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Effect of foliar-applied humic acid-based fertilizers on potato (*Solanum tuberosum* L.) yield, tuber quality, and nutrient uptake efficiency, with implications for sustainable fertilization

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Abstract

This study investigated the effects of foliar-applied humic acid-based fertilizers on potato (Solanum tuberosum L.) yield, tuber quality, and nutrient uptake efficiency under irrigated conditions in Western Kazakhstan. A three-year field experiment (2021–2023) was conducted using the Silvana potato variety, a medium-early cultivar with high yield potential. The randomized complete block design included five treatments: (1) Control (no fertilizers), (2) Reasil Micro Hydro Mix, (3) Reasil Micro Hydro Mix + Reasil Forte Carb-Nitrogen-Humic, (4) Potassium Humate, and (5) Potassium Humate + Reasil Forte Carb-Nitrogen-Humic. All fertilizers were applied as foliar sprays at three critical growth stages: stem formation, bud appearance, and tuber formation. The humic acid-based fertilizers used in the study were produced by LLC "Life Force Group". Potassium Humate is an 80% alkaline extract of humic and fulvic acids from leonardite. Reasil Micro Hydro Mix contains various essential micronutrients, including N, Mg, B, Fe, Zn, and amino acids. Reasil Forte Carb-Nitrogen-Humic is rich in N (20%, including 18% amide-N) and also contains humic acids (6.2%), hydroxycarboxylic acids (6.2%), and amino acids (6%). Results showed that foliar humic acid application significantly increased potato yield and improved tuber quality. The highest average marketable yield (28.79 t/ha) was obtained with Potassium Humate + Reasil Forte Carb-Nitrogen-Humic, reflecting a 20% increase over the control. Starch content was also highest in this treatment (16.9%), while vitamin C content was better maintained in treated plots under stress conditions. Additionally, nitrate accumulation in tubers was reduced, improving food safety. Nutrient uptake efficiency was significantly enhanced by humic acid-based foliar treatments. The Potassium Humate + Reasil Forte Carb-Nitrogen-Humic treatment recorded the highest N, P, and K absorption levels, confirming the role of foliar humic applications in optimizing nutrient translocation. These findings demonstrate that humic acid-based foliar fertilization is an effective strategy for increasing potato productivity while reducing reliance on conventional fertilizers. These findings highlight the potential of foliar-applied humic substances as a sustainable alternative to conventional fertilization, particularly in semi-arid agricultural systems.

Keywords: Foliar fertilization, humic substances, potato yield, nutrient uptake, starch content, sustainable agriculture.

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Introduction

Potato (*Solanum tuberosum* L.) is one of the most widely cultivated crops globally, playing a critical role in food security and economic sustainability. It serves as a staple food in many countries, providing essential

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nutrients such as carbohydrates, vitamins, and minerals. Also, potatoes are an important crop in the Central Asian Republics (Loebenstein and Manadilova, 2003). They are the second most important crop in Kazakhstan, after wheat, grown on about 205.000 ha and its yields average 19.5 t ha^{-1} (Alimkhanov et al., 2021).However, achieving high potato yields and quality is often constrained by environmental stress, nutrient availability, and soil fertility. To address these challenges, sustainable fertilization strategies have been explored, with increasing interest in humic substances as a plant growth enhancer (Mora et al., 2010; Chen et al., 2017; Akladious and Mohamed, 2018; Mukhametov et al., 2024).

Humic substances, including humic acid and fulvic acid, are naturally occurring organic molecules formed during the decomposition of plant and microbial residues. They have been widely studied for their role in improving plant growth, increasing stress resistance, and enhancing nutrient absorption (de Moura et al., 2023). While traditionally applied to the soil to improve structure and nutrient retention, recent research has demonstrated that humic substances can be highly effective when applied as foliar sprays, directly benefiting plant metabolism and nutrient uptake (Zhou et al., 2019; Bayat et al., 2021). Foliar application allows plants to absorb humic substances through leaf tissues, improving nutrient availability, photosynthetic efficiency, and enzymatic activity (Li et al., 2019; Tang et al., 2021).

Unlike soil applications that primarily modify soil fertility, foliar-applied humic substances enhance nutrient absorption directly through the leaves and facilitate internal nutrient translocation within the plant (Muminova et al., 2022; Tastanbekova et al., 2024). Studies have demonstrated that humic substances applied via foliar spraying improve nitrogen assimilation, increase enzymatic activity related to photosynthesis, and regulate hormonal balance, thereby enhancing plant growth and productivity (Zhou et al., 2019; Bayat et al., 2021). These effects are particularly valuable in potato cultivation, where efficient nutrient uptake directly impacts tuber development, starch accumulation, and overall yield quality.

The benefits of foliar-applied humic substances are particularly evident in crops like potatoes, where efficient nutrient uptake is crucial for tuber formation and quality. Studies have shown that foliar humic applications enhance nitrogen (N), phosphorus (P), and potassium (K) uptake, increasing translocation efficiency and improving overall plant health (Lumactud et al., 2022). Furthermore, humic substances have been reported to stimulate hormonal activities such as cytokinin and auxin production, leading to improved root and shoot development, stress tolerance, and yield stability (Akram et al., 2009; Kanai et al., 2011). These effects are particularly important under variable environmental conditions, where nutrient absorption from the soil may be limited.

Another advantage of foliar-applied humic substances is their ability to reduce dependence on conventional fertilizers while maintaining or even improving crop productivity. Research indicates that humic acids can enhance plant growth by increasing nitrate uptake, stimulating polyamine metabolism, and improving photosynthetic efficiency (Nardi et al., 2002; Mora et al., 2010). These mechanisms contribute to better tuber starch accumulation, improved vitamin C content, and higher marketability of potatoes (Chen et al., 2004; Suh et al., 2014).

Despite the growing evidence supporting the effectiveness of foliar humic substances, further research is needed to evaluate their performance under different climatic conditions and application rates (de Moura et al., 2023). While previous studies have examined their effects on various crops, there is limited data specifically on potatoes grown under Western Kazakhstan's agro-climatic conditions (Muminova et al., 2022; Tastanbekova et al., 2024). Understanding how foliar-applied humic substances influence tuber yield, quality, and nutrient uptake in these soils is essential for optimizing fertilization strategies.

This study aims to evaluate the impact of foliar-applied humic acid-based fertilizers on potato yield, tuber quality, and nutrient uptake efficiency under irrigated dark chestnut soil conditions in Western Kazakhstan. Specifically, the study will (i) Assess the effects of different humic acid formulations on potato yield and biomass production, (ii) Investigate changes in nutrient absorption and translocation efficiency following foliar humic acid application.

Material and Methods

Experimental Site and Climatic Conditions

The field experiments were conducted from 2021 to 2023 at the KH "Arystanov" farm in the Baiterek district, West Kazakhstan region. The experimental site is located at 52°16'06" N latitude and 51°02'44" E longitude. The soil in this region is classified as medium-depth dark chestnut soil with a heavy loamy texture. The humus content in the 0–30 cm soil layer ranged from 2.8% to 3.3%, and the soil pH was slightly alkaline (7.2–7.3). The pH of the aqueous extract was measured using electrodes.

The climate in the study area is sharply continental, with an average annual precipitation of 320 mm and an average annual temperature of +2.8°C. The frost-free period lasts 135–150 days, and the hydrothermal coefficient (HTC) varies between 0.7 and 0.8, indicating semi-arid conditions.

Experimental Design

The study was designed to evaluate the effects of foliar-applied humic acid-based fertilizers on potato (Solanum tuberosum L.) yield, tuber quality, and nutrient uptake efficiency. The trials were conducted using a randomized complete block design with five treatments and four replications, totaling 336 m^2. Each experimental plot measured 16.8 m^2 (2.1 m × 8 m). The distance between plots was not explicitly stated.

Plant Material and Fertilizer Treatments

The potato variety used in the study was Silvana, a medium-early, table variety known for its high marketability and adaptability. The plants are tall, semi-erect, with medium-sized, open leaves of light green to green color. Tubers are round with medium-depth eyes, smooth yellow skin, and yellow flesh. The variety is characterized by a marketable tuber weight of 92–148 g, starch content of 13.6–15.3%, and marketable yield ranging from 17 to 37.4 t/ha. The number of tubers per plant varies between 7 and 14, and its storage quality is rated at 91%.

The humic acid-based foliar fertilizers used in the experiment were sourced from LLC "Life Force Group" (Saratov, Russia) and included:

- Potassium Humate: An 80% alkaline extract of humic and fulvic acids derived from the leonardite mineral.
- Reasil Micro Hydro Mix: A micronutrient complex containing hydroxycarboxylic acids (18%) as a chelating agent, total nitrogen (12%), magnesium (4%), boron (2%), cobalt (0.1%), copper (0.8%), iron (5%), manganese (2.5%), molybdenum (0.25%), zinc (3%), and amino acids (8%), with a pH of 8.5.
- Reasil Forte Carb-Nitrogen-Humic: A nitrogen-rich formulation containing total nitrogen (20%), amide nitrogen (18%), humic acids (6.2%), hydroxycarboxylic acids (6.2%), and amino acids (6%).

All fertilizers were applied as foliar sprays at specific growth stages to ensure optimal nutrient absorption through the leaves. The treatments included:

- Control (T1): No fertilizer application.
- Reasil Micro Hydro Mix (T2): Applied three times at 1.0 L/ha per treatment.
- Reasil Micro Hydro Mix + Reasil Forte Carb-Nitrogen-Humic (T3): 1.0 L/ha Reasil Micro Hydro Mix in the first treatment, followed by 2.0 L/ha Reasil Forte Carb-Nitrogen-Humic in the second and third treatments.
- Potassium Humate (T4): Applied three times at 1.0 L/ha per treatment.
- Potassium Humate + Reasil Forte Carb-Nitrogen-Humic (T5): 1.0 L/ha Potassium Humate in the first treatment, followed by 2.0 L/ha Reasil Forte Carb-Nitrogen-Humic in the second and third treatments.

All fertilizers were dissolved in 200 L of water per hectare and applied using a manual sprayer with a working pressure of 0.3 atm.

Agronomic Practices

Soil preparation involved moldboard plowing to a depth of 22–25 cm, followed by pre-plant cultivation to 8–9 cm. Potatoes were planted using a potato planter at a row spacing of 0.7 m, with three inter-row cultivations conducted during the growing season.

Sowing and Harvesting Dates:

- 2021: Sowing on April 30, harvest on August 12 (104-day growth period).
- 2022: Sowing on May 3, harvest on August 15 (105-day growth period).
- 2023: Sowing on May 5, harvest on August 24 (112-day growth period).

No pre-germination of tubers was conducted before planting.

Irrigation and Fertilization

The experimental field was irrigated using sprinkler irrigation. Specific irrigation rates and seasonal water norms are detailed in the results section.

No basal (soil-applied) fertilization was performed. Only foliar-applied humic fertilizers were used.

Pest and Disease Management

Pest and disease development was not systematically studied during the experiment. However, visual inspections indicated that the crops remained healthy throughout the study period.

Data Collection and Analytical Methods

Tuber and vegetative mass samples were collected before harvesting. The following measurements and analyses were conducted acorrding to Kalra (1998), Jones (2001) and Singh (2024):

- Yield Determination: Harvesting was performed manually, and total tuber yield was recorded for each treatment.
- Nutrient Content Analysis: Nitrogen, phosphorus, and potassium concentrations in tubers and vegetative biomass were determined using wet ashing with concentrated sulfuric acid.
- Starch Content: Measured using a polarimeter after acid hydrolysis, following the Evers method.
- Vitamin C (Ascorbic Acid) Content: Extracted using a hydrochloric and metaphosphoric acid mixture and analyzed using the Murray method.
- Total Sugar Content: Determined after hydrolysis with a 10% hydrochloric acid solution.
- Nitrate Content: Measured using a standard ion-selective electrode.

Results and Discussion

Yield Performance of Potato under Humic Acid-Based Foliar Fertilization

The application of humic acid-based foliar fertilizers significantly influenced the yield performance of potato tubers throughout the three-year experimental period (2021–2023). The highest average yield (28.79 t/ha) was obtained from the Potassium Humate + Reasil Forte Carb-Nitrogen-Humic treatment (T5), reflecting a 20% increase over the control. The combination of humic substances with chelated micronutrients (Reasil Micro Hydro Mix + Reasil Forte-T3) also demonstrated a notable yield increase of 16% compared to the control, further supporting the role of humic acids in improving plant nutrient uptake and biomass production (Chen et al., 2017; Akladious and Mohamed, 2018; Zhou et al., 2019; Bayat et al., 2021).

Yield performance varied across the three years due to environmental conditions (Table 1). In 2021, favorable climatic conditions contributed to higher overall yields. The Potassium Humate + Reasil Forte treatment (T5) recorded the highest yield at 32.13 t/ha, while the control plot (T1) produced only 26.45 t/ha. However, 2022 was marked by adverse weather conditions, including high temperatures and low rainfall, leading to a decrease in yields across all treatments. The control treatment (T1) suffered the most significant reduction, yielding only 16.49 t/ha (a 38% decrease compared to 2021). In contrast, humic acid-treated plots showed improved resilience, with Potassium Humate + Reasil Forte Carb-Nitrogen-Humic (T5) maintaining 77% of its multi-year average, demonstrating the potential of humic substances to enhance stress tolerance in potato crops (Akladious and Mohamed, 2018; de Moura et al., 2023). The yield performance rebounded in 2023 with improved hydrothermal conditions. The Potassium Humate + Reasil Forte Carb-Nitrogen-Humic treatment (T5) once again exhibited the highest yield stability (31.99 t/ha), highlighting the long-term benefits of humic acid foliar applications under varying climatic conditions.

Table 1. Yield of Marketable Silvana Potato Tubers Under Irrigation Conditions (t/ha)

Treatments	2021	2022	2023	Average	Increase (t)	% Increase	Marketability, %
T1	26.45	16.49	29.20	24.05	-	100	91
T2	28.69	19.55	31.12	26.45	2.40	110	94
T3	30.18	20.50	33.15	27.94	3.89	116	95
T4	29.55	18.49	30.32	26.12	2.07	109	95
T5	32.13	22.25	31.99	28.79	4.74	120	96

T1: Control (No Fertilizer); T2 : Reasil Micro Hydro Mix; T3 : Reasil Micro Hydro Mix + Reasil Forte Carb-Nitrogen-Humic; T4 : Potassium Humate; T5 : Potassium Humate + Reasil Forte Carb-Nitrogen-Humic

Table 1 presents the yield data for different fertilizer treatments. The results indicate that three-time foliar application of humic acid-based fertilizers consistently increased potato yields compared to the control (T1). The data confirms that the highest marketable yield was consistently achieved with the combined application of Potassium Humate + Reasil Forte Carb-Nitrogen-Humic (T5). These findings align with previous studies that demonstrated humic acid's role in enhancing soil structure, increasing water retention, and improving plant tolerance to abiotic stress (Akram et al., 2009; Kanai et al., 2011).

Research suggests that humic acids contribute to improved soil microbial activity, which enhances nutrient availability even under challenging conditions. The ability of humic substances to stimulate root growth and increase water and nutrient absorption likely played a role in the observed yield stability, particularly in the dry 2022 season. Additionally, the increased uptake of essential nutrients such as nitrogen, phosphorus, and potassium in fertilized plots contributed to overall yield improvements (Suh et al., 2014; Akladious and

Mohamed, 2018; Li et al., 2019; Tang et al., 2021; Lumactud et al., 2022). The results of this study reinforce the benefits of incorporating humic acid-based fertilizers into potato cultivation strategies, particularly in regions with variable climatic conditions. By improving both yield and marketability, these fertilizers offer a sustainable approach to enhancing potato production in Western Kazakhstan.

Influence on Tuber Number and Size

Humic acid-based foliar fertilization significantly influenced tuber number and size distribution. The highest number of tubers per plant was recorded in the Potassium Humate + Reasil Forte Carb-Nitrogen-Humic treatment (T5), followed closely by Reasil Micro Hydro Mix + Reasil Forte Carb-Nitrogen-Humic (T3), both of which significantly outperformed the control (T1). Tuber formation showed noticeable variations across the years (Table 2). In 2021, the number of tubers per m^2 was highest in the Potassium Humate + Reasil Forte Carb-Nitrogen-Humic (T5, 33.5), while the control (T1) recorded only 21.1. The following year, environmental stress conditions led to an overall decline in tuber numbers, yet the fertilized treatments maintained significantly higher values than the control. By 2023, tuber numbers rebounded, with humic acid-treated plots demonstrating a consistent trend of improvement, reaffirming the role of foliar-applied humic substances in enhancing tuber formation and plant resilience.

Table 2. Structure of the Biological Yield of Marketable Silvana Potato Tubers

Treatments	Tubers per m^2				Tubers per plant				Tubers (kg) per bush			
	2021	2022	2023	Avg.	2021	2022	2023	Avg.	2021	2022	2023	Avg.
T1	26,0	15,1	20,7	20,6	4,8	4,1	4,9	4,6	0,46	0,41	0,45	0,44
T2	36,6	22,0	23,9	27,5	6,1	4,9	6,4	5,8	0,59	0,55	0,51	0,55
T3	35,5	28,3	36,1	33,3	6,9	6,0	7,8	6,9	0,69	0,48	0,60	0,59
T4	30,2	27,7	26,1	28,0	6,3	6,0	5,4	5,9	0,67	0,58	0,55	0,60
T5	34,4	29,0	35,3	32,9	7,2	7,6	5,9	6.9	0,74	0,65	0,62	0,67

T1: Control (No Fertilizer); T2 : Reasil Micro Hydro Mix; T3 : Reasil Micro Hydro Mix + Reasil Forte Carb-Nitrogen-Humic; T4 : Potassium Humate; T5 : Potassium Humate + Reasil Forte Carb-Nitrogen-Humic

The observed increase in tuber number and weight aligns with previous research findings that attributed these benefits to enhanced root development, improved soil aggregation, and increased nutrient availability (Butler and Muir, 2006; Liu et al., 2014; Zhao et al., 2020; Li et al., 2022; Budanov et al., 2023). Humic acids also stimulate hormonal activity, further promoting tuber formation (Rathor et al., 2024). The ability of humic substances to regulate osmotic stress is another key factor in their positive impact on tuber formation (Jindo et al., 2020). The results of this study reinforce the benefits of incorporating humic acid-based fertilizers into potato cultivation strategies, particularly in regions with variable climatic conditions. By improving both yield and marketability, these fertilizers offer a sustainable approach to enhancing potato production in Western Kazakhstan.

Effect on Starch, Vitamin C and Nitrate Content

Humic acid-based foliar fertilization significantly influenced the starch content in potato tubers (Table 3). In 2021, the highest starch concentration was observed in the Potassium Humate + Reasil Forte Carb-Nitrogen-Humic treatment (T5, 17.2%), while the control (T1) had the lowest (15.2%). However, in 2022, due to adverse environmental conditions, the starch content decreased across all treatments, with the Potassium Humate + Reasil Forte treatment dropping slightly to 15.7% and the control falling to 13.8%. By 2023, starch levels recovered, reaching a peak of 16.9% in the Potassium Humate + Reasil Forte treatment, while the control remained relatively lower at 14.8%. This pattern suggests that humic substances play a key role in stabilizing starch accumulation despite environmental stressors.

The vitamin C (ascorbic acid) content in potato tubers followed a relatively stable pattern across the years (Table 3). In 2021, the highest vitamin C concentration was recorded in the Potassium Humate + Reasil Forte treatment (23.8 mg/100g), while the control contained 23.9 mg/100g. In 2022, vitamin C levels dropped slightly due to environmental stress, but humic acid treatments helped maintain higher levels compared to the control. By 2023, vitamin C levels increased again, with the Potassium Humate + Reasil Forte Carb-Nitrogen-Humic treatment (T5) reaching 23.9 mg/100g. These results suggest that foliar-applied humic substances contribute to maintaining the nutritional quality of potatoes even under stress conditions.

Nitrate accumulation in potato tubers was significantly reduced in all humic acid-treated variants compared to the control (Table 3). In 2021, the highest nitrate content was recorded in the Potassium Humate + Reasil Forte Carb-Nitrogen-Humic (T5, 57 mg/kg raw mass), while the control (T1) had 49 mg/kg. In 2022, nitrate levels dropped across all treatments, with the lowest value of 39 mg/kg in the Potassium Humate (T4) treatment, compared to 36 mg/kg in the control (T1). By 2023, nitrate content further decreased, with the

Reasil Micro Hydro Mix + Reasil Forte Carb-Nitrogen-Humic (T3) treatment achieving the lowest recorded nitrate level of 24 mg/kg, highlighting humic substances' role in regulating nitrogen metabolism in plants and reducing excessive nitrate accumulation.

Table 3. Starch and Nutrient Content of Marketable Silvana Potato Tubers

Treatments	Starch (%)				Vitamin C (mg/100g)				NO_3 (mg/kg raw mass)			
	2021	2022	2023	Avg.	2021	2022	2023	Avg.	2021	2022	2023	Avg.
T1	15,2	13,8	14,8	14,6	23,9	20,8	23,1	22,6	49	36	35	40
T2	16,5	14,9	16,3	15,9	23,2	21,4	22,0	22,2	50	40	39	43
T3	17,3	15,9	16,0	16,4	23,6	21,8	23,0	22,8	55	41	24	40
T4	17,0	16,8	14,2	16,0	23,9	20,9	22,4	22,4	52	39	44	45
T5	17,2	15,7	16,9	16,6	23,8	21,6	23,9	23,1	57	42	33	44

T1: Control (No Fertilizer); T2 : Reasil Micro Hydro Mix; T3 : Reasil Micro Hydro Mix + Reasil Forte Carb-Nitrogen-Humic; T4 : Potassium Humate; T5 : Potassium Humate + Reasil Forte Carb-Nitrogen-Humic

These findings align with studies that reported humic acid's ability to stimulate starch synthesis enzymes such as AGPase, UGPase, and SSS, leading to increased starch accumulation in tubers (Tiessen et al., 2002; Li et al., 2019). Additionally, humic acids contributed to an increase in total sugars and dry matter content, making them a valuable tool for improving potato quality (de Moura et al., 2023). The results of this study reinforce the benefits of incorporating humic acid-based fertilizers into potato cultivation strategies, particularly in regions with variable climatic conditions. By improving both yield and marketability, these fertilizers offer a sustainable approach to enhancing potato production in Western Kazakhstan.

Nutrient Uptake Efficiency

Nutrient uptake fluctuated across the years (Table 4), largely influenced by soil moisture availability. In 2021, nutrient uptake was highest across all treatments due to optimal environmental conditions. However, in 2022, a decline in soil moisture led to lower nutrient absorption, but Humic acid-based foliar fertilizer treated plots still performed significantly better than the control. In 2023, nutrient uptake recovered, with Humic acid-based foliar fertilizer treated plants exhibiting sustained high levels of nitrogen and potassium absorption, emphasizing the long-term benefits of humic substances in improving plant nutrition. Since the treatments were applied as foliar sprays, nutrient uptake efficiency in potato plants was assessed based on their ability to absorb and utilize nitrogen (N), phosphorus (P), and potassium (K) from the applied solutions rather than soil sources. The highest nutrient uptake was recorded in the Potassium Humate + Reasil Forte Carb-Nitrogen-Humic treatment (T5), followed by Reasil Micro Hydro Mix + Reasil Forte Carb-Nitrogen-Humic (T3).

Nitrogen uptake varied significantly across the years, largely due to environmental conditions affecting foliar absorption. In 2021, nitrogen uptake was highest in all treatments, with the P Potassium Humate + Reasil Forte Carb-Nitrogen-Humic treatment (T5) reaching 161.4 kg/ha, compared to 111.6 kg/ha in the control (T1). However, in 2022, limited atmospheric moisture reduced nitrogen absorption efficiency, with the control dropping to 69.6 kg/ha and even the best-performing treatment 5 (Potassium Humate + Reasil Forte Carb-Nitrogen-Humic treatment) decreasing to 111.8 kg/ha. By 2023, nitrogen uptake rebounded, reaffirming the role of humic substances in improving nutrient bioavailability and translocation within plants.

Phosphorus uptake followed a similar trend, with the highest uptake in 2021, a decline in 2022, and recovery in 2023. In 2021, the Potassium Humate + Reasil Forte Carb-Nitrogen-Humic treatment (T5) recorded the highest phosphorus uptake at 74.1 kg/ha, whereas the control (T1) had the lowest at 51.1 kg/ha. The drought stress in 2022 reduced phosphorus absorption across all treatments, with the control dropping to 31.9 kg/ha and the Potassium Humate + Reasil Forte Carb-Nitrogen-Humic treatment (T5) decreasing to 51.3 kg/ha. By 2023, phosphorus uptake improved again, with humic acid-treated plants maintaining significantly higher levels than the control (T1).

Potassium uptake was also significantly affected by humic acid applications. In 2021, the Potassium Humate + Reasil Forte Carb-Nitrogen-Humic treatment (T5) exhibited the highest uptake at 208.5 kg/ha, while the control (T1) only absorbed 147.6 kg/ha. The drought conditions of 2022 negatively impacted potassium uptake, with the control declining to 92.0 kg/ha and the Potassium Humate + Reasil Forte Carb-Nitrogen-Humic treatment (T5) dropping to 144.4 kg/ha. In 2023, potassium absorption improved again, reinforcing the role of humic substances in enhancing potassium availability.

Table 4. Nutrient Uptake by Silvana Potatoes from Soil (kg/ha)

Treatments	Nitrogen (N)				Phosphorus (P_2O_5)				Potassium (K_2O)			
	2021	2022	2023	Avg.	2021	2022	2023	Avg.	2021	2022	2023	Avg.
T1	111,6	69,6	123,2	101,5	51,1	31,9	56,5	46,5	147,6	92,0	162,9	134,2
T2	122,1	83,2	132,5	112,6	56,0	38,1	60,7	51,6	161,6	110,1	175,3	149,0
T3	128,2	87,1	140,8	118,7	58,8	39,9	64,5	54,4	170,2	115,6	187,0	157,6
T4	147,6	92,4	151,5	130,5	66,6	41,7	68,4	58,9	167,3	104,7	171,7	147,9
T5	161,4	111,8	160,7	144,6	74,1	51,3	73,8	66,4	208,5	144,4	207,6	186,8

T1: Control (No Fertilizer); T2 : Reasil Micro Hydro Mix; T3 : Reasil Micro Hydro Mix + Reasil Forte Carb-Nitrogen-Humic; T4 : Potassium Humate; T5 : Potassium Humate + Reasil Forte Carb-Nitrogen-Humic

One of the primary benefits of foliar-applied humic substances is their ability to optimize nutrient use efficiency by enhancing translocation within the plant. Humic acids facilitate the uptake and redistribution of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K), reducing nutrient losses and ensuring a steady supply of nutrients during critical growth stages. Recent studies have also highlighted that foliar-applied humic substances can increase photosynthetic efficiency and enzymatic activity, leading to improved nutrient assimilation (Nikbakht et al., 2008; Verlinden et al., 2009; Xiong et al., 2023; Santi et al., 2024). This mechanism plays a crucial role in ensuring stable productivity under varying environmental conditions. These findings align with studies showing that foliar-applied humic substances enhance nutrient absorption, increase plant tolerance to stress, and improve metabolic functions. The results of this study reinforce the benefits of using humic acid-based foliar fertilizers as an effective strategy for increasing potato yield and quality under varying climatic conditions.

Conclusion

This study demonstrated that foliar-applied humic acid-based fertilizers significantly enhance potato yield, tuber quality, and nutrient uptake efficiency. The findings highlight the advantages of humic substances in improving plant metabolism, nutrient translocation, and stress tolerance, ultimately leading to higher productivity and better tuber quality.

The highest potato yield and starch content were consistently observed in the Potassium Humate + Reasil Forte treatment, indicating that humic acid application plays a crucial role in optimizing carbohydrate metabolism and biomass accumulation. Additionally, humic acid-treated plants exhibited improved vitamin C content and reduced nitrate accumulation, suggesting a positive impact on overall tuber nutritional quality.

One of the key benefits of foliar humic application is its ability to enhance nutrient uptake efficiency by facilitating the absorption and redistribution of essential macronutrients such as nitrogen, phosphorus, and potassium. The study confirmed that foliar humic acid application improves enzymatic activity and photosynthetic performance, contributing to more efficient nutrient utilization and plant growth.

Furthermore, the results suggest that foliar humic acid application is a sustainable fertilization strategy that can reduce reliance on excessive chemical fertilizers while maintaining high crop productivity. Given the environmental and economic benefits, humic acid-based foliar fertilization presents a promising approach for enhancing potato production under varying agro-climatic conditions, particularly in regions with limited soil fertility and water availability. Future research should focus on optimizing application rates and timing to maximize the efficiency of foliar-applied humic substances. Additionally, further studies on their interactions with different nutrient management strategies and their long-term impact on soil and plant health will be essential for developing comprehensive, sustainable fertilization programs.

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