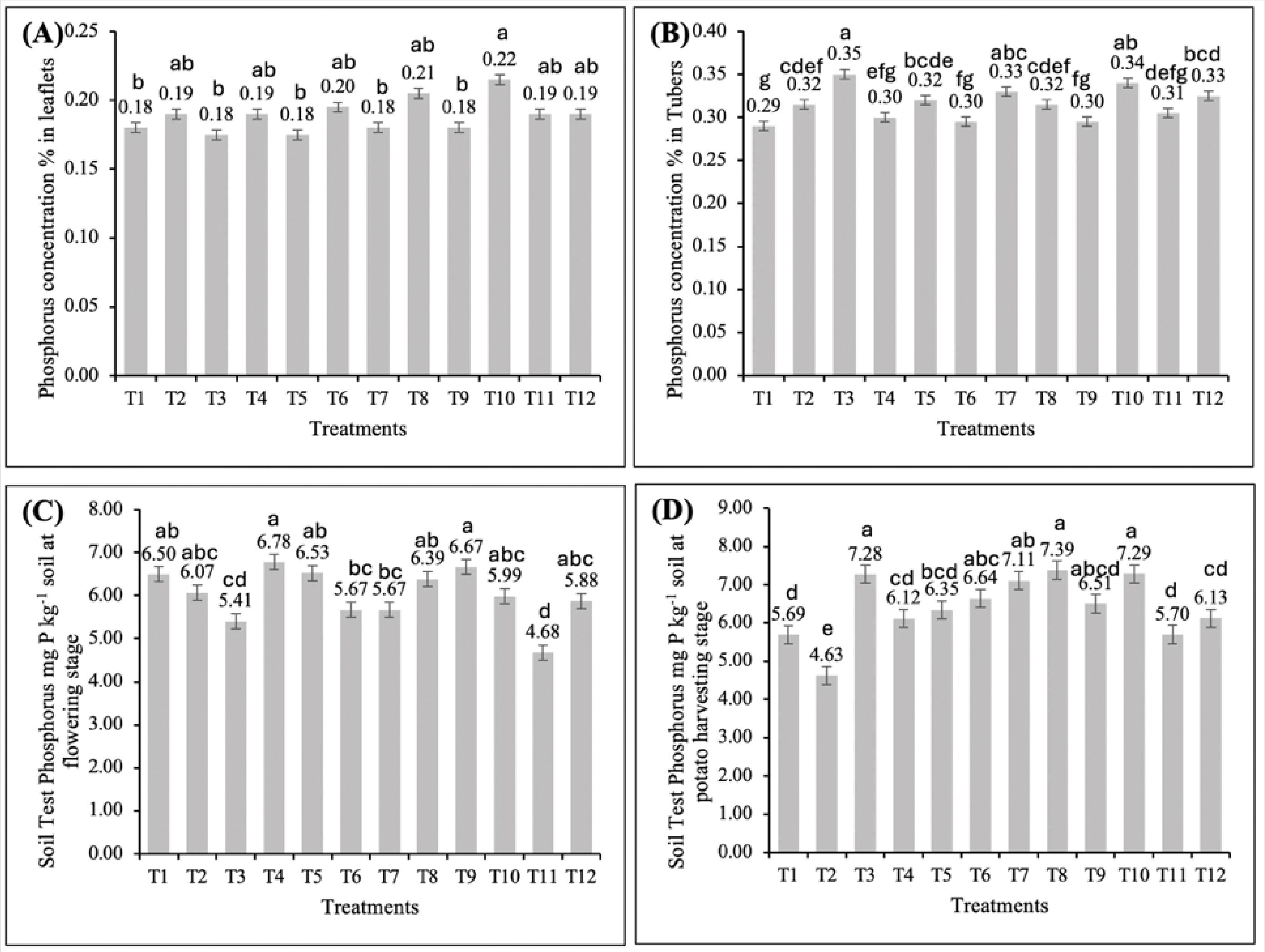
Note: The different letters denote significant differences among the mean values of treatments at $P < 0.05$ according to the Tukey's HSD test; T1-T12 – experimental treatments (details are given in Table 1).

Figure 2. Effect of humic acid, silicon, and mycorrhizal fungi on (A) number of leaves (leaflets and petioles) per plant, (B) number of stems per plant, (C) leaf area, (D) SPAD index, (E) weight of petioles (kg·ha^{-1}), (F) weight of leaflets (kg·ha^{-1}).

The highest value achieved at T4 (0 kg humic acid ha^{-1} + 150 mg silicon kg^{-1} soil with mycorrhizal inoculation) was 3.00 stems per plant. The percentage increase in the number of stems was recorded at 28.75% compared to the control treatment T1 (0 kg humic acid ha^{-1} + 0 mg silicon kg^{-1} soil without mycorrhizal inoculation), which had a value of 2.33 stems per plant. Additionally, T4 treatment yielded a percentage increase of 58.73 % compared to T11 (200 kg humic acid·ha^{-1} + 150 mg silicon·kg^{-1} soil without mycorrhizal inoculation), which achieved a value of 1.89 stems per plant, indicating a significant difference between both treatments. Leaf area is recognized as one of the key indicators of plant health due to the crucial role of leaf size in the photosynthesis process (Fig. 2 C). The highest value was observed at T10 (200 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil with mycorrhizal inoculation), which reached a value of 302.14, representing a percentage increase of 3% compared to the control treatment and 11.54% compared to the lowest treatment value of 270.88 at T2 (0 kg humic acid ha^{-1} + 0 mg silicon·kg^{-1} soil with mycorrhizal inoculation). The SPAD determination of leaf nitrogen content indicates the plant's ability to produce adequate tuber size and quality (Fig. 2D). The maximum value was observed at T5 (100 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil without mycorrhizal inoculation), achieving a value of 51.55, representing an increase of 39.33 % compared to the control treatment T1, which had a value of 36.99. Furthermore, the highest value at T5 significantly differed from T6 (100 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil with mycorrhizal inoculation), which recorded a value of 37.08. However, there was no significant difference among the other treatments. In this study, the weight of petioles and leaflets showed no significant differences among the treatments. The highest mean values were attained at T9 (200 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil without mycorrhizal inoculation) and T12 (200 kg humic acid·ha^{-1} + 150 mg silicon·kg^{-1} soil with mycorrhizal inoculation), which recorded values of 4.58 kg·ha^{-1} and 18.94 kg·ha^{-1}, respectively. The minimum mean values were observed at T2 and T4 treatments, with recorded values of 2.72 kg·ha^{-1} and 13.75 kg·ha^{-1}, respectively (Fig. 2 E-F).

Soil test phosphorus at harvest

Fig. 3 A, shows a significant difference that is apparent between T10, T9, and T1, which recorded the highest values of 0.22%, 0.18%, and 0.18%, respectively. The T10 treatment, exhibiting the greatest percentage increase of 22.22% compared to the control treatment, recorded a value of 0.18%. the analysis of the study data indicated highly significant differences among the phosphorus concentrations in the tuber treatments (Fig. 3 B). The maximum value was achieved at T3 (0 kg humic acid ha^{-1} + 150 mg silicon kg^{-1} soil without mycorrhizal inoculation), showing a value of 0.35% and a percentage increase of 20.69% compared to the control treatment, which recorded a mean value of 0.29%. Nonetheless, other significant differences were noted among the mean values of treatments T1 (control), T2 (0 kg humic acid ha^{-1} + 0 mg silicon kg^{-1} soil + with mycorrhizal inoculation) and T12. The mean values of soil test phosphorus at the flowering (bloom stage) significantly varied among the treatments (Fig. 3 C). The highest value was recorded at T4, with a mean value of 6.78 mg P kg soil^{-1}, showing a percentage increase of 4.31% compared to control treatment, which had a mean value of 6.50 mg P kg^{-1} soil. By contrast, the lowest mean value was observed at T11, with a value of 4.68 mg P kg^{-1} soil, recording a percentage decrease of 38.89% when compared to control treatment. However, the results presented significant differences among treatments, particularly between T3 and T4. At the potato harvest stage, notable significant differences were observed between the treatments, primarily T1, T2, and T11 (Fig. 3D). The maximum mean value was noted at T8 (100 kg humic acid ha^{-1} + 150 mg silicon kg^{-1} soil with mycorrhizal inoculation), which recorded a mean value of 7.39 mg P kg^{-1} soil, achieving a percentage increase of 29.88% compared to control



Note: The different letters denote significant differences among the mean values of treatments at $P < 0.05$ according to the Tukey's HSD test; Error bars show standard error; T1-T12 – experimental treatments (details are given in Table 1).

Figure 3. Effect of humic acid, silicon, and mycorrhizal fungi on (A.) phosphorus concentration % in leaflets, (B.) phosphorus concentration % in tubers, (C.) soil test phosphorus (mg P·kg^{-1} of soil) at the flowering stage, (D.) soil test phosphorus (mg P·kg^{-1} of soil) at the harvesting stage.

treatment's mean value of 5.69 mg P kg^{-1} soil. The T8 treatment significantly differed from other treatments such as T1, T2, T4,T5,T11, and T12, which recorded mean values of 5.69 mg P·kg^{-1} soil, 4.63 mg P·kg^{-1} soil, 6.12 mg P·kg^{-1} soil, 6.35 mg P·kg^{-1} soil, 5.70 mg P·kg^{-1} soil, and 6.13 mg P·kg^{-1} soil, respectively. The minimum mean value was observed at T2 (0 kg humic acid ha^{-1} + 0 mg silicon kg^{-1} soil with mycorrhizal inoculation), which achieved 4.63 mg P·kg^{-1} soil.

Soil pH at flowering

The study data revealed a notable difference between the T5 treatment (100 kg humic acid·ha^{-1} + 0 mg silicon·kg^{-1} soil with non-mycorrhizal inoculation), and T8 (100 kg humic acid·ha^{-1} + 150 mg silicon·kg^{-1} soil with mycorrhizal inoculation). However, the lowest mean soil pH value at T8 recorded a value of 7.70, which is lower than the soil pH recorded prior to the potato planting date. In contrast, the highest mean soil pH was recorded at T5 reaching 8.47. The percentage decrease in soil pH for T8 was approximately 3.50 % compared to T1 and 10% compared to T5 (Fig. 4).

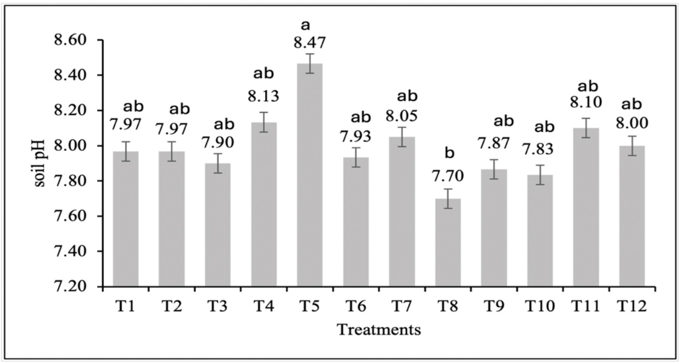


Figure 4. Effect of humic acid, silicon, and mycorrhizal fungi on soil pH at the flowering stage (60 days after planting). The different letters indicate significant differences among the mean values of treatments at $P < 0.05$ according to the Tukey's HSD test; Error bars show standard error; T1-T12 – experimental treatments (details are given in Table 1).

Phosphorus uptake in leaflets and tubers

The results indicate that leaflet phosphorus did not significantly differ among the treatments. However, the maximum mean value was observed in the T8 treatment (100 kg humic acid·ha^{-1} + 150 mg silicon·kg^{-1} soil with mycorrhizal inoculation), achieving 36.48 kg·ha^{-1}, which reflects a percentage increase of 6.67% compared to the control treatment (Fig. 5 A). Consequently, the data shows that phosphorus uptake in potato tubers significantly differed among the treatments. The maximum mean value was obtained in the T12 treatment (200 kg humic acid·ha^{-1} + 150 mg silicon·kg^{-1} soil with mycorrhizal inoculation), recording 15.53 kg·ha^{-1}, along with a percentage increase of 47.62% compared with the control treatment.

Humic acid rate, total tuber yield and phosphorus uptake

Humic acid is essential as an organic matter that enhances nutrient availability and promotes potato growth. In particular, the concentration of phosphorus in soils is critical for developing the crop's root system and facilitating energy transfer in the xylem and phloem of the crop. Understanding the relationship between humic acid, tuber yield, and phosphorus uptake can help optimize fertilization strategies to enhance potato productivity. Results indicated that varying humic acid application rates increasingly influenced the total potato yield (Fig 6. A). However, the boxplot illustrates that the median yield significantly increased compared to the 0 kg humic acid rate. The highest humic application rate surpassed the 0 kg humic acid·ha^{-1} rate but was slightly lower than the 100 kg humic acid·ha^{-1} rate; nonetheless, the highest humic acid application rate did not differ from the 100 kg humic acid·ha^{-1} rate concerning yield. Fig 6. B showed that the highest phosphorus uptake in tubers was observed at the maximum humic acid application, with an achieved value of 11.88 kg·ha^{-1}.

Principal component analysis of yield

Principal Component Analysis (PCA) predominantly elucidates the variations present within the datasets. Dimension

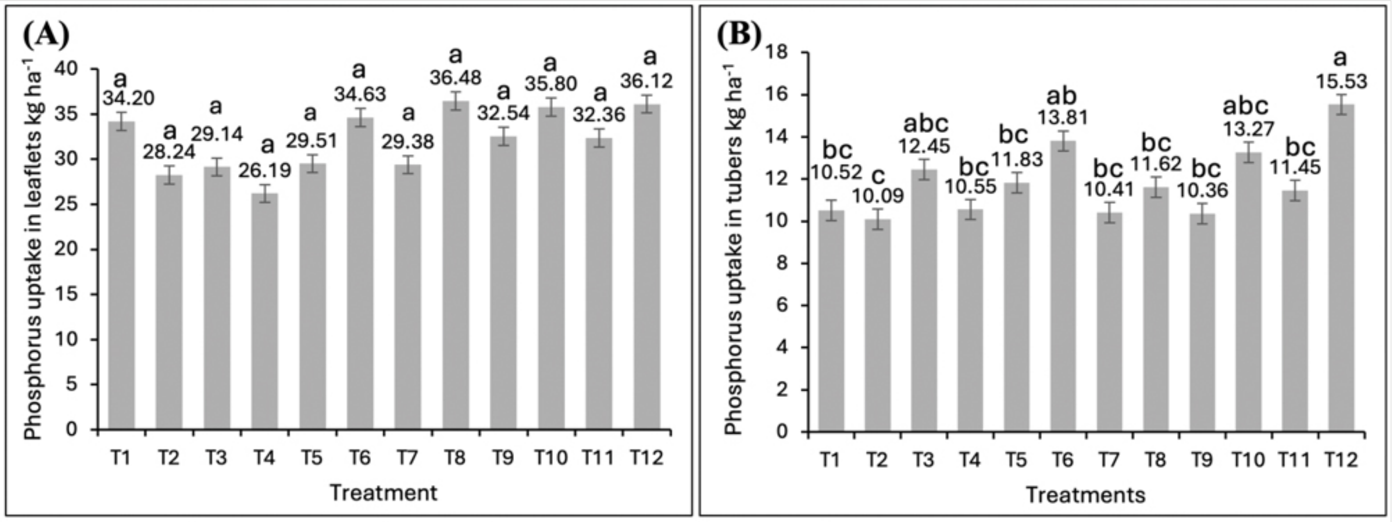
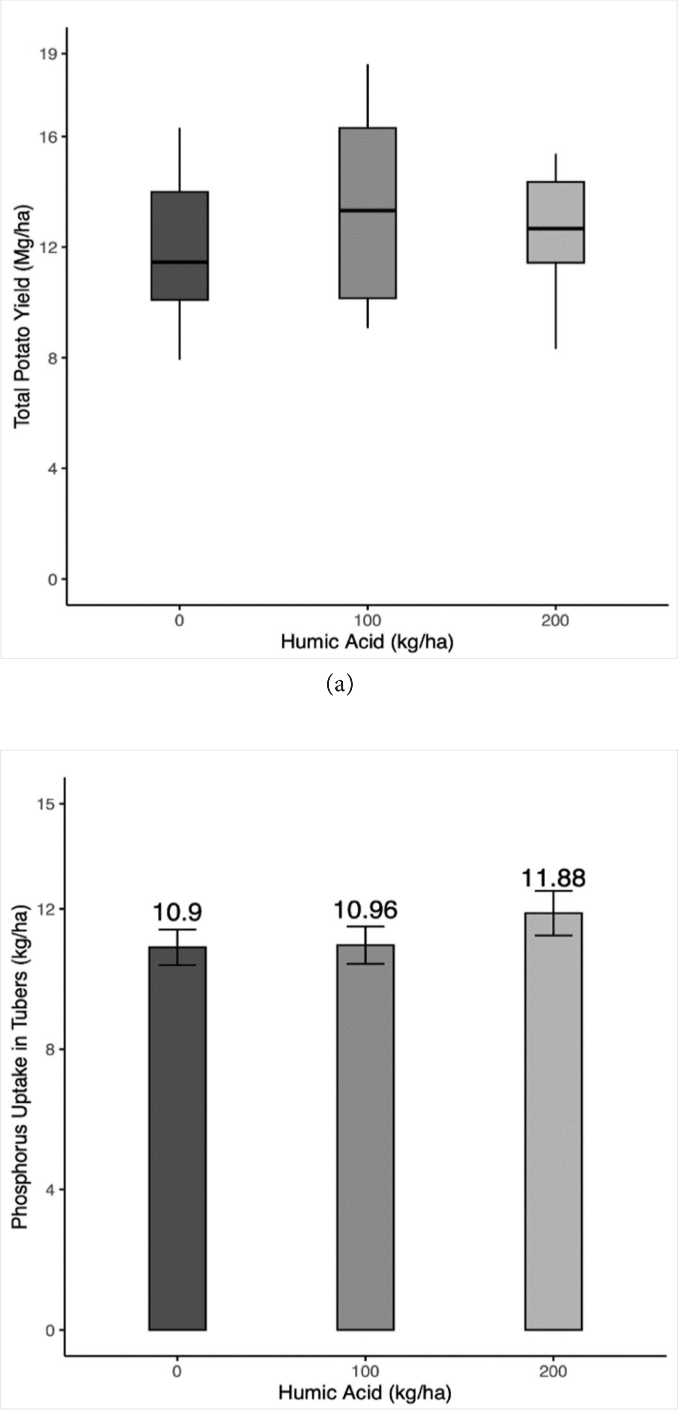


Figure 5. Effect of humic acid, silicon, and mycorrhizal fungi on (A.) phosphorus uptake in leaflets (kg·ha^{-1}), (B.) phosphorus uptake in tubers (kg·ha^{-1}). The different letters denote significant differences among the mean values of treatments at $P < 0.05$ according to the Tukey HSD test; Error bars show standard error; T1-T12 – experimental treatments (details are given in Table 1).

(Dim) 1 and Dimension 2 accounted for 41.4% of the total variance in the data, as illustrated in Fig. 7. Notably, the variables exerting the strongest influence include soil test phosphorus at harvest, phosphorus concentration in tubers, and phosphorus concentration in leaflets.



(a)

(b)

Figure 6. Effect of humic acid application rates on (A) Total potato yield; (B) Phosphorus uptake in tubers (kg·ha^{-1}). Error bars show standard error.

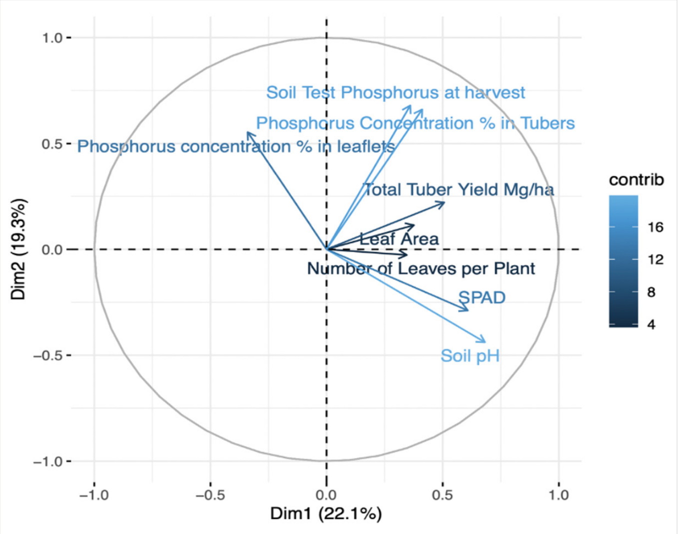
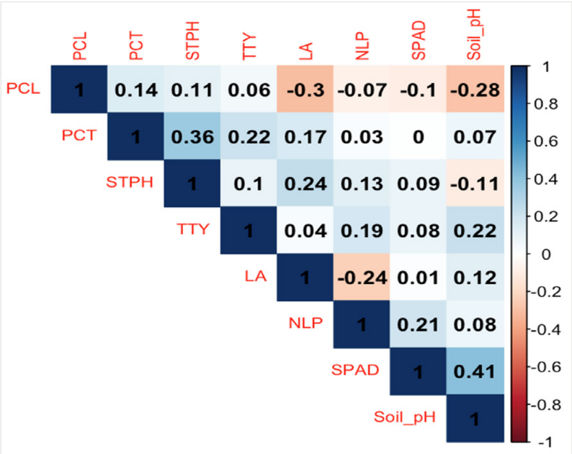


Figure 7. Principal component analysis (PCA) score plot of some individual traits determined under the three rates of humic acid application, silicon, and mycorrhiza inoculation

Correlation heatmap

The strongest correlation was observed between SPAD and soil pH, with a coefficient of 0.41, indicating that higher soil pH values are generally associated with higher SPAD values (Fig. 8). This may reflect improved chlorophyll content in leaves under certain pH conditions, which in turn can increase the availability of nutrients such as phosphorus in the soil. Another positive correlation was observed between phosphorus concentration in tubers (PCT), and soil test phosphorus at harvest (STPH), which achieved a correlation value of 0.36. Additionally, a positive correlation was distinguished between soil test phosphorus at harvest and leaf area (LA), and also between total tuber yield and soil pH. For both relations, correlation values are 0.24 and 0.22, respectively. The negative correlation observed between PCL and LA achieved a correlation value (-0.30), however, it is a moderate correlation, which means that other factors influence this relation.



	PCL	PCT	STPH	TTY	LA	NLP	SPAD	Soil_pH
PCL	1	0.14	0.11	0.06	-0.3	-0.07	-0.1	-0.28
PCT		1	0.36	0.22	0.17	0.03	0	0.07
STPH			1	0.1	0.24	0.13	0.09	-0.11
TTY				1	0.04	0.19	0.08	0.22
LA					1	-0.24	0.01	0.12
NLP						1	0.21	0.08
SPAD							1	0.41
Soil_pH								1

Note: the color gradient represents the strength and direction of correlations, with blue indicating positive correlations and red indicating negative correlations.

Figure 8. Correlation matrix showing the relationships between phosphorus concentration in leaves (PCL), phosphorus concentration in tubers (PCT), soil test phosphorus at harvest (STPH), total tuber yield (TTY), leaf area (LA), number of leaves per plant (NLP), SPAD (chlorophyll content), and soil pH

Discussion

Humic acid is rich in nutrients and plant hormones that enhance root development and shoot vigour in plants, promoting nutrient uptake and transport (Zhou et al., 2024). On the other hand, humic acids, silicon, and mycorrhizae can enhance photosynthesis in C3 plants, such as potatoes, by increasing phosphorus uptake, which boosts overall growth (Atero-Calvo et al., 2024; Khilji et al., 2024; Naji et al., 2023; Sarma et al., 2024). The current study found that the maximum total potato yield was reached at T11 (200 kg humic acid ha^{-1} + 150 mg silicon kg^{-1} soil without mycorrhizal inoculation); Table 3. These results are consistent with the observations made by (Abdel-Sattar et al., 2024; Gonzalez-Porras et al., 2024; Yu et al., 2024). However, the total yield, marketable potato yield, and other yield parameters, except the unmarketable tubers yield, did not record a significant difference amongst the treatments.

In this investigation, the economic analysis showed that humic acid treatments, especially at 100 and 200 kg·ha^{-1}, are economically advantageous for marketable potato yield when yield improvements compensate for the additional input cost (Table 4). The maximum net return was recorded at the fertilized treatments T6 and T11. These results align with recent research that investigated applying humic acid to enhance potato tuber yield, phosphorus uptake, and potato profitability (Xu et al., 2025). Furthermore, Liu et al. (2025) stated that AMF can improve the potato tuber yield and phosphorus uptake efficiency in tubers, enhancing the potential value of AMF plots, as the direct cost is minimal. In this study, the AMF had a low-cost amendment (< \$1 ha^{-1}), even though the marketable yield depends on its combination with humic acid and silicon. Ultimately, humic acid is the main driver of potato profitability, whereas the other amendments, such as silicon and mycorrhiza, improve returns only when they significantly contribute to potato yield relative to their cost.

The maximum number of stem values recorded at T4 treatments included only silicon and mycorrhizae inoculation (Fig. 2 B). Results corresponded to Wadas (2021), who reported that silicon improves drought tolerance in crop plants by regulating physiological and biochemical processes, including water relations, photosynthesis, nutrient absorption, reduction of oxidative stress, osmotic adjustment, and the expression of genes associated with the synthesis of phytohormones that mitigate drought stress. Conversely, the T4 treatment resulted in the highest leaf values, which consisted of humic acid without mycorrhizal applications. This observation could arise from the use of humic acid, which improves nutrient-use efficiency by affecting soil physical conditions, thus leading to increased total nutrient uptake through boosting root penetration, facilitating greater absorption of nutrients and moisture (Maruthi et al., 2024). However, leaf area and SPAD index were highest at T10 and T9, where both treatments had the greatest application of humic acid in this study (Fig. 2 C and D). These results can be attributed to the ability of humic acid to enhance potato resilience to water stress and reduce damage by regulating physiological and metabolic processes. This is consistent with several experiments that suggest humic acid can promote plant growth and development by improving photosynthesis parameters (Abdellatef et al., 2023; Hassanein et al., 2022; Zhou et al., 2024). This phenomenon could subsequently influence the plant's nutrient uptake and dry matter accumulation under untoward conditions. These data suggest that humic acid can enhance sustainable agriculture in arid and semi-arid environments (Man-hong et al., 2020).

Phosphorus is a substantial nutrient required by most crops (Al-Tameemi et al., 2024; Jasim et al., 2020a). Potatoes are known to have a high requirement for phosphorus due to this nutrient's role in various metabolic processes. Additionally, well-fertilized soil enhances crop production and the availability of soil nutrients. Fig. 3 A – D and Fig. 5 A and B indicate that the optimal phosphorus concentration and uptake in leaflets and tubers, as well as soil test phosphorus, were primarily observed with humic acid applications, silicon applications, and mycorrhizal inoculation. These results coincide with facts recorded by (Chafai et al., 2024; El-Sayed and El-Sayed, 2020; Mahmood et al., 2024; Man-hong et al., 2020; Maruthi et al., 2024; Naji et al., 2023; Zhou et al., 2024). Those who reported that it could be attributed to organic fertilizer enhance the retention and chelation of positive ions in the soil, resulting in lessening or blocking the adsorption and precipitation reactions of phosphorus. It acts as a chelating agent that reduces the loss of elements and their precipitation from the soil. Additionally, it decreases the degree of soil interaction in the rhizosphere zone by releasing hydrogen ions, various organic acids, and CO_2 gas during decomposition, which produces carbonic acid that dissolves insoluble phosphorus compounds. This process raises the soil test phosphorus, improving the phosphorus concentration in potato leaves and tubers.

Additionally, treatments inoculated with mycorrhizae play a vital role as fertility-enhancing microorganisms in soils, boosting soil health and increasing crop yields. Incorporating mycorrhizal fungi provides several benefits: enlarging the root system's reach by over 100 times, enhancing the absorption of immobile soil mineral nutrients, reducing abiotic stresses like drought and temperature fluctuations, and promoting soil flourishing aggregation. (Lee and Kim, 2007), reported that the findings could suggest that when silicate is adsorbed before the addition of phosphate, the number of sites available for phosphate in the soil is decreased.

The study data did not indicate any significant differences among the other treatments (Fig. 4). Soil pH regulates nutrient availability. Humic acid's ability to regulate fluctuations in soil pH depends on the quantity of its carboxylic and phenolic functional groups. The analysis of soil pH indicated a declining trend with the addition of humic acid concentrations (Laskosky et al., 2020). In a long-term, continuous field experiment on peanut cultivation, the use of humic acid did not significantly affect soil pH. The impact of humic acid on soil pH depends on the experimental conditions, the species of plant grown, and the amount of humic acid used. More studies need to be conducted to identify the optimal conditions specific to each application of humic acid in order to determine its effects on fluctuations in soil pH.

Fig. 6 B indicates that the highest mean value was observed at 200 kg humic acid· ha^{-1}, achieving a value of 11.88 kg P·ha^{-1} with a percentage increase of 9% compared to the 0 kg humic acid rate. This can be attributed to humic acid's ability to improve phosphorus availability in soils by chelating phosphorus ions, preventing these ions from being absorbed by calcium in calcareous soils (Atero-Calvo et al., 2024; Li et al., 2019). Furthermore, adding maximum humic acid can boost root development and decrease the soil pH within the rhizosphere (root zone), in turn, increasing nutrient availability and accelerating phosphorus absorption (Maruthi et al., 2024). However, a study that was conducted to examine the relations between AMF and silicon fertilizer stated that phosphorus content decreased in the shoot system when the soil test phosphorus was low, in turn, silicon precipitation on root cell walls, and the augmentation of the conflict between AMF and other phosphorus-solubilizing bacteria (Qiu et al., 2025). Silicon application could boost AMF infection and phosphorus uptake because silicon can improve photosynthesis, which, in turn, increases the plant carbon concentration, a factor important to mycorrhizal energy (Qiu et al., 2024).

Nevertheless, AMF colonization was not quantified in potato roots. Furthermore, AMF can substantially affect phosphorus concentration and uptake, and the lack of colonization measurement of potato root can be a limitation in validating this aspect. Future research on AMF colonization is recommended to yield more definitive insights.

Principal component analysis (Fig. 7) resulted in variables displaying a strong positive correlation with one another. This correlation is attributed to the association between the increments of soil phosphorus through humic acid and the corresponding increase in phosphorus concentration within both tubers and leaves (Man-hong et al., 2020). The outputs indicate that the factors studied have a positive effect on total tuber yield, attributable to the increased concentration of phosphorus, which enhances the yield. Conversely, soil pH negatively influences phosphorus concentration variables, as raised soil pH diminishes phosphorus uptake (Jasim et al., 2020a) .

The heatmap indicated that higher soil pH within the range 7.0–7.22 can enhance phosphorus availability, which indirectly promotes chlorophyll synthesis (SPAD), as shown in Fig. 8. Phosphorus is crucial for energy transfer (ATP synthesis) and cell division, both of which support leaf enlargement. A moderate correlation suggests that while phosphorus plays a role in leaf growth, other factors (like nitrogen and water availability) also contribute (Al-Tameemi et al., 2024). When crops grow larger (greater LA), the total biomass increases, but the phosphorus concentration in leaves (PCL) may decrease due to dilution - the same amount of phosphorus is spread across more tissue (Baruah et al., 2024). This is common in nutrient uptake investigations, where faster-growing plants show declining tissue nutrient concentrations regardless of suitable nutrient supply.

Conclusion

This study demonstrates the vital role of humic acid and silicon in enhancing soil phosphorus availability and phosphorus uptake in potato leaflets and tubers under the conditions of the experiment. Arbuscular mycorrhizal fungi (AMF) inoculation contributed to increased marketable tuber yield and reduced unmarketable tuber yield, particularly when applied in combination with humic acid. The highest treatment rate increased phosphorus uptake in tubers by 47.62% compared with the unfertilised control, although total tuber yield and most yield components did not differ significantly among the treatments. Overall, the combined use of humic acid, silicon and AMF improved soil test phosphorus, phosphorus concentration and phosphorus uptake in potato foliage and tubers, indicating that these amendments can be integrated into nutrient management strategies for potato production in calcareous soils to support more sustainable cropping systems. Future studies should examine higher rates and different sources of humic acid and silicon, together with quantified AMF colonisation, across soils with contrasting initial phosphorus status and environmental conditions in order to optimise recommendations.

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CrediT Authorship Declaration

Ahmed Jasim: methodology, investigation, software, validation, data curation, writing – original draft, conceptualisation, review and editing, supervision and preparation of the final version of the manuscript.

Declaration of Competing Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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