Synergistic Effects of Microbial Biostimulants and Foliar Amino Acids on Potato (*Solanum tuberosum* L.) Growth, Yield, and Water-Use Efficiency under Deficit Irrigation

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Abstract

Water scarcity constrains potato (Solanum tuberosum L.) production in Iraq. Two field experiments were conducted during spring 2024 and autumn 2024–2025 in Babylon Governorate to evaluate the effects of deficit irrigation, microbial biostimulants, and foliar-applied amino acids on potato growth and yield. Experiments were arranged in a split–split-plot randomized complete block design with three replications. Treatments included three irrigation levels (100%, 50%, and 30% depletion of available soil water), three soil microbial inoculation regimes (no inoculation; Trichoderma + arbuscular mycorrhizal fungi; Trichoderma + arbuscular mycorrhizal fungi + Bacillus), and three foliar amino acid rates (0, 2, and 4 kg ha^{-1}). Severe water deficit significantly reduced vegetative growth, leaf area, marketable tuber number, and yield. Soil inoculation with microbial consortia improved growth and yield traits, while foliar application of amino acids at 4 kg ha^{-1} further enhanced marketable yield. Significant interactions among irrigation, microbial inoculation, and amino acid application were observed. Integrating microbial biostimulants with amino acids improved potato productivity under water-limited conditions.

Keywords: Potato; deficit irrigation; microbial inoculants; amino acids; yield; water-use efficiency.

Introduction

Sustainable agricultural systems require innovative strategies capable of enhancing crop productivity while reducing reliance on conventional chemical fertilizers and mitigating the impacts of environmental stressors. In this context, biostimulants have gained considerable global attention as promising tools for improving plant performance, optimizing nutrient dynamics, and strengthening plant tolerance to abiotic stress. Their capacity to enhance nutrient- and water-use efficiency, regulate physiological processes, and stimulate growth at low application rates positions them as a key component of modern, climate-resilient agricultural practices [10,16].

Biostimulants encompass diverse categories that differ in composition and

ISSN 2072-3857

mode of action. Abiotic biostimulants—such as humic substances and protein hydrolysates enriched with amino acids—enhance soil properties and stimulate plant metabolism [13]. Biotic biostimulants include algal extracts, plant-derived compounds, arbuscular mycorrhizal fungi, *Trichoderma* spp., and beneficial microbial genera such as *Bacillus* and *Pseudomonas* [18]. The functional efficiency of these materials is closely linked to the physicochemical properties of their active components, including solubility, particle size, and molecular configuration, which collectively govern their penetration and bioavailability within plant tissues [2].

Soil microbial communities represent a critical component of terrestrial ecosystems, playing essential roles in nutrient cycling, organic matter decomposition, energy flow, and maintaining soil health and fertility [1]. Environmental parameters such as soil pH, moisture content, temperature, and land-management practices significantly influence the composition and diversity of soil microbiota [17,5]. High microbial diversity is positively associated with ecosystem stability and the suppression of plant pathogens, whereas biodiversity loss disrupts soil ecological functions and compromises plant growth and productivity [24,25].

Amino acids, traditionally recognized as structural units for protein synthesis, are increasingly understood to play multifunctional roles in plant physiology. They participate in enzymatic regulation, cellular signaling, membrane transport, nitrogen assimilation, and the modulation of photosynthesis and chlorophyll biosynthesis [20]. Their involvement in plant adaptive responses to environmental stress-particularly drought and salinity-further underscores their importance in enhancing water-use efficiency and maintaining metabolic stability under water-limited conditions [11].

Water scarcity remains a significant global challenge, affecting agricultural productivity and threatening food security. Inefficient irrigation practices contribute to the depletion of freshwater resources, while climate change exacerbates water shortages and increases variability in rainfall patterns [6,23]. The United Nations 2030 Sustainable Development Agenda emphasizes the urgent need to improve water-use efficiency across agricultural systems and enhance the resilience of crops to water-deficit conditions [22].

Given the positive outcomes reported for biostimulants in various field crops, integrating soil-applied microbial inoculants with foliar-applied amino acids may represent an effective strategy for enhancing the growth, yield, and quality of potato (*Solanum tuberosum L.*), particularly under water deficit conditions. Potatoes are highly responsive to environmental stress, especially fluctuations in water availability, making them an appropriate model crop for evaluating bio stimulant effectiveness. Based on this premise, the present study investigates whether the combined application of microbial biostimulants and amino acids can modulate plant physiological responses, improve irrigation water-use efficiency, and enhance vegetative, quantitative, and qualitative characteristics of potato plants grown under deficit-irrigation regimes.

Materials and Methods

Experimental Location and Duration

Two field experiments were conducted in the Al-Dablah region, southeast of Babylon Governorate, Iraq (Longitude

ISSN 2072-3857

44.39° E, Latitude 32.3° N). The first experiment was performed during the spring season of 2024, while the second experiment was carried out in the autumn season of 2024–2025. The study aimed to evaluate the role of soil application of beneficial microorganisms and foliar spraying with amino acids under variable irrigation regimes in improving the vegetative growth and the quantitative and qualitative yield traits of potato (*Solanum tuberosum L.*).

Experimental Design and Treatment Structure

The experiments were arranged as a Split-Split-Plot within a Randomized Complete Block Design (RCBD) with three replications. The study included three experimental factors:

- Factor A (Main Plots): Variable Irrigation Levels

A1: Irrigation at 0% depletion of available soil water (control treatment without water stress)

A2: Irrigation at 50% depletion of available soil water

A3: Irrigation at 70% depletion of available soil water

- Factor B (Sub-Plots): Soil Application of Microbial Inoculants

B1: Without microbial inoculation (control)

B2: Trichoderma spp. + Mycorrhiza spp. at 5 g per plant for each inoculant

B3: Trichoderma spp. + Mycorrhiza spp. + Bacillus spp. at 5 g per plant for each inoculant

- Factor C (Sub-Sub-Plots): Foliar Spraying with Amino Acids

C1: Spraying with water only (control)

C2: Amino acids at 2 kg ha^{-1}

C3: Amino acids at 4 kg ha^{-1}

The combination of these levels resulted in 27 treatments. With three replications, the total number of experimental units was 81, Each main plot was divided into three experimental lines, and each line was further subdivided into nine experimental units. Therefore, each main plot contained 27 different treatments. The dimensions of each experimental unit were 2.5 m × 1.25 m (3.125 m^2). The spacing between main plots within each block was 1.5 m, between sub-sub plots 1.0 m, and between blocks 2.0 m. The total experimental field area was 1125 m^2 (25 m × 45 m).

Soil Characteristics and Field Management

Composite soil samples were collected from the surface layer (0–30 cm depth) before planting and analyzed in the laboratories of the Department of Soil and Water Sciences, College of Agriculture, Al-Qasim Green University. Selected physical and chemical properties of the experimental soil are presented in Table 1.

Basal fertilization of NPK (15:15:15) was applied according to local agronomic recommendations at 300 kg ha^{-1}, broadcast during soil preparation and 30 days after planting. Supplemental nitrogen fertilizer (urea) was added at 200 kg ha^{-1} in two equal doses at 30 and 60 days after planting. All other cultural practices, including weeding, hilling, and pest control, were carried out uniformly for all treatments whenever required.

Soil Application of Microbial Inoculants

Microbial inoculants of *Trichoderma spp.*, (6–7 $\times 10^{11}$ spores g^{-1}) arbuscular mycorrhizal fungi (45–55 spores g^{-1}), and *Bacillus spp.* (27–30 $\times 10^{9}$ CFU g^{-1}) were supplied as individual cultures. The fungal inoculants consisted of spores and hyphal fragments thoroughly mixed with sterilized peat moss carrier at a 1:1 ratio. The bacterial inoculant was prepared as liquid cultures and subsequently loaded onto sterilized peat moss at a rate of 5 kg carrier per liter of culture. Inoculants were applied individually at planting close to the seed tubers from

ISSN 2072-3857

three directions at a rate of 5 g per plant for each microbial type.

Foliar Application of Amino Acids

A commercial powder formulation of mixed amino acids (glycine, lysine, glutamic acid, and leucine) with a total amino acid content of 50% was used for foliar application. Spraying was conducted in the early morning until complete wetting of the plant foliage was achieved. Applications were carried out three times at 15-day intervals after full emergence.

Working solutions corresponding to application rates of 2 and 4 kg ha^{-1} were prepared by dissolving 0.625 and 1.25 g L^{-1} of the amino acid formulation, respectively. A suitable spreading agent was added to the spray solution to ensure uniform coverage of the plant canopy

Table 1. Selected physical and chemical properties of the experimental soil

Property	Value	Unit
pH	7.43	–
Electrical conductivity (EC)	4.5	dS m^{-1}
Organic matter	1.05	%
Available water content	11.02	%
Sand	226	g kg^{-1}
Silt	235	g kg^{-1}
Clay	539	g kg^{-1}
Soil texture	Clay loam	–
Bulk density	1.63	g cm^{-3}
Field capacity	27.04	%
Permanent wilting point	16.02	%

Planting Method

Seed tubers of the potato cultivar ‘Elmunda’ (Dutch origin) were obtained from Nahar Al-Awrad Company, Baghdad, 15 days prior to planting. Healthy, uniform tubers with a diameter of 35–55 mm and free from mechanical or biological damage were selected. Tubers were stored under shade at ambient temperature to allow proper sprouting.

Planting was performed on 15 January 2024 for the spring experiment and on 20 September 2024 for the autumn experiment. Harvesting took place on 10 May 2024 and 10 January 2025 for the first and second experiments, respectively. Depletion irrigation treatments were initiated after ensuring complete seedling emergence. Each experimental unit contained 20 plants planted at 25 cm spacing along ridges.

Measured Growth and Yield Indicators

Vegetative Growth Traits

Mean plant height (cm): Ten plants were randomly selected from each experimental unit, and stem height from the soil surface to the apical tip was measured using a flexible measuring tape.

Mean number of leaves (leaf $plant^{-1}$): The same ten plants were used to determine the average number of leaves.

Mean leaf area (cm^2 $plant^{-1}$): Ten leaves were sampled from the selected plants. A cork borer was used to obtain 30 discs (1.5 cm diameter). Leaves and discs were oven-dried at 70°C until constant weight. Leaf area was calculated using:

ISSN 2072-3857

Leaf Area (cm²) = Leaf Area of Discs × Dry Weight of Leaves/Dry Weight of Discs

Marketable Tubers per Plant

Marketable tubers (weight > 25 g) were counted after grading. The average number was calculated as:

Number of marketable tubers per plant = Number of marketable tubers/ Actual number of plants per experimental unit

Yield Traits

Marketable tuber yield (ton ha^{-1}), Calculated by multiplying the average marketable yield per plant by the number of plants per hectare per experimental unit.

Non-marketable tuber yield (ton ha^{-1}), including small, cracked, deformed, or mechanically damaged tubers

Statistical Analysis

All collected data were analyzed using GenStat statistical software version 12.1. Treatment means were compared using Least Significant Difference (LSD) test at the 0.05 probability level to determine significant differences among treatments.

Results and Discussion

Plant Height

Statistical analysis indicated that plant height was significantly influenced by irrigation regimes, soil inoculation with the microbial consortium, foliar application of amino acids, as well as their two- and three-factor interactions across both growing seasons. Plants subjected to full irrigation exhibited the greatest height values, particularly when combined with the complete microbial consortium and high-rate amino acid spraying. This outcome highlights a pronounced synergistic interaction between adequate water supply and bio stimulant application in promoting vegetative development, Table 2

Table 2: Effect of variable irrigation, biostimulants and their interaction on plant height rate (cm)

Treatment	Spring	Fall	Treatment	Spring	Fall	Treatment	Spring	Fall
A1	53.65	73.39	B1	48.90	66.20	C1	48.32	65.45
A2	52.84	70.73	B2	49.62	67.20	C2	49.98	67.68
A3	43.47	53.94	B3	51.44	69.67	C3	51.66	69.93
$LSD_{(0.05)}$	0.401	11.95	$LSD_{(0.05)}$	0.368	0.53	$LSD_{(0.05)}$	0.210	0.29
A×B			A×C			B×C		
A1B1	52.38	76.53	A1C1	51.61	75.43	B1C1	47.17	63.88
A1B2	53.72	78.49	A1C2	53.78	78.57	B1C2	48.97	66.28
A1B3	54.85	80.16	A1C3	55.56	81.18	B1C3	50.55	68.43
A2B1	51.49	68.93	A2C1	52.03	69.66	B2C1	48.03	65.05
A2B2	51.61	69.09	A2C2	52.69	70.52	B2C2	49.79	67.42
A2B3	55.42	74.18	A2C3	53.80	72.02	B2C3	51.06	69.12
A3B1	42.82	53.13	A3C1	41.33	51.27	B3C1	49.77	67.43
A3B2	43.55	54.02	A3C2	43.49	53.95	B3C2	51.20	69.34
A3B3	44.06	54.66	A3C3	45.61	56.59	B3C3	53.35	72.24
$LSD_{(0.05)}$	0.592	11.93	$LSD_{(0.05)}$	0.440	11.94	$LSD_{(0.05)}$	0.456	0.65
A×B×C								

ISSN 2072-3857

A1B1C1	50.31	73.52	A2B1C1	50.70	67.89	A3B1C1	40.49	50.24
A1B1C2	52.53	76.75	A2B1C2	51.33	68.69	A3B1C2	43.04	53.40
A1B1C3	54.30	79.34	A2B1C3	52.43	70.20	A3B1C3	44.92	55.75
A1B2C1	51.97	75.95	A2B2C1	50.29	67.32	A3B2C1	41.83	51.90
A1B2C2	54.05	78.93	A2B2C2	51.80	69.37	A3B2C2	43.51	53.96
A1B2C3	55.15	80.58	A2B2C3	52.73	70.58	A3B2C3	45.30	56.21
A1B3C1	52.57	76.83	A2B3C1	55.09	73.77	A3B3C1	41.66	51.68
A1B3C2	54.76	80.03	A2B3C2	54.92	73.49	A3B3C2	43.91	54.49
A1B3C3	57.22	83.62	A2B3C3	56.24	75.28	A3B3C3	46.61	57.82
$LSD_{(0.05)}$	0.762	11.91	$LSD_{(0.05)}$	0.762	11.91	$LSD_{(0.05)}$	0.762	11.91

A1, A2, and A3 represent irrigation levels at 100%, 50%, and 30% of available water, respectively. B1 indicates no soil microbial application, B2 refers to soil application of Trichoderma (5 g plant^{-1}) plus Mycorrhiza (5 g plant^{-1}), while B3 includes Trichoderma (5 g plant^{-1}), Mycorrhiza (5 g plant^{-1}), and Bacillus (5 g plant^{-1}). C1 denotes no foliar application of amino acids, whereas C2 and C3 represent amino acid application rates of 2 and 4 kg ha^{-1}, respectively.

Such enhancement can be explained by improved plant water balance and increased nutrient acquisition efficiency. In addition, beneficial microorganisms stimulate root growth and induce the production of phytohormones [8,12], which collectively support cell elongation processes and overall shoot growth.

Number of Leaves and Leaf Area

The findings demonstrated that irrigation level exerted a significant effect on leaf number (Table 3) and leaf area (Table 4) of potato plants. Reduced irrigation resulted in a noticeable decline in both parameters, whereas fully irrigated treatments achieved the highest averages during the two seasons. Furthermore, soil application of the microbial consortium and foliar spraying with amino acids, particularly at higher concentrations, significantly enhanced leaf production and leaf area, with the strongest responses observed under combined treatments.

Table 3 Effect of variable irrigation, biostimulants and their interaction on the average number of leaves (leaf. plant^{-1})

Treatment	Spring	Fall	Treatment	Spring	Fall	Treatment	Spring	Fall
A1	61.05	70.55	B1	53.69	63.26	C1	50.49	60.70
A2	58.60	66.37	B2	55.40	65.29	C2	55.56	65.68
A3	44.28	58.31	B3	54.83	66.68	C3	57.87	68.84
$LSD_{(0.05)}$	1.24	1.95	$LSD_{(0.05)}$	0.93	0.86	$LSD_{(0.05)}$	0.89	0.24
A×B			A×C			B×C		
A1B1	59.72	69.46	A1C1	55.70	65.08	B1C1	50.32	59.17
A1B2	61.17	70.00	A1C2	61.82	71.08	B1C2	54.01	63.71

ISSN 2072-3857

A1B3	62.27	72.18	A1C3	65.64	75.48	B1C3	56.75	66.91
A2B1	57.20	62.11	A2C1	53.12	61.57	B2C1	51.75	61.05
A2B2	60.24	66.79	A2C2	61.02	67.80	B2C2	56.00	65.95
A2B3	58.35	70.21	A2C3	61.65	69.74	B2C3	58.46	68.86
A3B1	44.15	58.22	A3C1	42.65	55.46	B3C1	49.41	61.90
A3B2	44.80	59.07	A3C2	43.85	58.16	B3C2	56.69	67.37
A3B3	43.88	57.64	A3C3	46.32	61.31	B3C3	58.41	70.76
$LSD_{(0.05)}$	1.60	2.02	$LSD_{(0.05)}$	1.59	1.93	$LSD_{(0.05)}$	1.52	0.91
A×B×C								
A1B1C1	54.19	65.35	A2B1C1	54.85	56.88	A3B1C1	41.91	55.27
A1B1C2	60.53	69.27	A2B1C2	57.00	63.19	A3B1C2	44.50	58.68
A1B1C3	64.44	73.75	A2B1C3	59.76	66.25	A3B1C3	46.05	60.72
A1B2C1	55.88	63.95	A2B2C1	56.40	62.53	A3B2C1	42.98	56.67
A1B2C2	62.04	71.00	A2B2C2	61.24	67.89	A3B2C2	44.72	58.97
A1B2C3	65.59	75.06	A2B2C3	63.09	69.94	A3B2C3	46.69	61.57
A1B3C1	57.04	65.95	A2B3C1	48.12	65.29	A3B3C1	43.07	54.45
A1B3C2	62.88	72.96	A2B3C2	64.83	72.31	A3B3C2	42.35	56.84
A1B3C3	66.88	77.62	A2B3C3	62.11	73.04	A3B3C3	46.23	61.63
$LSD_{(0.05)}$	2.65	2.07	$LSD_{(0.05)}$	2.65	2.07	$LSD_{(0.05)}$	2.65	2.07

A1, A2, and A3 represent irrigation levels at 100%, 50%, and 30% of available water, respectively. B1 indicates no soil microbial application, B2 refers to soil application of Trichoderma (5 g plant^{-1}) plus Mycorrhiza (5 g plant^{-1}), while B3 includes Trichoderma (5 g plant^{-1}), Mycorrhiza (5 g plant^{-1}), and Bacillus (5 g plant^{-1}). C1 denotes no foliar application of amino acids, whereas C2 and C3 represent amino acid application rates of 2 and 4 kg ha^{-1}, respectively.

Leaf number and leaf area are key indicators of photosynthetic capacity. Water deficit conditions commonly induce stomatal closure and suppress leaf expansion, thereby reducing effective photosynthetic surface area and limiting CO_2 assimilation, which ultimately lowers dry matter accumulation [9,15]. Conversely, microbial inoculation improves plant water relations, osmotic adjustment, and nutrient availability [3]. Amino acids also play a critical role in nitrate assimilation and protein biosynthesis, reducing metabolic energy demands and enhancing vegetative growth performance [12].

ISSN 2072-3857

Table 4 Effect of variable irrigation, biostimulants and their interaction on average leaf area (cm^2. $plant^{-1}$)

Treatment	Spring	Fall	Treatment	Spring	Fall	Treatment	Spring	Fall
A1	3279.9	3417.1	B1	2618.9	2919.5	C1	2438.8	2835.2
A2	2800.6	3397.4	B2	2731.3	3216.9	C2	2740.5	3196.2
A3	2073.9	2637.6	B3	2804.1	3315.7	C3	2975.1	3420.7
$LSD_{(0.05)}$	148.4	72.20	$LSD_{(0.05)}$	33.25	16.40	$LSD_{(0.05)}$	35.86	13.10
A×B			A×C			B×C		
A1B1	3134.1	3187.1	A1C1	2928.0	3003.4	B1C1	2360.3	2526.5
A1B2	3277.9	3415.2	A1C2	3345.9	3508.2	B1C2	2586.6	3021.1
A1B3	3427.7	3649.1	A1C3	3565.7	3739.8	B1C3	2909.9	3210.9
A2B1	2657.4	3068.1	A2C1	2483.5	3048.6	B2C1	2486.5	2935.0
A2B2	2798.9	3559.1	A2C2	2776.3	3395.1	B2C2	2745.1	3268.9
A2B3	2945.5	3564.9	A2C3	3142.0	3748.5	B2C3	2959.4	3446.9
A3B1	2065.3	2503.2	A3C1	1904.9	2453.5	B3C1	2466.5	3044.0
A3B2	2117.3	2676.5	A3C2	2099.3	2685.4	B3C2	2889.7	3298.7
A3B3	2039.1	2733.0	A3C3	2217.5	2773.8	B3C3	3056.0	3604.3
$LSD_{(0.05)}$	145.2	70.64	$LSD_{(0.05)}$	144.9	70.68	$LSD_{(0.05)}$	58.91	23.88
A×B×C								
A1B1C1	2790.0	2744.6	A2B1C1	2400.8	2527.4	A3B1C1	1890.3	2307.5
A1B1C2	3172.2	3332.7	A2B1C2	2471.5	3180.8	A3B1C2	2115.9	2549.9
A1B1C3	3440.2	3484.1	A2B1C3	3100.0	3496.2	A3B1C3	2189.7	2652.3
A1B2C1	3032.4	3116.1	A2B2C1	2474.8	3168.9	A3B2C1	1961.4	2519.9
A1B2C2	3293.9	3460.2	A2B2C2	2793.7	3664.2	A3B2C2	2147.9	2682.4
A1B2C3	3507.3	3669.2	A2B2C3	3128.3	3844.3	A3B2C3	2242.5	2827.2
A1B3C1	2961.7	3149.4	A2B3C1	2574.9	3449.6	A3B3C1	1863.0	2533.1
A1B3C2	3571.5	3731.8	A2B3C2	3063.8	3340.3	A3B3C2	2033.9	2824.0
A1B3C3	3749.8	4066.2	A2B3C3	3197.8	3904.9	A3B3C3	2220.4	2481.9
$LSD_{(0.05)}$	156.38	72.67	$LSD_{(0.05)}$	156.38	72.67	$LSD_{(0.05)}$	156.38	72.67

A1, A2, and A3 represent irrigation levels at 100%, 50%, and 30% of available water, respectively. B1 indicates no soil microbial application, B2 refers to soil application of Trichoderma (5 g $plant^{-1}$) plus Mycorrhiza (5 g $plant^{-1}$), while B3 includes Trichoderma (5 g $plant^{-1}$), Mycorrhiza (5 g $plant^{-1}$), and Bacillus (5 g $plant^{-1}$). C1 denotes no foliar application of amino acids, whereas C2 and C3 represent amino acid application rates of 2 and 4 kg ha^{-1}, respectively.

Average Number of Marketable Tubers

The number of marketable tubers was significantly affected by irrigation treatments. Full and moderate irrigation levels produced the highest tuber numbers, whereas low irrigation markedly reduced tuber formation. In addition, soil application of microbial consortia, particularly dual or triple combinations, resulted in a significant

ISSN 2072-3857

increase in marketable tuber number in both seasons, Table 5.

Table 5 The role of variable irrigation, biostimulants and their interaction in the average number of marketable tubers (tuber.plant^{-1})

Treatment	Spring	Fall	Treatment	Spring	Fall	Treatment	Spring	Fall
A1	7.33	7.02	B1	6.67	6.50	C1	6.28	6.28
A2	7.36	7.30	B2	7.07	6.78	C2	7.00	6.57
A3	5.98	5.85	B3	6.93	6.59	C3	7.40	7.02
$LSD_{(0.05)}$	0.15	0.19	$LSD_{(0.05)}$	0.14	0.03	$LSD_{(0.05)}$	0.09	0.17
A×B			A×C			B×C		
A1B1	7.04	6.75	A1C1	6.67	6.36	B1C1	6.06	5.99
A1B2	7.44	7.25	A1C2	7.41	6.37	B1C2	6.79	6.50
A1B3	7.51	7.58	A1C3	7.90	7.44	B1C3	7.17	7.03
A2B1	7.11	6.74	A2C1	6.52	6.28	B2C1	6.48	6.70
A2B2	7.54	7.68	A2C2	7.56	6.91	B2C2	7.21	6.50
A2B3	7.45	7.33	A2C3	8.01	7.51	B2C3	7.53	7.05
A3B1	5.87	5.32	A3C1	5.63	5.59	B3C1	6.28	6.17
A3B2	6.25	6.46	A3C2	6.03	5.85	B3C2	7.00	6.62
A3B3	5.82	5.59	A3C3	6.27	6.14	B3C3	7.49	6.99
$LSD_{(0.05)}$	0.22	0.23	$LSD_{(0.05)}$	0.17	N.S	$LSD_{(0.05)}$	N.S	0.27
A×B×C								
A1B1C1	6.15	6.30	A2B1C1	6.40	6.19	A3B1C1	5.63	5.52
A1B1C2	7.16	6.93	A2B1C2	7.21	6.84	A3B1C2	6.02	5.73
A1B1C3	7.80	7.09	A2B1C3	7.73	7.97	A3B1C3	5.97	6.14
A1B2C1	6.96	6.70	A2B2C1	6.71	7.13	A3B2C1	5.78	6.12
A1B2C2	7.48	6.78	A2B2C2	7.66	6.98	A3B2C2	6.48	5.96
A1B2C3	7.87	6.63	A2B2C3	8.23	7.75	A3B2C3	6.49	6.70
A1B3C1	6.91	6.78	A2B3C1	6.44	6.61	A3B3C1	5.50	5.11
A1B3C2	7.59	7.06	A2B3C2	7.82	7.80	A3B3C2	5.60	5.77
A1B3C3	8.03	7.86	A2B3C3	8.08	7.99	A3B3C3	6.36	5.98
$LSD_{(0.05)}$	0.30	0.48	$LSD_{(0.05)}$	0.30	0.48	$LSD_{(0.05)}$	0.30	0.48

A1, A2, and A3 represent irrigation levels at 100%, 50%, and 30% of available water, respectively. B1 indicates no soil microbial application, B2 refers to soil application of Trichoderma (5 g plant^{-1}) plus Mycorrhiza (5 g plant^{-1}), while B3 includes Trichoderma (5 g plant^{-1}), Mycorrhiza (5 g plant^{-1}), and Bacillus (5 g plant^{-1}). C1 denotes no foliar application of amino acids, whereas C2 and C3 represent amino acid application rates of 2 and 4 kg ha^{-1}, respectively.

This improvement is mainly attributed to the ability of beneficial microorganisms to enhance water and nutrient uptake and stimulate root system development, thereby facilitating the translocation of photosynthates toward

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tuber formation [4]. Likewise, foliar application of amino acids, especially at the higher rate, promoted tuber number through improved vegetative growth and increased photosynthetic efficiency [14].

Marketable Yield

Marketable yield was significantly higher under full and moderate irrigation regimes compared with low irrigation, which caused a pronounced yield reduction (Table 6). The highest yield values were recorded when the complete microbial consortium was applied to the soil, while foliar spraying with amino acids at the high level further enhanced marketable yield across both growing seasons.

Table 6 The role of variable irrigation, biostimulants and their interaction in the average marketable yield (ton ha^{-1})

Treatment	Spring	Fall	Treatment	Spring	Fall	Treatment	Spring	Fall
A1	50.46	39.86	B1	42.91	31.30	C1	41.26	30.33
A2	50.01	39.78	B2	44.43	34.24	C2	45.32	35.47
A3	36.29	24.67	B3	49.42	38.78	C3	50.18	38.50
$LSD_{(0.05)}$	0.60	5.38	$LSD_{(0.05)}$	0.58	0.86	$LSD_{(0.05)}$	0.60	0.86
A×B			A×C			B×C		
A1B1	47.15	35.62	A1C1	44.41	34.11	B1C1	38.46	25.69
A1B2	48.41	38.99	A1C2	50.72	40.75	B1C2	43.51	33.12
A1B3	55.82	44.97	A1C3	56.25	44.72	B1C3	46.74	35.09
A2B1	48.68	36.41	A2C1	46.40	35.34	B2C1	41.01	30.96
A2B2	48.50	38.77	A2C2	49.46	41.06	B2C2	43.20	34.58
A2B3	52.83	43.17	A2C3	54.16	42.94	B2C3	49.07	37.17
A3B1	32.88	21.88	A3C1	32.98	21.55	B3C1	44.32	34.36
A3B2	36.38	23.96	A3C2	35.77	24.61	B3C2	49.24	38.72
A3B3	39.62	28.19	A3C3	40.12	27.86	B3C3	54.72	43.25
$LSD_{(0.05)}$	0.92	5.29	$LSD_{(0.05)}$	0.95	5.28	$LSD_{(0.05)}$	1.00	1.45
A×B×C								
A1B1C1	41.00	28.13	A2B1C1	45.70	28.93	A3B1C1	28.68	20.01
A1B1C2	48.99	37.19	A2B1C2	48.70	40.34	A3B1C2	32.85	21.83
A1B1C3	51.46	41.52	A2B1C3	51.65	39.95	A3B1C3	37.11	23.79
A1B2C1	42.46	35.39	A2B2C1	45.53	37.14	A3B2C1	35.04	20.34
A1B2C2	47.96	40.45	A2B2C2	47.53	39.24	A3B2C2	34.12	24.07
A1B2C3	54.81	41.13	A2B2C3	52.44	42.92	A3B2C3	39.98	27.47
A1B3C1	49.76	38.80	A2B3C1	47.97	39.97	A3B3C1	35.23	24.31
A1B3C2	55.22	44.61	A2B3C2	52.14	43.59	A3B3C2	40.35	27.95
A1B3C3	62.49	51.50	A2B3C3	58.39	45.96	A3B3C3	43.28	32.30
$LSD_{(0.05)}$	1.70	5.30	$LSD_{(0.05)}$	1.70	5.30	$LSD_{(0.05)}$	1.70	5.30

A1, A2, and A3 represent irrigation levels at 100%, 50%, and 30% of available water, respectively. B1 indicates no soil microbial application, B2 refers to soil application of

ISSN 2072-3857

Trichoderma (5 g plant^{-1}) plus Mycorrhiza (5 g plant^{-1}), while B3 includes Trichoderma (5 g plant^{-1}), Mycorrhiza (5 g plant^{-1}), and Bacillus (5 g plant^{-1}). C1 denotes no foliar application of amino acids, whereas C2 and C3 represent amino acid application rates of 2 and 4 kg ha^{-1}, respectively.

Yield reduction under water-limited conditions can be attributed to intensified water stress, which restricts root expansion and stolon development, in addition to decreasing tuber number and individual tuber weight. This decline is often associated with reduced leaf area and chlorophyll content, leading to lower dry matter accumulation [21]. These results align with previous reports [21,7] that emphasize the high sensitivity of potato plants to water stress, particularly during tuber initiation and bulking stages.

Non-Marketable Yield

Non-marketable yield exhibited significant variation in response to irrigation levels and treatment interactions. Certain treatments, especially those associated with excessive or unbalanced vegetative growth, led to an increase in non-marketable tubers (Table 7). In contrast, foliar application of amino acids at the higher concentration contributed to a reduction in this yield fraction, reflecting an overall improvement in tuber quality.

Table 7 The role of variable irrigation, biostimulants and their interaction in the average yield of unmarketable crop (ton ha^{-1})

Treatment	Spring	Fall	Treatment	Spring	Fall	Treatment	Spring	Fall
A1	1.24	1.13	B1	1.25	0.85	C1	1.35	0.92
A2	1.30	0.75	B2	1.24	0.89	C2	1.20	0.89
A3	1.12	0.75	B3	1.17	0.89	C3	1.11	0.82
$LSD_{(0.05)}$	N.S	0.03	$LSD_{(0.05)}$	N.S	N.S	$LSD_{(0.05)}$	0.11	0.02
A×B			A×C			B×C		
A1B1	1.20	0.99	A1C1	1.29	1.12	B1C1	1.44	0.95
A1B2	1.33	1.13	A1C2	1.26	1.20	B1C2	1.14	0.83
A1B3	1.20	1.27	A1C3	1.18	1.07	B1C3	1.18	0.77
A2B1	1.37	0.80	A2C1	1.51	0.83	B2C1	1.35	0.93
A2B2	1.28	0.77	A2C2	1.26	0.73	B2C2	1.26	0.90
A2B3	1.27	0.68	A2C3	1.15	0.69	B2C3	1.12	0.86
A3B1	1.19	0.76	A3C1	1.25	0.82	B3C1	1.26	0.90
A3B2	1.12	0.78	A3C2	1.10	0.74	B3C2	1.22	0.94
A3B3	1.04	0.72	A3C3	1.00	0.70	B3C3	1.03	0.84
$LSD_{(0.05)}$	N.S	0.10	$LSD_{(0.05)}$	N.S	0.04	$LSD_{(0.05)}$	N.S	0.07
A×B×C								
A1B1C1	1.25	1.02	A2B1C1	1.69	0.95	A3B1C1	1.38	0.88
A1B1C2	1.16	1.00	A2B1C2	1.14	0.77	A3B1C2	1.13	0.73
A1B1C3	1.19	0.95	A2B1C3	1.27	0.68	A3B1C3	1.07	0.67

ISSN 2072-3857

A1B2C1	1.47	1.21	A2B2C1	1.46	0.78	A3B2C1	1.12	0.79
A1B2C2	1.31	1.14	A2B2C2	1.32	0.77	A3B2C2	1.14	0.79
A1B2C3	1.22	1.05	A2B2C3	1.07	0.76	A3B2C3	1.10	0.75
A1B3C1	1.14	1.13	A2B3C1	1.38	0.77	A3B3C1	1.25	0.79
A1B3C2	1.31	1.47	A2B3C2	1.32	0.66	A3B3C2	1.02	0.69
A1B3C3	1.15	1.20	A2B3C3	1.10	0.63	A3B3C3	0.85	0.69
$LSD_{(0.05)}$	N.S	0.11	$LSD_{(0.05)}$	N.S	0.11	$LSD_{(0.05)}$	N.S	0.11

A1, A2, and A3 represent irrigation levels at 100%, 50%, and 30% of available water, respectively. B1 indicates no soil microbial application, B2 refers to soil application of Trichoderma (5 g plant^{-1}) plus Mycorrhiza (5 g plant^{-1}), while B3 includes Trichoderma (5 g plant^{-1}), Mycorrhiza (5 g plant^{-1}), and Bacillus (5 g plant^{-1}). C1 denotes no foliar application of amino acids, whereas C2 and C3 represent amino acid application rates of 2 and 4 kg ha^{-1}, respectively.

Conclusion

Severe deficit irrigation substantially reduced potato productivity. However, integrating moderate water deficit with soil inoculation using Trichoderma, arbuscular mycorrhizal fungi, and Bacillus, alongside foliar amino acid application, synergistically enhanced growth, increased marketable yield, and improved irrigation water-use efficiency, offering a sustainable strategy for potato production under water-limited conditions.

ISSN 2072-3857

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ISSN 2072-3857