Journal of Agricultural Science; Vol. 17, No. 4; 2025
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Evaluating the Impact of S8 Matrix Nutrition on Quantitative Traits of New Potato Cultivars Under Water Stress

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Received: December 21, 2024 Accepted: February 5, 2025 Online Published: March 15, 2025

doi:10.5539/jas.v17n4p104 URL: https://doi.org/10.5539/jas.v17n4p104

Abstract

This study aimed to enhance the tuber yield of potato (*Solanum tuberosum*) cultivars using a sulfonated silicon nutrient solution enriched with additional nutrition, referred to as S8 Matrix. The research also sought to identify the most effective application method for this nutrient solution under both water deficit stress and normal irrigation conditions. The experiment was conducted over two years (2022 and 2023) at the Ardabil Potato Research Station, utilizing a split factorial design based on a randomized complete block design with three replications.

The main experimental factors included irrigation levels (100%, 75%, and 50% of the plant available water), foliar application of the nutrient solution at four plant growth stages, and three potato cultivars (Agria, Rona, and Takta). Key traits such as plant height, number of main stems per plant, tuber number, tuber weight per plant, tuber yield, and water use efficiency were evaluated.

Analysis of variance revealed significant differences among irrigation levels, nutrient solution treatments, and cultivars, as well as their interactions. Foliar spraying with the sulfonated silicon nutrient solution containing S8 Matrix (at a concentration of 3 liters per 1,000 liters of water) during the flowering, tuber formation, and tuber bulking stages notably improved tuber yield and water use efficiency, with the Takta cultivar demonstrating the highest performance.

Keywords: quantitative traits, S8 Matrix nutrition, silicon, *Solanum tuberosum*, sulfur, water stress

1. Introduction

The growing competition in global markets for grains and other agricultural products has exacerbated food price volatility, heightening the risk of food shortages and social unrest, particularly in low-income countries. One effective strategy to mitigate these risks is focusing on the production of essential and nutritious crops such as potatoes. Iran ranks as the 13th largest potato producer globally (Food and Agriculture Organization [FAO], 2021).

According to Iran's Ministry of Agriculture-Jahad, the country cultivated approximately 142,000 hectares of potatoes in 2020, producing 5.3 million tons with an average yield of 37 tons per hectare (Ministry of Agriculture-Jahad, 2022). Per capita potato consumption in Iran is currently 56 kg and is projected to increase to 63 kg by 2027 (Kazemi, Banayan Aval, & Ghorbani, 2016). To meet this growing demand, improved agricultural practices and scientific innovations are critical. Despite advancements, global food production has only increased by 20% in the last three decades, whereas developing countries need to boost food production by 70% by 2030 to meet population growth demands (FAO, 2021).

1.1 Water Stress and Potato Production

Water deficit stress is a significant environmental factor limiting crop productivity and natural vegetation growth. Although potatoes are relatively water-efficient, water stress severely affects tuber yield and quality (Sun, Cui, & Liu, 2015). Climate change further intensifies this issue, with its variable impacts across regions, threatening global potato production (Arnell & Reynard, 1996).

In Iran, prolonged droughts have drastically reduced underground water levels and surface water availability in many fertile plains, increasing pressure to reduce agricultural water consumption and allocate more for domestic and industrial purposes (Hassanpanah, Gurbanov, Gadimov, & Shahriari, 2008). Climate change is already impacting irrigated agriculture, leading to increased water demand and reduced availability in critical areas (Lorenzo, 2022).

As agriculture is the largest water consumer, even minor reductions in irrigation can significantly impact resource allocation (Neocleous & Savvas, 2022). However, water stress in fertilized fields can induce nutrient deficiencies, as soil physicochemical properties limit nutrient mobility and uptake (Amtmann & Blatt, 2009). Micronutrient fertilization has proven effective in mitigating water stress effects (Ahmed et al., 2022), with strategies involving exogenous nutrient applications showing potential to alleviate nutrient deficits under such conditions (Choudhary, Patel, & Pagar, 2014).

Water stress in potato plants results in reduced fresh and dry biomass (Farooq, Wahid, Kobayashi, Fujita, & Basra, 2009), decreased leaf area development (Shao, Chu, Lu, & Kagn, 2008), reduced photosynthesis and dry matter production (Nayyar & Gupta, 2006), and impaired tuber growth (Ierna & Mauromicale, 2012). Other adverse effects include lower harvest index, diminished tuber dry matter, and fewer tubers per plant (Schittenhelma, Sourell, & Lopmeierc, 2006).

1.2 Nutrient Role in Enhancing Stress Tolerance

The S8 Matrix nutrient solution used in this study contains 60% sulfur compounds, 2% silicon, 20% potassium, 3% nitrogen, 2500 ppm iron, and 200 ppm zinc. Sulfur enhances plant resistance to diseases, drought, and cold, while reducing nitrate accumulation (Kaya, Tuna, & Higgs, 2006). Elemental sulfur improves nitrogen efficiency and boosts potato tuber yields under water deficit conditions during critical growth stages (Potarzycki & Wendel, 2023).

Potassium, essential for crop quality and quantity, strengthens resistance to drought, salinity, and diseases, particularly under water-limited conditions (Xu et al., 2021). Studies show that combining sulfur with beneficial microorganisms like Thiobacillus significantly improves tuber yield, tuber number, and nutrient content (Golmoradi Marani et al., 2017). Foliar application of silicon further enhances tuber yield and water use efficiency (Kaya et al., 2006; Gerami & Torabipour, 2021).

1.3 Silicon's Multifaceted Benefits

Silicon plays a pivotal role in improving crop yield and stress resistance, including tolerance to heat, cold, drought, and salinity (Kaya et al., 2006; Wang et al., 2016). It enhances nitrogen fixation (Epstein, 2009), antioxidant enzyme activity (Kaya et al., 2006), and calcium absorption under drought conditions (Kaplan & Orman, 1998). Silicon also increases resistance to diseases and pests, improves seed germination, enhances soil fertility, and mitigates damage from salinity (Ma, 2004; Van Bockhaven et al., 2013).

1.4 Objective

This research aimed to improve tuber yield and water use efficiency in potato crops through the application of a sulfonated silicon nutrient solution with elemental sulfur (S8 Matrix) during the 2022 and 2023 growing seasons.

2. Method

2.1 Description of the Study Area

The research was conducted at the Potato Research Station in Ardabil Province, Iran, during the growing seasons of 2022 and 2023. The experimental site is located at 48°17′35.88″ E longitude and 38°14′59.28″ N latitude. The region receives an average annual rainfall of 310 mm, with recorded temperatures ranging from a minimum 1.98 °C to a maximum 21.58 °C.

Soil and water analyses revealed that the soil at the experimental site has a pH of 7.7, while the irrigation water has a pH of 7.1. The soil texture is classified as loamy clay according to the USDA texture triangle, with low organic matter content (0.7%).

2.2 Soil and Water Properties

The detailed physicochemical properties of the soil and water used in the experiment are summarized in Table 1.

Table 1. Physicochemical properties of the soil and water at the experimental site

Description	**Soil**	**Water**
Salinity	1.25 dS m^{-1}	1500 µS cm^{-1}
pH	7.64	7.66
Saturation (%)	29	-
Calcium oxide (%)	7.50	-
Texture	Clay-loam	-
Organic Carbon (%)	0.97	-
Total Nitrogen (%)	0.10	-
Absorbable P (mg kg^{-1})	3.40	-
Potassium (mg kg^{-1})	230	-
Zinc (mg kg^{-1})	1.22	-
Iron (mg kg^{-1})	3.22	-
Copper (mg kg^{-1})	3.20	-
Manganese (mg kg^{-1})	4.20	-
Carbonate (mg kg^{-1})	-	0
Bicarbonate (mg kg^{-1})	-	382
Sulfate (mg kg^{-1})	-	155
Chlorine (mg kg^{-1})	-	195
Sodium (mg kg^{-1})	-	123.98
Calcium (mg kg^{-1})	-	118
Magnesium (mg kg^{-1})	-	44.2
SAR (Sodium Adsorption Ratio)	-	2.46
TDS (mg L^{-1})	-	75
Total Hardness (mg L^{-1})	-	480

This description provides a comprehensive overview of the study's environmental conditions and soil-water characteristics, which form the basis for interpreting the results.

2.3 Treatments and Experimental Design

The field experiment employed a factorial design with three factors, each tested at multiple levels:

(1) Irrigation Levels:

100% of the plant available water;

75% of the plant available water;

50% of the plant available water.

(2) Foliar Spraying with Nutrient Solution:

Stage 1: Beginning of flowering;

Stage 2: Beginning of flowering and tuber formation;

Stage 3: Beginning of flowering, tuber formation, and tuber bulking;

Stage 4: Control (no nutrient solution applied).

(3) Potato Varieties:

Agria;

Rona;

Takta.

(4) Nutrient Solution:

The S8 Matrix nutrition solution, containing elemental sulfur (S8), was applied at a concentration of 3 liters per 1,000 liters of water. The solution composition includes:

60% Sulfur;

2% Silicon;

20% Potassium;

3% Nitrogen;

2,500 ppm Iron;

200 ppm Zinc.

The nutrient solution is registered with the Soil and Water Institute under registration number 08492 and certificate number 8342/243 (dated January 15, 2020).

(5) Experimental Setup:

Plots were 5 meters long, and two rows, with furrow planting at a density of 75 × 25 cm and a planting depth of 10 cm. Drip irrigation was employed. All standard field practices—irrigation, weeding, pest control, and disease management—were uniformly applied.

(6) Weed and Pest Management:

Weeds: Treated with 4 liters of Paraquat and 250 ml of Sencor per hectare;

Colorado Potato Beetle: Controlled with 250 ml of Confidor (Imidacloprid) per hectare;

Earthling up: Conducted in two stages.

(7) Fertilization Schedule:

Urea Fertilizer: 250 kg/ha applied in three stages—planting, weeding, and earthling up;

Ammonium Phosphate Fertilizer: 100 kg/ha applied in two stages—50% at planting and 50% during tuberization;

Potassium Sulfate Fertilizer: 100 kg/ha applied at planting, based on soil test recommendations.

(8) Irrigation Calculations:

Water application was based on crop growth stages and water requirements. Parameters included:

Field Capacity (FC): 29.1%;

Permanent Wilting Point (PWP): 14.6%;

Soil Density: 1 g cm^{-3};

Available Water (AW): 18.705%;

Raw Water (RAW): 6.547%;

The Maximum Allowable Depletion (MAD) was set at 0.35, triggering irrigation when soil moisture depletion reached 35% of the total available water.

(9) Irrigation Monitoring:

Soil moisture levels were monitored using a PMS-714 portable hygrometer (manufactured in Taiwan). Irrigation commenced when soil moisture dropped to 21.147%, ensuring optimal plant hydration while avoiding overwatering.

(10) Calculations:

(a) Available Water (AW)

$$AW\ (\theta) = (\theta fc - \theta pwp)/100 \times BD \tag{1}$$

Substituting values: $AW\,(\theta) = (29.1 - 14.6)/100 \times 1.29 = 18.705\%$.

(b) Raw Water (RAW)

$$RAW = AW \times MAD \tag{2}$$

Substituting values: $RAW = 18.705 \times 0.35 = 6.547\%$.

(c) Soil Moisture (%)

$$\text{Soil Moisture } (\%) = RAW + PWP \tag{3}$$

Substituting values: *Soil Moisture* (%) = 6.547 + 14.6 = 21.147%.

The amount of available water and the water consumption for the studied treatments are presented in Tables 2 and 3, respectively.

Table 2. The amount of available water at different growth stages: planting, beginning of tuberization, and tuber harvest

Stages	First Stage	Second Stage	Difference
Planting	Fc * Root development in planting stage * 1 ha = 582 m^3/ha	Soil moisture at the beginning of irritation * Root development in planting stag * 1 ha = 423 m^3/ha	582 − 423 = 159 m^3/ha
Planting-Beginning of Tuberization	Fc * Root development in planting-beginning of tuberization stage * 1 ha = 873 m^3/ha	Soil moisture at the beginning of irritation * Root development in planting-beginning of tuberization stage * 1 ha = 634 m^3/ha	873 − 634 = 239 m^3/ha
Beginning of Tuberogenesis-Harvesting of the Tubers	Fc * Root development at the beginning of tuberogenesis-harvesting of the tubers stage * 1 ha = 1455 m^3/ha	Soil moisture at the beginning of irritation * Root development at the beginning of tuberogenesis-harvesting of the tubers stage * 1 ha = 740 m^3/ha	1455 – 740 = 715 m^3/ha

Table 3. Water consumption during planting, tuberization onset, and tuber harvesting

Stages	100% of the Plant's Available Water (m^3/ha)	75% of the Plant's Available Water (m^3/ha)	50% of the Plant's Available Water (m^3/ha)
Planting	160	120	80
Planting-Beginning of Tuberization	240	180	120
Beginning of Tuberogenesis-Harvesting of the Tubers	715	540	358

During the growth period, various parameters were measured, including plant height, number of main stems per plant, tuber number and weight per plant, and tuber yield. For data analysis, the Kolmogorov-Smirnov test was used to assess data distribution normality. Bartlett's test was applied to examine homogeneity of variance using SPSS. Analysis of variance (ANOVA) was conducted with SAS 9.1 statistical software. The least significant difference (LSD) was calculated at a 5% significance level to compare means for significant effects. Factor analysis was performed using Minitab 16 software.

3. Results

The results of the combined analysis of variance indicated significant differences between the different levels of water stress, nutrient solution treatments, cultivars, and the interaction effects of water stress and nutrient solution. Furthermore, significant interactions were observed between water stress, nutrient solution, and cultivars for the number of tubers per plant, tuber weight per plant, tuber yield, plant height, the number of main stems per plant, and water use efficiency.

Additionally, the interaction of nutrient solution and cultivars significantly affected tuber number per plant, tuber weight per plant, tuber yield, number of main stems per plant, and water use efficiency. The interaction of year, water stress, and cultivars had significant effects on tuber yield and water use efficiency, while the interaction of year, nutrient solution, and cultivars significantly affected the number of tubers per plant, tuber weight per plant, and water use efficiency. Moreover, the interaction between

water stress and cultivars significantly affected the number of tubers per plant, tuber yield, and the number of main stems per plant.

Furthermore, the interaction of year, water stress, nutrient solution, and the interaction of year and water stress showed significant differences for tuber weight per plant, tuber yield, and water use efficiency. The probability of one specific test showed significant differences at the 1% and 5% levels (data not shown).

Tuber yield and tuber weight per plant in the 'Takta' cultivar were highest in treatments with a nutrient solution of 3 liters per thousand, applied during all three stages: flowering, tuber formation, and tuber bulking, under the condition of 100% plant available water. These treatments were placed in group A. 'Takta' also showed the highest tuber yield and tuber weight per plant in treatments with nutrient solution during two stages (flowering and tuber formation) under 75% plant available water, and in all three stages under 50% plant available water (Table 4).

The highest number of tubers per plant was observed in the 'Rona' cultivar, particularly in treatments with a nutrient solution during all three stages of flowering, tuber formation, and tuber bulking, under the condition of 100% plant available water, placing it in group A (Table 4).

In terms of plant height, 'Takta' exhibited the tallest plants when treated with a nutrient solution of 3 liters per thousand during all three stages (flowering, tuber formation, and tuber bulking) under 100% available water, and these treatments were placed in group A. The highest number of main stems per plant was observed in 'Takta', particularly in treatments with nutrient solution during the flowering stage, two stages (flowering and tuber formation), and all three stages (flowering, tuber formation, and tuber bulking) under 50%, 75%, and 100% plant available water. Finally, the highest water use efficiency was recorded for 'Takta' in treatments with a nutrient solution during all three stages under both 50% and 100% plant available water, and during two stages (flowering and tuber formation) under 75% available water (Table 4).

Table 4. Mean Comparison of traits across different levels of available water, nutrient solution, and potato cultivars

Available water	**Spraying of nutrient solution**	**Cultivars**	**Tuber number per plant**	**Tuber weight per plant (g)**	**Tuber yield (t ha^{-1})**
Flowering stage, normal (100% of the plant's available water)	Agria	734.5	ijklm	38.93	jklmno
Normal (100%)	Rona	897.6	cde	47.57	cdef
Normal (100%)	Takta	860.7	defg	50.61	bcd
Flowering and tuber formation stages, normal (100%)	Agria	810.4	fghi	42.95	ghij
Normal (100%)	Rona	919	cd	48.71	cde
Normal (100%)	Takta	956.4	bc	50.69	bc
Flowering, tuber formation, and bulking stages, normal (100%)	Agria	867.2	def	45.96	defg
Normal (100%)	Rona	1023	b	54.23	b
Normal (100%)	Takta	1185	a	62.8	a
Control (no nutrient solution)	Agria	601.5	qrs	36.88	lmnopq
Control (no nutrient solution)	Rona	698.1	jklmno	42	ghijk
Control (no nutrient solution)	Takta	754.4	hijkl	45.61	defgh
Flowering stage, Mild Stress (75%)	Agria	660.7	mnopq	35.02	opqr
Mild Stress (75%)	Rona	773.4	hijk	40.99	ijklm
Mild Stress (75%)	Takta	788.7	ghij	41.27	hijkl
Flowering and tuber formation stages, mild stress	Agria	688.8	lmnop	36.51	nopqr
Mild Stress (75%)	Rona	836.8	defgh	44.35	efghi
Mild Stress (75%)	Takta	936.8	bc	51.08	bc
Flowering, tuber formation, and bulking stages, mild stress	Agria	719.4	jklmn	38.13	klmnop
Mild Stress (75%)	Rona	824.4	efgh	43.69	fghi
Mild Stress (75%)	Takta	860.1	defg	45.59	efgh
Control (no nutrient solution)	Agria	Agria	Agria	33.79	pqr
Control (no nutrient solution)	Rona	694.7	klmno	36.82	mnopq
Control (no nutrient solution)	Takta	758.8	hijkl	40.22	ijklmn
Flowering stage, Severe Stress (50%)	Agria	523.6	st	27.75	tu
Severe Stress (50%)	Rona	685.1	lmnop	36.31	nopqr
Severe Stress (50%)	Takta	623	opqr	33.02	qrs
Flowering and tuber formation stages, severe stress	Agria	606.8	pqr	32.17	rs
Severe Stress (50%)	Rona	655.9	mnopq	34.76	opqr
Severe Stress (50%)	Takta	735.2	ijklm	38.97	jklmno
Flowering, tuber formation, and bulking stages, severe stress	Agria	620.8	opqr	32.9	qrs
Severe Stress (50%)	Rona	726	jklm	38.48	klmno
Severe Stress (50%)	Takta	723.4	jklm	38.34	klmno
Control (no nutrient solution)	Agria	456	t	24.17	u
Control (no nutrient solution)	Rona	552.8	rs	29.3	st
Control (no nutrient solution)	Takta	610.4	pqr	32.35	rs

Note. * Means followed by similar letters are not significantly different at the 5% probability level, using the LSD test.

All table data have been prepared based on: 1-LSD test; 2-Using SAS software version 9.1.

Table 4 continued. Mean comparisons for water use efficiency, main stem number, plant height, cultivars, nutrient solutions, and water levels into a unified format

Available water	**Spraying of nutrient solution**	**Cultivars**	**Plant height (cm)**	**Number of main stems per plant**	**Water efficiency (kg m^{-3})**
Agria	f-m	3.33	de	8.06	mno
Rona	b-h	3.67	cd	10.18	c-g use
Takta	b-e	4.33	ab	9.74	d-i
Agria	b-f	3	e	9.05	h-m
Rona	c-k	3	e	10.36	c-f
Takta	bc	4.33	ab	10.65	cd
Agria	b	3.67	cd	10.57	cde
Rona	bcd	3.67	cd	12.22	b
Takta	a	4.67	a	14.44	a
Agria	h-m	3	e	6.34	p
Rona	h-m	3	e	7.22	op
Takta	f-l	3	e	8.59	j-n
Agria	k-n	3	e	8.06	mno
Rona	g-m	3	e	9.5	e-k
Takta	b-j	4.33	ab	9.57	d-j
Agria	i-n	3.67	cd	8.78	i-n
Rona	e-l	4	bc	10.5	cde
Takta	b-e	4.67	a	12.15	b
Agria	b-j	3	e	9.03	h-m
Rona	d-l	3.67	cd	10.45	cde
Takta	c-l	4.5	a	10.91	c
Agria	no	3	e	7.47	no
Rona	mno	3	e	8.43	k-n
Takta	g-m	3.33	de	9.21	g-l
Agria	mno	3.67	cd	7.29	op
Rona	j-n	3.67	cd	9.27	f-l
Takta	e-l	4.33	ab	8.81	i-n
Agria	lmn	3	e	8.67	i-n
Rona	h-m	3	e	9.48	e-k
Takta	b-g	4.67	a	10.52	cde
Agria	b-i	4	bc	9.61	d-j
Rona	h-m	3	e	11.17	bc
Takta	c-k	4.67	a	11.15	bc
Agria	o	3	e	8.31	l-o
Rona	o	3	e	10.07	c-h
Takta	o	3	e	8.81	i-n

Note. * Means followed by similar letters are not significantly different at the 5% probability level, using the LSD test.

All table data have been prepared based on: 1-LSD test; 2-Using SAS software version 9.1.

3.1 Results Obtained in 2022 and 2023

3.1.1 Tuber Yield and Tuber Weight per Plant

2022: The highest tuber yield and tuber weight per plant were observed in treatments with a nutrient solution of 3 liters per thousand liters during all three stages (flowering, tuber formation, and tuber bulking) under 100% plant available water. These were also the highest in treatments during two stages (flowering and tuber formation) under 50% and 75% plant available water.

2023: The highest tuber yield and tuber weight per plant were recorded in treatments with a nutrient solution during both two stages (flowering and tuber formation) and all three stages (flowering, tuber formation, and tuber bulking) under 50%, 75%, and 100% plant available water.

3.1.2 Plant Height, Number of Main Stems per Plant, and Water Use Efficiency

2022: The highest values for plant height, number of main stems per plant, and water use efficiency were recorded in treatments with a nutrient solution during all three stages (flowering, tuber formation, and tuber bulking) under 50% and 100% plant available water. These traits were also highest in treatments during two stages (flowering and tuber formation) under 50% and 75% plant available water.

2023: Similar to 2022, the highest values for these traits were observed in treatments with a nutrient solution during all three stages (flowering, tuber formation, and tuber bulking) under 50%, 75%, and 100% plant available water.

3.1.3 Number of Tubers per Plant

Both 2022 and 2023: The highest number of tubers per plant was found in treatments with a nutrient solution during both two stages (flowering and tuber formation) and all three stages (flowering, tuber formation, and tuber bulking) under 50%, 75%, and 100% plant available water (Table 5).

These findings highlight the importance of nutrient application timing and water availability for optimizing potato growth, tuber yield, and overall plant health. The results suggest that providing a balanced nutrient solution at key stages of growth, especially under different water stress conditions, significantly enhances various growth parameters and yields across both years of study.

Table 5. Mean Comparison of traits across different levels of available water and nutrient solution in 2022 and 2023

Year	Available water	Spraying of nutrient solution	Tuber number per plant	Tuber weight per plant (g)	Tuber yield (t ha^{-1})
2022	Normal (100% of the plant's available water)	Flowering stage	6 b	803.5 gh	42.59 cdefg
		The stages of flowering and tuber formation	6.67 a	870.4 d	46.13 bc
		The stages of flowering, tuber formation and bulking	7 a	1048 a	55.54 a
		Control (no nutrient solution)	4.67 d	779.1 hi	41.29 defg
	Mild Stress (75% of the plant's available water)	Flowering stage	4.67 d	728.4 k	38.61 ghi
		The stages of flowering and tuber formation	5.33 c	833.4 ef	44.17 cde
		The stages of flowering, tuber formation and bulking	5.22 cd	771.6 ij	40.19 efg
		Control (no nutrient solution)	4.75 cd	724.9 k	38.32 ghi
	Severe Stress (50% of the plant's available water)	Flowering stage	4 e	560.2 n	29.69 l
		The stages of flowering and tuber formation	5 cd	609.4 m	32.3 kl
		The stages of flowering, tuber formation and bulking	5 cd	643.6 l	34.11 jk
		Control (no nutrient solution)	4.67 d	539.8 n	28.61 l
2023	Normal (100% of the plant's available water)	Flowering stage	6.89 a	858.3 de	45.49 bcd
		The stages of flowering and tuber formation	6.67 a	920.1 c	48.77 b
		The stages of flowering, tuber formation and bulking	7 a	1002 b	83.12 a
		Control (no nutrient solution)	4.67 d	590.4 m	44.63 bcde
	Mild Stress (75% of the plant's available water)	Flowering stage	4.67 d	746.8 jk	39.58 fgh
		The stages of flowering and tuber formation	5.33 c	826.2 fg	43.79 cdef
		The stages of flowering, tuber formation and bulking	5.33 c	831 f	44.04 cde
		Control (no nutrient solution)	4.67 d	669.1 l	35.46 hijk
	Severe Stress (50% of the plant's available water)	Flowering stage	4 e	660.9 l	35.03 ijk
		The stages of flowering and tuber formation	5 cd	722.6 k	38.3 ghij
		The stages of flowering, tuber formation and bulking	5 cd	736.5 k	39.03 ghi
		Control (no nutrient solution)	4.67 d	539.8 n	28.61 l

Note. * Means followed by similar letters are not significantly different at the 5% probability level, using the LSD test.

All table data have been prepared based on: 1-LSD test; 2-Using SAS software version 9.1.

Table 5 continued. Mean comparison of traits across different levels of available water and nutrient solution in 2022 and 2023

Year	Available water	Spraying of nutrient solution	Plant height (cm)	Number of main stems per plant	Water use efficiency (kg m^{-3})
2022	Normal (100% of the plant's available water)	flowering stage	67.22 bc	3.78 abc	7.32 fgh
		the stages of flowering and tuber formation	71.22 b	3.44 cde	7.93 efgh
		the stages of flowering, tuber formation and bulking	80.33 a	4 ab	9.54 bcdefg
		control (no nutrient solution)	63.67 cd	3 e	7.1 gh
	Mild stress (75% of the plant's available water)	flowering stage	64.33 cd	3.44 cde	8.58 defgh
		the stages of flowering and tuber formation	66.56 bcd	4.11 a	10.12bcde
		the stages of flowering, tuber formation and bulking	68.78 bc	3.56 bcd	9.37 cdefg
		control (no nutrient solution)	60.11 d	3.11 de	8.8 defgh
	Severe Stress (50% of the plant's available water)	flowering stage	63.22 cd	3.89 abc	10.21bcde
		the stages of flowering and tuber formation	65.67 bcd	3.56 bcd	11.1 bcd
		the stages of flowering, tuber formation and bulking	67.56 bc	3.89 abc	11.72bc
		control (no nutrient solution)	52.2 e	3 e	9.83 bcdef
2023	Normal (100% of the plant's available water)	flowering stage	71.56 b	3.78 abc	11.33bcd
		the stages of flowering and tuber formation	71.78 b	3.44 cde	12.11b
		the stages of flowering, tuber formation and bulking	81.22 a	4 ab	15.28a
		control (no nutrient solution)	65.89 bcd	3 e	7.67 efgh
	Mild Stress (75% of the plant's available water)	flowering stage	66.67 bcd	3.44 cde	9.25 cdefgh
		the stages of flowering and tuber formation	67.78 bc	4.11 a	10.83bcd
		the stages of flowering, tuber formation and bulking	67.67 bc	3.56 bcd	10.88bcd
		control (no nutrient solution)	60.22 d	3.11 de	8.12 efgh
	Severe Stress (50% of the plant's available water)	flowering stage	62.44 cd	3.89 abc	6.71 h
		the stages of flowering and tuber formation	65.44 bcd	3.56 bcd	8.01 efgh
		the stages of flowering, tuber formation and bulking	68.11 bc	3.89 abc	9.56 bcdefg
		control (no nutrient solution)	53.29 e	3 e	9.83 bcdef

Note. [*] Means followed by similar letters are not significantly different at the 5% probability level, using the LSD test.

All table data have been prepared based on: 1-LSD test; 2-Using SAS software version 9.1.

3.2 Quantitative Observations

In both 2022 and 2023, the 'Rona' and 'Takta' cultivars consistently exhibited the highest tuber yield, tuber number, and tuber weight across all irrigation levels (50%, 75%, and 100% plant available water). This suggests that these cultivars are highly productive under varying water availability conditions.

3.2.1 Plant Height, Number of Main Stems per Plant, and Water Use Efficiency

2022: 'Takta' exhibited the highest plant height, number of main stems per plant, and water use efficiency under all irrigation levels (50%, 75%, and 100% plant available water). 'Rona' showed the highest values for these traits specifically under the 50% plant available water condition, suggesting it may be better adapted to more water-limited environments in that year.

2023: 'Takta' again exhibited the highest plant height, number of main stems per plant, and water use efficiency across all levels of plant available water (50%, 75%, and 100%). This indicates that 'Takta' is consistently more efficient in its growth and water use over time.

In summary, the 'Takta' cultivar demonstrated overall superior growth and water use efficiency in both years, while 'Rona' showed advantages under reduced water availability in 2022. Both cultivars performed well across varying water availability conditions (Table 6).

Table 6. Mean Comparison of Traits Across Different Levels of Available Water and Potato Cultivars in 2022 and 2023

Year	Available water	Cultivars	Tuber number per plant	Tuber weight per plant (g)	Tuber yield (t ha^{-1})
2022	normal (100% of the plant's available water)	Agria	5.5 c	774.3 de	41.04 e
		Rona	6.75 a	905.9 ab	48.01 bc
		Takta	6 b	945.4 a	50.11 b
	Mild Stress (75% of the plant's available water)	Agria	4.83 def	656.5 ghi	34.8 fgh
		Rona	5 de	782.3 de	41.46 e
		Takta	5.17 cde	855 bc	45.31 cd
	Severe Stress (50% of the plant's available water)	Agria	4.5 f	525 k	27.83 j
		Rona	4.75 ef	601.5 ij	31.88 hi
		Takta	4.75 ef	638.2 hi	33.82 gh
2023	normal (100% of the plant's available water)	Agria	6.17 b	732.5 ef	41.32 e
		Rona	6.75 a	863 bc	48.24 bc
		Takta	6 b	933 a	54.45 a
	Mild Stress (75% of the plant's available water)	Agria	4.75 ef	696.6 fgh	36.92 fg
		Rona	5 de	782.3 de	41.46 e
		Takta	5.25 cd	825.8 cd	43.77 de
	Severe Stress (50% of the plant's available water)	Agria	4.5 f	578.6 jk	30.67 ij
		Rona	4.75 ef	708.4 fg	37.55 f
		Takta	4.75 ef	707.8 fg	37.51 f

Note. [*] Means followed by similar letters are not significantly different at the 5% probability level, using the LSD test.

All table data have been prepared based on: 1-LSD test; 2-Using SAS software version 9.1.

Table 6 continued. Mean Comparison of Traits Across Different Levels of Available Water and Potato Cultivars in 2022 and 2023

Year	Available water	Cultivars	Plant height (cm)	Number of main stems per plant	Water use efficiency (kg m^{-3})
2022	Normal (100% of the plant's available water)	Agria	68.33 bcd	3.25 b	7.05 k
		Rona	68.08 bcd	3.33 b	8.25 hi
		Takta	75.42 a	4.08 a	8.61 ghi
	Mild Stress (75% of the plant's available water)	Agria	62.92 fg	3.17 b	7.97 ij
		Rona	64 defg	3.42 b	9.5 ef
		Takta	67.92 bcde	4.08 a	10.38 cd
	Severe Stress (50% of the plant's available water)	Agria	60.54 g	3.42 b	9.56 ef
		Rona	60.75 fg	3.17 b	10.96 bc
		Takta	65.2 cdefg	4.17 a	11.62 b
2023	Normal (100% of the plant's available water)	Agria	70.33 b	3.25 b	9.96 de
		Rona	70.5 b	3.33 b	11.74 b
		Takta	77 a	4.08 a	13.1 a
	Mild Stress (75% of the plant's available water)	Agria	63.17 efg	3.17 b	8.83 fgh
		Rona	64.33 defg	42.3 b	9.94 de
		Takta	69.25 bc	4.08 a	10.54 cd
	Severe Stress (50% of the plant's available water)	Agria	60.43 g	3.42 b	7.37 jk
		Rona	61.03 fg	3.17 b	9.04 fg
		Takta	65.51 cdef	4.17 a	9.18 efg

Note. [*] Means followed by similar letters are not significantly different at the 5% probability level, using the LSD test.

All table data have been prepared based on: 1-LSD test; 2-Using SAS software version 9.1.

3.2.2 Tuber Yield and Tuber Weight

2022: Both ‘Rona’ and ‘Takta’ exhibited the highest tuber yield and tuber weight when treated with a nutrient solution during all three stages: flowering, tuber formation, and tuber bulking. This suggests that providing nutrients at all growth stages maximizes tuber production for these cultivars.

2023: ‘Rona’ and ‘Takta’ showed the highest tuber yield and tuber weight when treated with a nutrient solution during two stages: flowering and tuber formation. This indicates that fewer stages of nutrient application can still provide significant benefits in terms of yield and weight in the second year.

3.2.3 Tuber Number per Plant

In both 2022 and 2023, ‘Takta’ and ‘Rona’ had the highest number of tubers per plant when treated with a nutrient solution during both two and three stages. This demonstrates the positive impact of foliar nutrient application on tuber production for both cultivars.

3.2.4 Plant Height, Number of Main Stems per Plant, and Water Use Efficiency

2022 and 2023: ‘Takta’ exhibited the highest plant height, number of main stems per plant, and water use efficiency in nutrient solution treatments applied during both two stages (flowering and tuber formation) and all three stages (flowering, tuber formation, and tuber bulking). This highlights the cultivar’s consistent performance across different irrigation treatments, indicating that nutrient applications at these stages enhance plant growth and water use efficiency.

In summary, ‘Takta’ and ‘Rona’ performed well across multiple parameters in both years, showing the benefits of foliar nutrient treatments. ‘Takta’ particularly demonstrated superior growth, yield, and water efficiency under nutrient treatments during multiple growth stages (Table 7).

Table 7. Mean Comparison of Traits in Nutrient Solution and Potato Cultivars in 2022 and 2023

Year	**Nutrient solution**	**Cultivars**	**Tuber number per plant**	**Tuber weight per plant (g)**	**Tuber yield (t ha^{-1})**
2022	Flowering stage	Agria	4.33 d	620.7 i	32.9 klm
		Rona	5.33 bc	712.8 fgh	37.78 hij
		Takta	5 c	758.7 def	40.12 efgh
	The stages of flowering and tuber formation	Agria	5.33 bc	663.5 hi	35.17 jkl
		Rona	5.67 ab	793.5 cde	42.06 cdef
		Takta	6 a	856 bc	45.37 bcd
	The stages of flowering, tuber formation and bulking	Agria	6 a	772.9 fgh	38.31 ghij
		Rona	6 a	856.3 bc	45.38 bcd
		Takta	5.22 bc	883.9 b	46.85 b
	Control (no nutrient solution)	Agria	4.11 d	600.7 i	31.84 lm
		Rona	5 c	690.4 gh	36.59 ij
		Takta	5 c	752.7 defg	39.89 efghi
2023	Flowering stage	Agria	5.22 bc	658.5 hi	34.9 jklm
		Rona	5.33 bc	857.9 bc	45.47 bc
		Takta	5 c	749.6 defg	39.73 efghi
	The stages of flowering and tuber formation	Agria	5.33 bc	740.5 efg	39.24 fghi
		Rona	5.67 ab	814.13 cd	43.16 cde
		Takta	6 a	914.2 ab	48.45 ab
	The stages of flowering, tuber formation and bulking	Agria	6 a	748.6 defg	39.68 efghi
		Rona	6 a	859.4 bc	45.55 bc
		Takta	5.33 bc	961.7 a	50.97 a
	Control (no nutrient solution)	Agria	4 d	529.3 j	31.39 m
		Rona	5 c	606.7 i	35.49 jk
		Takta	5 c	663.3 hi	41.82 defg

Note. * Means followed by similar letters are not significantly different at the 5% probability level, using the LSD test.

All table data have been prepared based on: 1-LSD test; 2-Using SAS software version 9.1.

Table 7 continued. Mean Comparison of Traits in Nutrient Solution and Potato Cultivars in 2022 and 2023

Year	Nutrient solution	Cultivars	Plant height (cm)	Number of main stems per plant	Water use efficiency (kg m^{-3})
2022	Flowering stage	Agria	60.78 hijk	3.33 bcd	7.78 mno
		Rona	64.89 efghi	3.44 bc	8.98 ijk
		Takta	69.11 bcde	4.33 a	9.61 ghij
	The stages of flowering and tuber formation	Agria	65.33 efghi	3.22 cd	8.39 klmn
		Rona	65.56 efghi	3.33 bcd	9.97 efgh
		Takta	72.56 abc	4.56 a	10.79 cde
	The stages of flowering, tuber formation and bulking	Agria	71.67 abcd	3.56 b	9.11 hijk
		Rona	68.78 bcdef	3.44 bc	10.62 cdef
		Takta	76.22 a	4.44 a	10.9 cd
	Control (no nutrient solution)	Agria	57.94 jk	3 d	7.52 no
		Rona	57.89 jk	3 d	8.7 jkl
		Takta	60.15 ijk	3.11 cd	9.52 ghij
2023	Flowering stage	Agria	63.33 fghij	3.33 bcd	7.83 lmno
		Rona	67.33 cdefg	3.44 bc	10.31 defg
		Takta	70 bcde	4.33 a	9.14 hijk
	The stages of flowering and tuber formation	Agria	65.67 efgh	3.22 cd	9.28 hijk
		Rona	66.44 defg	3.33 bcd	10.26 defg
		Takta	72.89 ab	4.56 a	11.42 bc
	The stages of flowering, tuber formation and bulking	Agria	71.89 abcd	3.56 b	10.36 defg
		Rona	44.68 bcdef	3.44 bc	11.39 b
		Takta	76.67 a	4.44 a	13.43 a
	Control (no nutrient solution)	Agria	57.68 k	3 d	7.41 o
		Rona	58.93 jk	3 d	8.45 klm
		Takta	62.79 ghijk	3.11 cd	9.77 fghi

Note. * Means followed by similar letters are not significantly different at the 5% probability level, using the LSD test.

All table data have been prepared based on: 1-LSD test; 2-Using SAS software version 9.1.

3.2.5 Performance of ‘Takta’ and ‘Rona’ Cultivars

‘Takta’: Exhibited the highest tuber yield, tuber weight, tuber number, plant height, number of main stems per plant, and water use efficiency under the following conditions:

Nutrient solution at a dose of 3 liters per thousand during the flowering stage;

Nutrient solution during two stages (flowering and tuber formation);

Nutrient solution during three stages (flowering, tuber formation, and tuber bulking);

Under 100% plant available water.

These results suggest that ‘Takta’ benefits significantly from a more comprehensive nutrient management strategy, especially when full irrigation is provided.

‘Rona’: Showed the highest values for the same traits under nutrient solution treatments during the flowering stage under 100% plant available water.

‘Rona’ also exhibited the highest performance under nutrient solution treatments during:

Flowering stage and two-stage treatments under 75% plant available water;

Flowering stage and three-stage treatments under 75% plant available water;

These findings indicate that ‘Rona’ thrives with nutrient solutions applied at earlier stages and does well under reduced irrigation levels (75%).

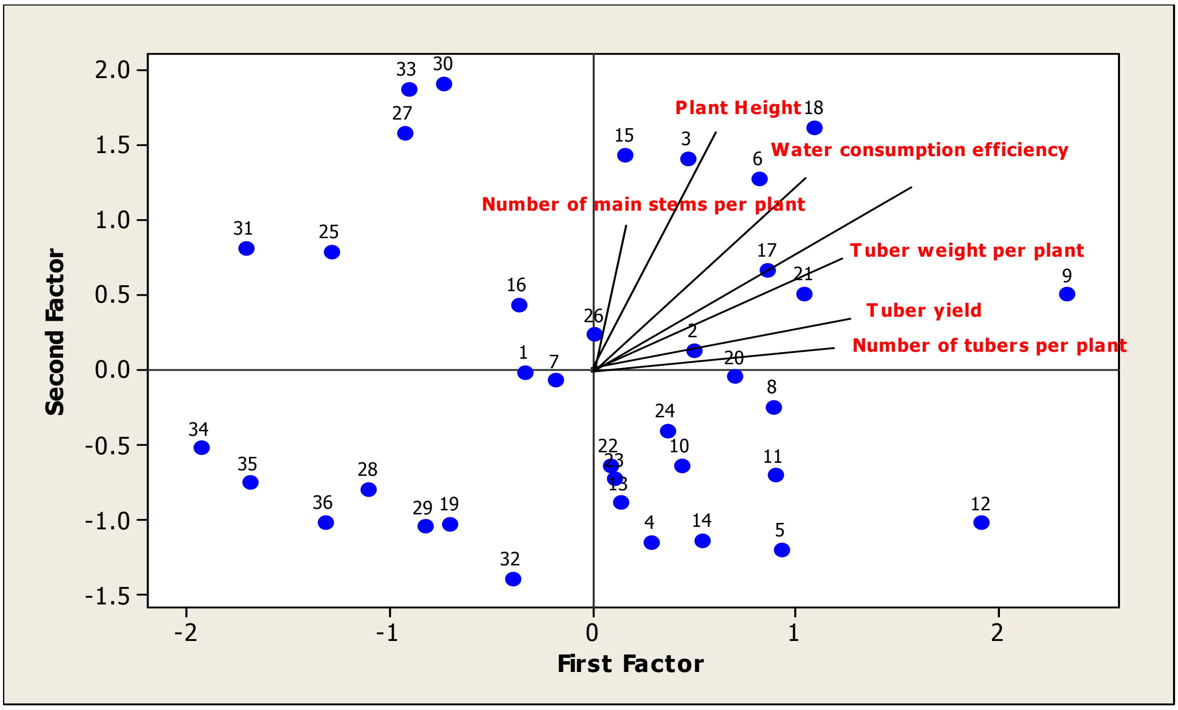
Summary:

‘Takta’ demonstrated superior growth and yield under optimal nutrient conditions (flowering, tuber formation, and tuber bulking stages) and under full irrigation (100% plant available water).

‘Rona’ showed the highest performance with fewer stages of nutrient application, particularly when irrigation levels were reduced to 75% of the plant’s available water.

Visual representation:

Figure 1 would likely illustrate these results, showing the comparative performance of 'Takta' and 'Rona' across the various treatments (Figure 1).



Normal (100% of the plant's available water)											
Nutrient solution under flowering stage			Nutrient solution under the stages of flowering and tuber formation			Nutrient solution under the stages of flowering, tuber formation and bulking			Control (no nutrient solution) nutrient solution under		
Agria	Rona	Takta	Agria	Rona	Takta	Agria	Rona	Takta	Agria	Rona	Takta
1	2	3	4	5	6	7	8	9	10	11	12
Mild Stress (75% of the plant's available water)											
Nutrient solution under flowering stage			Nutrient solution under the stages of flowering and tuber formation			Nutrient solution under the stages of flowering, tuber formation and bulking			Control (no nutrient solution) nutrient solution under		
Agria	Rona	Takta	Agria	Rona	Takta	Agria	Rona	Takta	Agria	Rona	Takta
13	14	15	16	17	18	19	20	21	22	23	24
Severe Stress (50% of the plant's available water)											
Nutrient solution under flowering stage			Nutrient solution under the stages of flowering and tuber formation			Nutrient solution under the stages of flowering, tuber formation and bulking			Control (no nutrient solution) nutrient solution under		
Agria	Rona	Takta	Agria	Rona	Takta	Agria	Rona	Takta	Agria	Rona	Takta
25	26	27	28	29	30	31	32	33	34	35	36

Figure 1. Biplot of factor analysis for evaluated traits at different levels of available water

According to Table 8, the effective traits measured in the study were grouped into four distinct factors. These factors collectively explained a significant portion of the total variance in the experimental data.

Factor groupings:

Factor 1: Tuber Yield, Tuber Weight per Plant, and Plant Height

Explanation of variance: 33.60%.

Key traits: Tuber yield, tuber weight per plant, and plant height were highly correlated, indicating that these traits are closely related and may respond similarly to environmental factors and treatments.

Factor 2: Number of Main Stems per Plant

Explanation of variance: 20.30%.

Key trait: The number of main stems per plant was identified as a separate factor, which suggests that this characteristic has a distinct influence on plant development and yield.

Factor 3: Tuber Number per Plant

Explanation of variance: 19.70%.

Key trait: The tuber number per plant was a separate factor, reflecting its significant role in determining overall yield and the productivity of the plant.

Factor 4: Water Use Efficiency under Different Levels of Plant Available Water (50%, 75%, and 100%)

Explanation of variance: 17.90%.

Key trait: Water use efficiency was grouped as a separate factor, highlighting its importance in managing water resources efficiently for optimal plant growth and yield under varying irrigation conditions.

Summary:

Factor 1 explains the largest portion of the variance (33.60%), reflecting the combined importance of tuber yield, tuber weight, and plant height.

The other factors, particularly the number of stems and tuber number, also account for significant portions of the variance, but water use efficiency plays a slightly smaller role (17.90%).

These findings provide insight into the most influential traits for optimizing potato production under various irrigation conditions, guiding future research and cultivation strategies (Table 8).

Table 8. Factor values for evaluated traits at different levels of available water

Trait	Factor 1	Factor 2	Factor 3	Factor 4	Eigenvalue	Variance (%)
Tuber number per plant	0.372	0.023	0.896	0.209	1.0746	17.90
Tuber yield	0.876	0.170	0.328	0.249	1.1812	19.70
Tuber weight per plant	0.790	0.232	0.395	0.351	1.2201	20.30
Plant height	0.592	0.396	0.263	0.208	2.0152	33.60
Number of main stems per plant	0.186	0.947	0.024	0.227		
Water use efficiency	0.317	0.289	0.229	0.867		

Key points:

Factor 1 (Tuber Yield, Tuber Weight, and Plant Height) has the highest variance contribution of 33.60% and is strongly influenced by tuber yield (0.876), tuber weight per plant (0.790), and plant height (0.592).

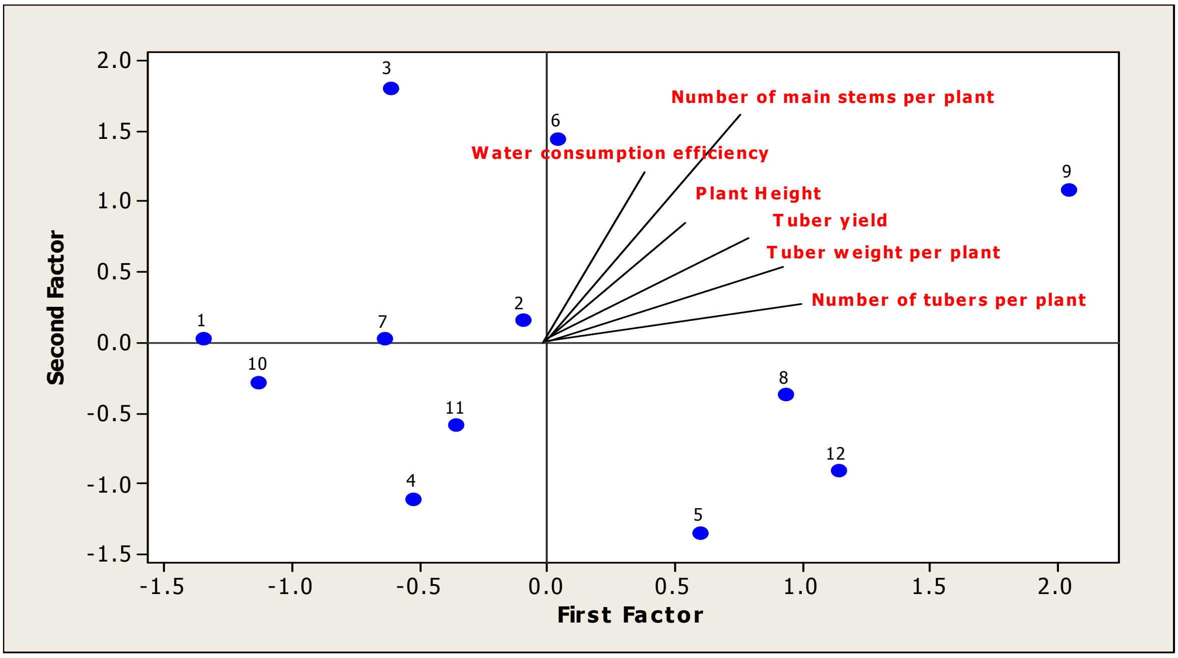
Factor 2 (Number of Main Stems per Plant) is most associated with the number of main stems per plant (0.947) and has a variance contribution of 20.30%.

Factor 3 (Tuber Number per Plant) explains 19.70% of the variance, with the strongest factor loading on tuber number per plant (0.896).

Factor 4 (Water Use Efficiency) contributes 17.90% to the total variance, with the highest loading on water use efficiency (0.867).

The Eigen values represent the amount of variance explained by each factor, and the Variance (%) shows the percentage of the total variance accounted for by each factor.

This analysis indicates that Factor 1 (tuber yield, tuber weight, and plant height) is the most significant in determining the success of potato cultivation, while Factor 4 focuses on water use efficiency, which is crucial for efficient resource management (Table 9).



Normal (100% of the plant's available water)											
Nutrient solution under flowering stage		Nutrient solution under the stages of flowering and tuber formation				Nutrient solution under the stages of flowering, tuber formation and bulking			Control (no nutrient solution) nutrient solution under		
Agria	Rona	Takta	Agria	Rona	Takta	Agria	Rona	Takta	Agria	Rona	Takta
1	2	3	4	5	6	7	8	9	10	11	12

Figure 2. Biplot of factor analysis for evaluated traits under normal conditions (100% of the plant's available water)

Table 9. Factor values for evaluated traits under normal conditions (100% of the plant's available water)

Traits	Factor 1	Factor 2	Factor 3
tuber number per plant	0.228	0.132	**0.963**
tuber yield	**0.926**	0.290	0.198
tuber weight per plant	**0.739**	0.392	0.440
plant height	**0.611**	0.502	0.101
number of main stems per plant	0.343	**0.905**	0.175
water use efficiency	**0.739**	0.371	0.430
Eigen value	2.4923	1.4645	1.3856
Variance(%)	41.50	24.40	23.10

3.2.6 Factor Analysis Results Under Normal Conditions (100% Plant Available Water)

Factor 1: Tuber Yield, Tuber Weight per Plant, Water Use Efficiency

This factor has the highest variance explanation (41.50%) and includes tuber yield (0.926), tuber weight per plant (0.739), and water use efficiency (0.739). This indicates that the most important contributing factors to overall plant productivity and water use efficiency are tuber yield and weight, as well as water use efficiency.

Factor 2: Number of Main Stems per Plant

Factor 2 explains 24.40% of the variance and is strongly associated with the number of main stems per plant (0.905), highlighting the significance of stem development as an important determinant of plant structure.

Factor 3: Tuber Number per Plant

Factor 3 explains 23.10% of the variance and is most strongly linked to tuber number per plant (0.963), showing that this factor is critical for yield determination.

Key insights:

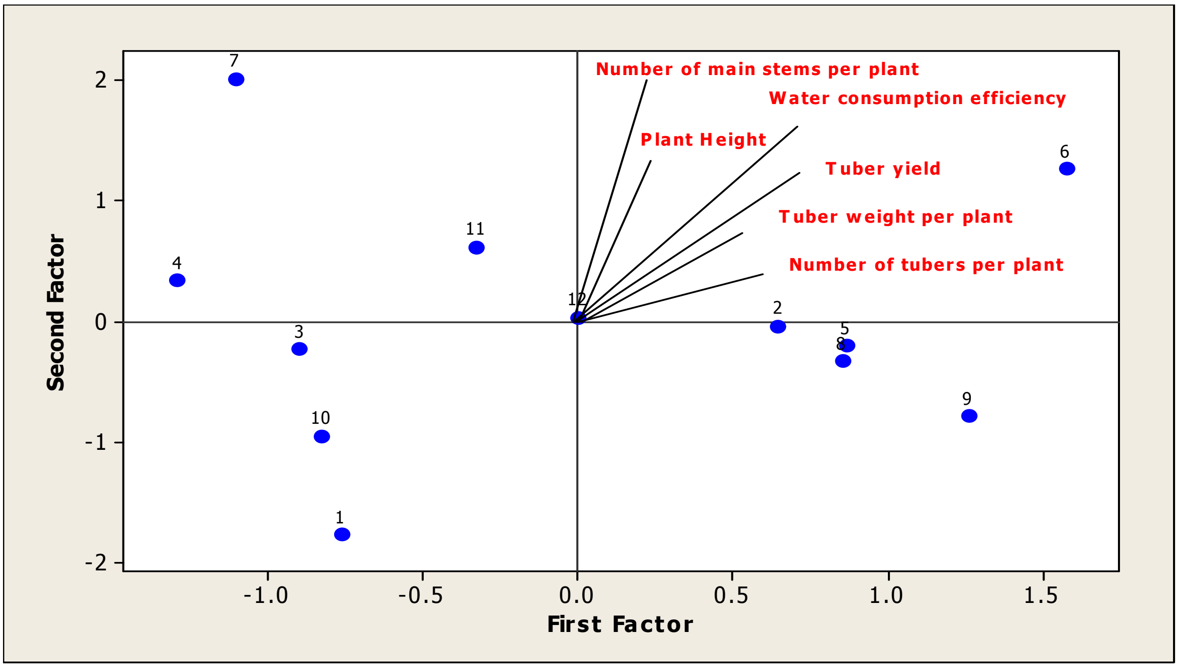
Factor 1 explaining the highest variance, shows that tuber yield, tuber weight, and water use efficiency are highly interconnected and play a major role in plant growth under normal water conditions.

Factor 2 emphasizes the importance of the number of main stems per plant as a key factor for determining plant structure.

Factor 3 highlights that tuber number per plant is a primary factor in the determination of yield.

Additional observations:

‘Takta’ Cultivar: The highest tuber yield, tuber weight, tuber number, plant height, number of main stems per plant, and water use efficiency for ‘Takta’ were observed under nutrient solution treatments at a dose of 3 liters per thousand, applied during two stages (flowering and tuber formation) and all three stages (flowering, tuber formation, and tuber bulking) under 100% plant available water.



Mild Stress (75% of the plant’s available water)											
Nutrient solution under flowering stage			Nutrient solution under the stages of flowering and tuber formation			Nutrient solution under the stages of flowering, tuber formation and bulking			Control (no nutrient solution) nutrient solution under		
Agria	Rona	Takta	Agria	Rona	Takta	Agria	Rona	Takta	Agria	Rona	Takta
13	14	15	16	17	18	19	20	21	22	23	24

Figure 3. Biplot of factor analysis for evaluated traits under mild stress conditions
(75% of the plant’s available water)

Table 10. Factor values for evaluated traits under mild stress conditions (75% of the plant's available water)

Traits	Factor 1	Factor 2	Factor 3
Tuber number per plant	0.267	**0.933**	-0.110
Tuber yield	**0.864**	0.274	-0.339
Tuber weight per plant	**0.840**	0.270	-0.333
Plant height	0.434	**0.553**	-0.306
Number of main stems per plant	0.502	0.132	**-0.824**
Water use efficiency	**0.845**	0.289	-0.356
Eigen value	2.7175	1.3273	1.1425
Variance(%)	45.30	22.10	19.00

Based on description of Table 10, here's an interpretation of the factor analysis results under Mild Stress Conditions (75% of plant available water):

Table 10 overview:

Factor 1 (45.30% variance) includes tuber yield, tuber weight per plant, and water use efficiency.

Factor 2 (22.10% variance) includes tuber number per plant and plant height.

Factor 3 (19.00% variance) is primarily focused on number of main stems per plant.

The Eigen values show the contribution of each factor to the overall variance, with Factor 1 contributing the most (2.7175), followed by Factor 2 (1.3273), and Factor 3 (1.1425).

Key implications for factor analysis:

Factor 1: This factor is crucial as it explains the largest portion of the variance (45.30%). It links key growth traits such as tuber yield, tuber weight per plant, and water use efficiency, which are important indicators of overall plant performance under mild stress.

Factor 2: Tuber number per plant and plant height are key to understanding how these traits behave together, especially under the mild stress condition. This suggests that the plant's ability to produce tubers and its physical growth are significantly related.

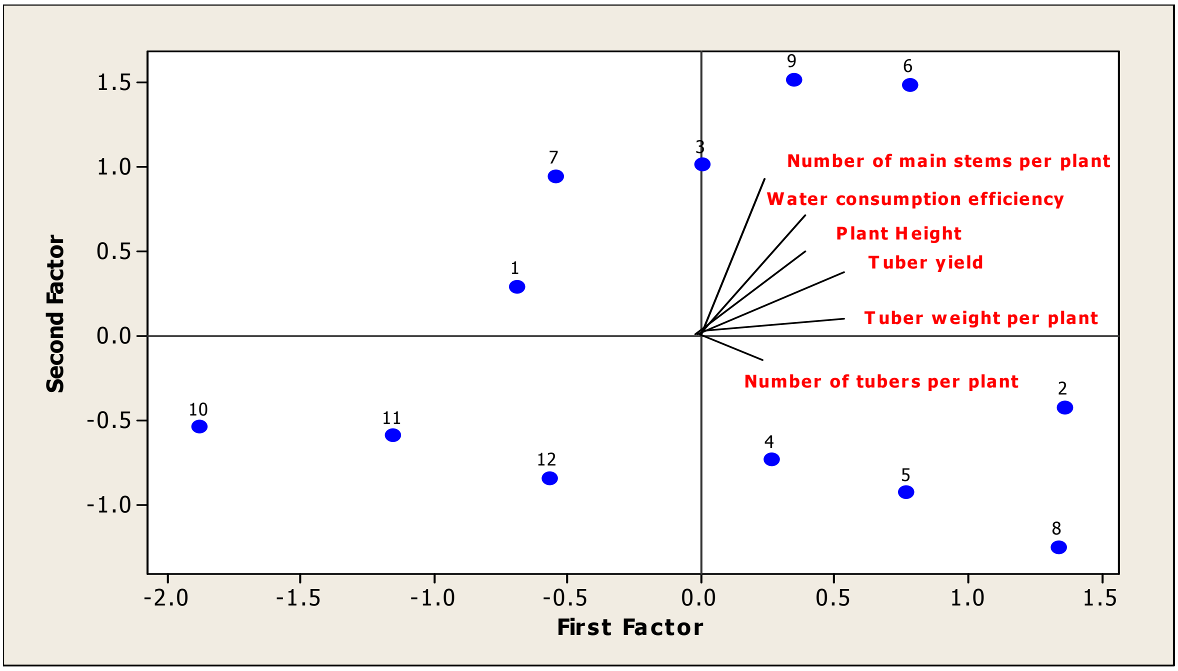
Factor 3: This factor, explaining 19% of the variance, is tied to the number of main stems per plant. This indicates a structural aspect of plant growth under stress.

3.2.7 Interpretation Under Severe Stress (50% Plant Available Water)

Based on the results you've provided, 'Takta' exhibited the highest values across tuber yield, tuber weight, tuber number, plant height, number of main stems per plant, and water use efficiency under nutrient solution treatments at a dose of 3 liters per thousand, applied during two or three stages (flowering, tuber formation, and tuber bulking). This suggests that Takta is highly adaptable to severe stress and thrives with specific nutrient treatments (Figure 4).

Figure 4 interpretation:

The biplot for severe stress conditions (50% plant available water) in Figure 4 would likely display how different treatments (stages of flowering, tuber formation, and tuber bulking) affect the performance of 'Takta' and other cultivars under severe stress conditions. Since 'Takta' shows the highest performance across multiple traits under the specified treatments, you would expect it to appear as the most advantageous cultivar in the biplot.



Severe Stress (50% of the plant's available water)											
Nutrient solution under flowering stage			Nutrient solution under the stages of flowering and tuber formation			Nutrient solution under the stages of flowering, tuber formation and bulking			Control (no nutrient solution) nutrient solution under		
Agria	Rona	Takta	Agria	Rona	Takta	Agria	Rona	Takta	Agria	Rona	Takta
25	26	27	28	29	30	31	32	33	34	35	36

Figure 4. Biplot of factor analysis for evaluated traits under severe stress conditions (50% of the plant's available water)

Table 11. Factor values for evaluated traits under severe stress conditions (50% of the plant's available water).

Traits	Factor 1	Factor 2	Factor 3
tuber number per plant	0.224	-0.066	-0.931
tuber yield	0.887	0.272	-0.220
tuber weight per plant	0.880	0.269	-0.218
plant height	0.643	0.663	-0.153
number of main stems per plant	0.236	0.963	0.104
water use efficiency	0.027	0.581	-0.438
Eigen value	2.2375	1.5203	1.1904
Variance(%)	37.30	25.30	19.80

Based on Table 11, here is the interpretation of the factor analysis under Severe Stress Conditions (50% of the plant's available water):

Table 11 overview:

Factor 1 (37.30% variance) includes tuber yield, tuber weight per plant, and plant height.

Factor 2 (25.30% variance) includes plant height, number of main stems per plant, and water use efficiency.

Factor 3 (19.80% variance) is associated with tuber number per plant.

The Eigen values indicate the contribution of each factor to the overall variance:

Factor 1: 2.2375;

Factor 2: 1.5203;

Factor 3: 1.1904.

Key implications for factor analysis:

Factor 1: This factor is the most important under severe stress, as it explains the greatest portion of variance (37.30%). It includes tuber yield, tuber weight, and plant height—key traits for assessing overall plant performance under harsh conditions. These factors reflect the plant's ability to sustain growth and produce tubers despite stress.

Factor 2: This factor explains 25.30% of the variance and is linked to plant height, number of main stems per plant, and water use efficiency. The relationship between these traits indicates the structural aspects of plant growth and its efficiency in using available water under severe stress.

Factor 3: This factor, accounting for 19.80% of the variance, focuses solely on tuber number per plant. This suggests that tuber production under severe water stress is an independent factor from other growth characteristics such as plant height or number of stems.

3.2.8 Interpretation of Traits Under Severe Stress (50% Available Water)

The data suggests that under severe stress conditions, tuber yield, tuber weight, and plant height are most significantly influenced by Factor 1, while Factor 2 emphasizes the importance of plant height and water use efficiency. Factor 3 indicates that tuber number per plant remains a distinct factor, suggesting that under water stress, the plant's ability to produce multiple tubers is independent of its overall growth.

4. Discussion

This study explored the impact of water stress on potato growth and yield, analyzing various quantitative parameters. The reduction in plant height due to water stress aligns with previous studies by Donnelly et al. (2003), and Schittenhelm et al. (2006). Similarly, a decrease in the number of tubers per plant has been documented by Schittenhelm et al. (2006), and Badarau et al. (2013), consistent with our findings. In addition, several studies, including those by Shock and Feibert (2002), Hassanpanah (2009), and Sobhani and Hamidi (2013), have shown that water stress negatively impacts tuber yield.

The seasonal development of potato tubers is heavily influenced by weather conditions and nutrient availability during the growing season, as noted by Grzebisz and Potarzycki (2020), and Koch et al. (2020). Begum et al. (2018) emphasize that potatoes require sufficient humidity during stolon formation and tuber development. Water shortages during these critical periods disrupt assimilate production, causing a sugar deficiency in the stolons, which results in reduced tuber numbers and the death of prearranged sets. This highlights the importance of water availability before and during flowering. Furthermore, breaks in tuber growth caused by water stress can lead to undersized and deformed tubers, as indicated by Begum et al. (2018).

Water use efficiency (WUE) is closely tied to nutrient management and the efficiency of nutrient uptake, particularly nitrogen and sulfur. A shortage of water and nitrogen disrupts the development of photosynthetic organs, affecting tuber growth (White et al., 2016). To optimize tuber growth under stress conditions, it is critical to balance nitrogen with sulfur, as sulfur regulates the growth of competing potato organs (Grzebisz et al., 2022). The initial stages of tuber formation and bulking are particularly sensitive to environmental stress, emphasizing the importance of applying nutrient solutions during these stages (Hassanpanah et al., 2008; Hassanpanah, 2009).

Field experiments have demonstrated that the application of silicon and sulfur can enhance the commercial yield of potato cultivars. Silicon has been found to improve drought tolerance and overall plant productivity (Gerami & Torabipour, 2021; Kaya et al., 2006; Wang et al., 2016). These findings are consistent with our results, where foliar spraying with S8 Matrix nutrition during flowering, tuber formation, and tuber bulking significantly improved tuber yield and WUE. Under normal conditions, tuber yield increased by 17.19 t/ha and WUE by 5.85 kg/m^3. Under mild stress, tuber yield was 5.37 t/ha and WUE was 1.7 kg/m^3, while under severe stress, tuber yield increased by 5.99 t/ha, with a WUE of 0.03 kg/m^3. These results highlight the significant role of nutrient solutions under water deficit conditions, with the S8 Matrix nutrition showing a strong positive impact on tuber yield and WUE.

5. Conclusions

This study evaluated the effects of applying a sulfonated silicon nutrient solution (S8 Matrix) combined with elemental sulfur under different irrigation levels on potato winter cultivation. The findings highlighted the following key outcomes:

5.1 Impact on Growth and Yield Parameters

The 'Takta' cultivar demonstrated the highest tuber yield (up to 62.8 t/ha under optimal irrigation) and plant height (up to 81.22 cm), especially when the nutrient solution was applied during flowering, tuber formation, and tuber bulking stages. The 'Rona' cultivar excelled in the number of tubers per plant under similar conditions, showcasing its adaptability to nutrient applications. Under severe water stress (50% irrigation), the nutrient solution significantly mitigated yield losses, enhancing tuber weight and water use efficiency.

5.2 Water Use Efficiency (WUE)

The S8 Matrix nutrient solution improved WUE across all cultivars. 'Takta' exhibited the highest WUE under all irrigation levels, indicating its efficiency in utilizing water resources when supplemented with balanced nutrition.

5.3 Adaptation to Water Stress

The study underscores the role of targeted nutrient management in alleviating the adverse effects of water deficit stress. The application of the nutrient solution during critical growth stages (flowering and tuber bulking) improved the performance of all cultivars, even under reduced irrigation.

5.4 Optimal Cultivation Practices

The combination of sulfonated silicon and sulfur in the S8 Matrix significantly enhanced resistance to environmental stressors while promoting growth and productivity. The use of foliar spraying at specific growth stages is recommended as an effective strategy for improving potato yield and resilience, particularly in water-scarce regions.

5.5 Practical Recommendations

Best Cultivars: The 'Takta' cultivar is recommended for regions prone to water stress due to its superior yield, growth characteristics, and efficiency under varying irrigation levels.

Nutrient Application Timing: Foliar spraying of the S8 Matrix nutrient solution during flowering, tuber formation, and tuber bulking stages provides the most substantial benefits.

Water Management: Adopting deficit irrigation practices (75% of plant available water) combined with targeted nutrient solutions can optimize resource use without significant yield losses.

5.6 Final Note

These results provide valuable insights for improving potato cultivation under challenging environmental conditions. By integrating advanced nutrient solutions with optimized planting arrangements, growers can enhance productivity and sustainability, contributing to food security in water-scarce regions.

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Acknowledgments

The authors would like to thank the management and staff of the Seed and Plant Breeding Research Institute, as well as the Ardabil Agricultural and Natural Resources Research Centre, Iran, for their support and assistance in conducting this study.

Authors Contributions

Dr. Davoud Hassanpanah and Dr. Sayad Parastar Anzabi were responsible for study design, revising, responsible for data collection and drafted the manuscript it. All authors read and approved the final manuscript. Other project partners have helped with field, laboratory, and storage work.

Funding

This work was supported by Seed and Plant Breeding Research Institute and Ardabil Agricultural and Natural Resources Research Centre, Iran [project number: 24-37-03-002-010024].

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed Consent

Obtained.

Ethics Approval

The Publication Ethics Committee of the Canadian Center of Science and Education.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and Peer Review

Not commissioned; externally double-blind peer reviewed.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data Sharing Statement

No additional data are available.

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