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Synergistic effects of *Trichoderma* consortium and natural potassium fertilization on potato quality under water scarcity in sandy calcareous soil

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Abstract

Excessive use of chemical fertilizers affects the environment and soil health, while using natural fertilizers like nutrient ores is constrained by their low solubility. To address this issue, this research aimed to evaluate the function of *Trichoderma* consortium in solubilizing, and releasing potassium and alleviating the effects of water scarcity in potato plants grown in sandy calcareous soil. The field experiment was performed throughout two winter seasons of 2022/2023 and 2023/2024. Three irrigation levels (Full, Moderate, and Stress Irrigation) were designated in the primary plot. The sub-plot was designated for organic treatments (T1 = Chemical Fertilizers (CF), T2 = 50% CF + micro, T3 = 50% mica + *Trichoderma* consortium, T4 = *Trichoderma* consortium); microbial inoculum concentrations were 10^6 spores/mL. Varying irrigation conditions revealed that water deficit significantly reduced yield components, marketable yield, and tuber quality. However, the application of 50% mica combined with the *Trichoderma* consortium significantly enhanced tuber number and weight, total yield, and irrigation water productivity compared to chemical fertilization. Notably, this treatment achieved yield improvements of up to 34.7% and increased water productivity by 42.3% over two seasons. Under moderate irrigation, the consortium-based treatment maintained yields comparable to full irrigation with chemical fertilizers, indicating its potential for water-saving agriculture. Biochemical analysis revealed that water stress increased antioxidant compounds, while the consortium treatment promoted higher carbohydrate accumulation under optimal irrigation. Overall, the *Trichoderma* consortium represents a promising eco-friendly biofertilizer strategy for enhancing potassium availability, improving crop productivity, and increasing water use efficiency under limited irrigation conditions.

Keywords: Ground rock, K-solubilizing microorganisms, Organic agriculture, K-availability

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Introduction

Nutrient management is a crucial technique for achieving high plant productivity and preserving soil fertility[1]. Nitrogen (N), phosphorus (P), and potassium (K) are the principal macronutrients that govern, plant growth and development[2]. These vital elements are crucial for physiological activities; potassium, in particular, is necessary for the growth, production, and quality of agricultural plants. It participates in protein synthesis, enzyme activation, glycolysis, and redox processes related to sugar transport[3]. Potassium constitutes approximately 5% of plant matter and is vital for stomatal conductance, photosynthesis, phloem transport, and cellular ion equilibrium. The global potassium fertilizer market is valued at $12.6 billion annually[4]. Potassium deficits pose a challenge as potassium diminishes readily in soils due to crop absorption, runoff, leaching, and soil erosion. The direct application of synthetic fertilizers may improve various processes and alter soil properties; however, the depletion of natural resources poses a significant concern due to limited availability. Additionally, the production process necessitates substantial amounts of non-renewable chemicals and high energy input from petroleum-based sources, resulting in increased cost[5–7]. Moreover, the application of extensive fertilizer leads to soil degradation, diminished biodiversity, and environmental contamination. Biofertilizers may address these challenges by enhancing agricultural output, preserving soil health and vitality, and mitigating the cumulative environmental effects associated with chemical fertilizers[8].

The application of microbial biofertilizers is a more environmentally sustainable approach, as they are less harmful to plants and provide access to all soil nutrients. Despite the establishment of symbiotic relationships between plants and microorganisms, and the identification of some microorganisms that enhance abiotic stress tolerance[9], our comprehension of these interactions under abiotic stress remains elementary. Furthermore, the utilization of alternative nutrient sources, such as potassium ore (mica), could mitigate the adverse effects of chemical fertilizers due to various advantages, including low cost and ease of procurement. Ground rock is utilized in organic agriculture to release macro- and micronutrients for plants. Simultaneously, the use of rocks is constrained by their low solubility, and the chemical elements contained inside these minerals are released only gradually. The availability of nutrients in rocks can be enhanced by employing soil microorganisms that facilitate rock solubilization and release chemical components from them. Feldspar is the predominant mineral, constituting almost fifty percent of the Earth's crust. It contains a silicon-oxygen-aluminum tetrahedron with potassium occupying the interstitial spaces to neutralize the matrix's charge. The cost of potassium fertilizer is directly influenced by the roasting reagents[10]. Consequently, it is essential to employ a more economical and environmentally sustainable approach to diminish the expenses associated with

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commercial potassium fertilizer and reliance on imported synthetic potassium, thereby benefiting the farmers.

Trichoderma is a genus of filamentous fungi within the Hypocreaceae family, recognized for its widespread occurrence in soils, decomposing wood, and plant roots globally. These rapidly growing, green-spored ascomycetes display opportunistic avirulent symbiotic interaction with plants, functioning as saprophytes that degrade organic matter while colonizing rhizospheres[11]. *Trichoderma* functions as a versatile bio-input: it provides biocontrol against numerous pathogens (such as *Fusarium, Alternaria,* and *Rhizoctonia*), promotes plant growth through phytohormones like IAA, and facilitates mineral solubilization (phosphates, potassium, micronutrients via organic acids, chelation)[12,13]. *Trichoderma* possesses the capability to synthesize enzymes, antibiotics, and siderophores, facilitating nutritional competition and antagonism against pathogens[14]. Furthermore, it is important in solubilizing insoluble minerals such as phosphates, potassium, iron, zinc, copper, and manganese, hence enhancing their accessibility to plants in nutrient-deficient soils[15,16]. *Trichoderma* solubilizes potassium largely through acidification via organic acids, reducing pH by 0.5−1.0 degrees and dissolving minerals[17]. Additionally, they facilitate the chelation of related cations and produce extracellular polysaccharides that assist in the release of potassium[18]. *Trichoderma* consortia consist of multi-strain formulations of compatible *Trichoderma* species cultivated together, improving biocontrol, nutrient solubilization, and plant development compared to single-strain applications[19]. Consortia surpass monocultures by synergizing antagonism, promoting growth (increased IAA, acids), and enhancing stress tolerance, hence augmenting cucumber yields and seed germination[20].

Potassium fertilization is crucial for potassium-demanding crops like potatoes, as certain soil types, such as calcareous soils, are comparatively deficient in potassium. The potato (*Solanum tuberosum* L.) is a crucial food crop that serves as an economical energy source for human nutrition. Moreover, it is an economical food rich in starch, minerals, vitamins C and B, and amino acids, and is globally esteemed. In Egypt, the potato is a significant vegetable crop, with a total production of 6.9 million tons in 2023, cultivated across approximately 235,625 ha, yielding an average of 29.2 ton·ha^{-1}, according to FAOSTAT[21]. Potassium has a crucial role in the growth and development of potato plants, aiding their adaptation to biotic and abiotic stressors, including pathogens, drought, and extreme temperatures[22]. Potassium absorber effectively alleviates drought stress in potatoes by enhancing osmotic adaptation and diminishing oxidative damage[22]. Stegelmeier et al.[23] indicated that more than 50% of existing agricultural land is moderately or severely affected by soil degradation processes including erosion, acidification, compaction, salinization, and pollution. Moreover, unsustainable farming practices coupled with droughts have resulted in a decrease in groundwater levels throughout numerous regions. Combined with climate change and the reduction in natural resource availability, this presents a significant challenge for agriculture to satisfy current food demand. A combination of inorganic and organic fertilizers was employed to achieve increased production. The combined use of potassium rocks and the co-inoculation of potassium-solubilizing microorganisms may facilitate a more rapid and sustained availability of potassium for optimal plant growth. Nevertheless, there is limited knowledge regarding the synergistic effects of rock materials and co-inoculation with potassium-solubilizing microorganisms on mineral availability in sandy calcareous soils, as well as on mineral content and growth of potatoes under different irrigation regimes. Furthermore, it is imperative to save water resources while ensuring high yields and product quality, as water is becoming progressively limited and expensive[24]. Consequently, the use of irrigation strategies that improve water use efficiency in agricultural output is imperative. Therefore, this study was conducted in field conditions to evaluate the effects of soil fertilization with potassium ore (mica) and the co-inoculation of potassium-solubilizing microorganisms under different irrigation regimes on potassium uptake, as well as growth and yield of potato plants, with the objective of optimizing mineral potassium consumption through mica utilization.

Materials and methods

Trichoderma consortium

Trichoderma harzianum and *T. longibrachiatium* were isolated from heavy metal contaminated soil and mushroom wastes on Czapek's dextrose agar medium, which comprised 3% dextrose, 0.3% $NaNO_3$, 0.1% KH_2PO_4, 0.05% KCl, 0.001% $FeSO_4{\cdot}7H_2O$, 0.05% $MgSO_4$, and 1.8% agar in 100 mL of distilled water, utilizing the dilution plate method for soil and the direct plate method for mushroom waste[25,26]. Both isolates were morphologically identified on Czapek's dextrose agar medium. Prior to commencing the experiment, both isolates were cultivated on identical plates using Czapek's dextrose agar medium and incubated at 28 °C for 4 d to identify any antagonistic interaction between the two isolates.

Assessment of potassium solubilization and organic acid synthesis

Potassium solubilization by *T. harzianum* and *T. longibrachiatium* was evaluated using the plate assay as per Shanware et al.[27] and Mahmoud et al.[8]. *Trichoderma* species were inoculated onto Aleksandrov solid agar medium supplemented with 0.1% mica (comprising 0.5% glucose, 0.01% $Ca_3(PO4)_2$, 0.01% $CaCO_3$, 0.025% $MgSO_4{\cdot}7H_2O$, 0.001% $FeCl_3$, 1.8% agar, and 100 mL doubled distilled water). The inoculated plates were incubated at 28 °C for 4 d, resulting in the formation of halo zones indicative of potassium-solubilizing activities. *T. harzianum* and *T. longibrachiatium* were evaluated for organic acid generation utilizing a plate test based on pH variation, as per Dezam et al.[28], with the adjustment of the pH indicator to phenol red. The organic acid test medium utilized was Czapek's agar, comprising 3% sucrose, 0.2% $NaNO_3$, 0.1% KH_2PO_4, 0.05% KCl, 0.001% $FeSO_4{\cdot}7H_2O$, 0.05% $MgSO_4$, and 1.8% agar, with fortified with an initial pH 7.2, augmented by 0.1 g·L^{-1} phenol red as a pH indicator for acid formation. Pure cultures of *Trichoderma* were inoculated at the center of the plates and incubated at 28 °C for 5 d, with the creation of yellow zones suggesting acid production.

Plant materials and experimental field

Potato tubers (cv. Cara) were cultivated in rows measuring 20 m in length, 0.5 m breadth, and spaced 0.3 m apart, utilizing a drip irrigation system. Each row utilized a single line with a spacing of 0.3 m between drippers, and the discharge rate was 4 L^{-1} per dripper. The prescribed agricultural practices were implemented in accordance with the extension guide for potatoes provided by the Ministry of Agriculture, Egypt. The field experiment was executed throughout two winter seasons, 2022/2023 and 2023/2024, at the Arab El-Awammer Research Station, Agricultural Research Center (A.R.C.), located in Assiut Governorate, Egypt (27°17′03.3" N, 31°13 '25.4" E).

Table 1. Physical and chemical properties of representative composite soil sample from the field trial site.

Chemical properties	pH (1:1)	8.21
	EC (ds m^{-1}) (1:1)	0.52
	Soluble cations (mmol kg^{-1})	
	Ca^{++}	2.06
	Mg^{++}	1.54
	Na^{+}	0.58
	K^{+}	0.92
	Soluble anions (mmol kg−1)	
	$CO_3^{--} + HCO_3^{-}$	2.89
	Cl^{-}	1.94
	Available Phosphorus (mg kg^{-1})	8.31
	Total nitrogen (%)	0.09
Physical properties	Particle size distribution (%)	
	Sand	89.7
	Silt	7.2
	Clay	3.1
	Texture class	sandy
	Moisture content (Volumetric %)	
	S. P.	24.2
	F.C.	11.2
	W.P.	4.6
	O.M (%)	0.8
	$CaCO_3$ (g kg^{-1})	254
	Bulk density (ton m^{-3})	1.6

The experimental soil is classified as sandy calcareous soil (Table 1), and the methodologies outlined by Klute[29] and Jackson[30] were employed to define its physical and chemical features. Table 2 presents the climate data for the study region for the two winter seasons. Potassium sulfate was added at a rate of 236.7 kg·ha^{-1} at 100%, and 50% was 118.3 kg·ha^{-1} at 50%; mica was 595.2 kg·ha^{-1}. Nitrogen and phosphate fertilizers were added according to the recommendations of the Egyptian Ministry of Agriculture.

Design of experiments

The present field experiment was structured as a randomized complete block design (RCBD) in a split-plot configuration and conducted in triplicate, with each plot covering an area of 10 m^2. Three irrigation levels (Full irrigation (100% ETc), Moderate Irrigation (80% ETc), and Stress Irrigation (60% ETc)) were designated in the primary plot. The sub-plot was designated for organic treatments (T1 = Chemical Fertilizers (CF), T2 = 50% CF + micro, T3 = 50% mica + micro, T4 = micro). The micro used in the current investigation is *T. harzianum* and *T. longibrachiatium*; the inocula were prepared as follows: the spores of 3 d old cultures were scraped and suspended in sterilized distilled water to a final concentration 10^6 spores·mL^{-1}. The reference evapotranspiration was computed utilizing the CROPWAT model as delineated by Penman-Monteith[31], as clarified in Eq. (1):

$$\text{Crop evapotranspiration (ETc)}: \quad ETc = ETo \; x \; Kc \tag{1}$$

where, ETo is the reference evapotranspiration, and Kc is the crop coefficient according to FAO 56[32].

Irrigation water applied (I.Ra) was assessed using Eq. (2), where it reflects the quantity of actual irrigation water utilized

$$\text{I.}Ra = \frac{ETc + LF}{Er} \tag{2}$$

where, I.Ra is the total real irrigation water applied in mm per interval, ETc is the crop evapotranspiration calculated via the Penman-Monteith equation, LF is the leaching factor of 10%, and Er is the efficiency of the irrigation system.

Table 2. Average monthly meteorological data of Assiut weather station during two seasons (2022/2023 and 2023/2024).

Year	Month	Tmax (°C)	Tmin (°C)	RH	WS (km·h^{-1})	Sunshine
2022/2023	October	30.2	17.6	48.8%	15.7	10.0
	November	25.7	12.1	51.4%	12	9.4
	December	22.9	9.3	57.6%	9.6	9.0
	January	21.1	7.1	56%	10.1	8.9
	February	20.2	6.1	51%	11.8	9.7
2023/2024	October	31.9	18.7	47.5%	13.9	10.0
	November	28.9	14.8	50%	10.4	9.4
	December	23.4	9.9	60.2%	8.9	9.0
	January	20.9	7.1	53.2%	9.1	8.9
	February	21.9	8.2	46.3%	10.5	9.7

Tmax = Maximum temperature (°C); Tmin = Minimum temperature (°C); RH = Relative humidity (%); WS = Wind speed (km·h^{-1}) (fieldclimate.com, Asyut, Egypt 00001125).

Measurements of yield and its components

In the final week of January, during both cultivated seasons, potato tubers were harvested, and ten individual plants from each plot were randomly selected to assess tuber weight per plant (kg), tuber count per plant, average tuber weight, weight of marketable tuber per plant (kg), count of marketable tubers per plant, average weight of marketable tuber, and dry matter percentage. The total yield (ton·ha^{-1}) and marketable yield (ton·ha^{-1}) were calculated based on total tubers produced in each plot.

Collection of samples for analysis

Tuber samples from each plot were randomly taken following the assessment of yield and yield-related parameters to conduct biochemical and quality analyses. Clean tubers were categorized into two groups: one for assessing nitrogen (N), phosphorus (P), potassium (K), protein, dry matter percentage, and starch yield, and the other for evaluating total carbohydrates, total antioxidants, total phenols, and total flavonoids in their fresh state.

Examination of the chemical composition of the potato tuber

For NPK measurements, tubers were sectioned and then subjected to oven drying at 70 °C until a stable weight was achieved. Precisely 0.5 g of dried tuber, pounded to a fine powder, was weighed for wet digestion using H_2SO_4 in conjunction with $HClO_4$, adhering to the approach outlined by Chapman & Pratt[33]. The nitrogen content (%) was assessed using the micro-Kjeldahl method as outlined by Jackson[30]. Total phosphorus and potassium were measured using methods outlined by Jackson[30] and Page et al.[34], respectively. The protein content of potato tubers was determined by multiplying the nitrogen percentage by 6.25, according to Hymowitz et al.[35].

Quality characteristics of potato tubers

The yield of dry tubers (ton·ha^{-1}) was ascertained in accordance with Haque et al.[36] following Eq. (3):

$$\text{Dry matter (\%)} = \frac{\text{Dry weight (g)}}{\text{Fresh weight (g)}} \times 100 \tag{3}$$

The yield of tuber starch was determined using the Eqs (4 and 5):

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$$\text{Starch yield (ton} \cdot \text{ha}^{-1}) = \text{Tuber dry yield} \times \text{Starch percentage} \quad (4)$$

$$\text{Tuber dry yield} = \frac{\text{Total tuber yield} \times \text{Dry matter percentage}}{100} \quad (5)$$

The starch percentage was determined using the Burton[37] Eq. (6):

$$\text{Starch (\%)} = 17.457 + [0.891 \times (\text{Dry matter percentage} - 24.182)]. \quad (6)$$

The total carbohydrate content was measured using a spectrophotometer; total antioxidants were quantified utilizing the phosphor-molybdenum method as delineated by Prieto et al.[38], incorporating ammonium molybdate reagent. The absorbance was measured at 695 nm using a spectrophotometer, and the findings were obtained using an ascorbic acid standard curve serving as the antioxidant reference. The Folin-Ciocalteu method, as described by Singleton et al.[39], was employed to quantify total phenolic content. Absorbance was measured at 765 nm utilizing a spectrophotometer, with values obtained from the gallic acid standard curve. Total flavonoids were measured using an aluminum chloride reagent as per the method developed by Da Silva et al.[40]. The yellow color was measured at 415 nm with a spectrophotometer, with values obtained from the quercetin standard curve.

Statistical analysis

Analysis of variance (ANOVA) was performed using Statistix 8.1 software according to the experimental design. The normality of the data was assessed using the Shapiro–Wilk test before performing ANOVA. Treatment means were compared using Tukey's multiple comparison test at a significance level of $p \leq 0.05$. Data are presented as mean ± standard deviation (SD). Exact *p*-values are reported throughout the Results section. Cluster analysis was performed on the obtained data using the unweighted pair group method with arithmetic averages (UPGMA) and the Bray–Curtis dissimilarity index using PAST 4.17 software[41].

Results

Trichoderma consortium and evaluation for potassium solubilization and organic acid synthesis

The growth of *T. harzianum* and *T. longibrachiatium* on Czapek's dextrose agar medium at 28 °C for 4 d showed no antagonistic interaction between the two isolates, hence endorsing their use in consortium application. The growth of *T. harzianum* on Czapek's dextrose agar medium exhibited smooth mycelial development, transitioning to a bright green hue within 2 d. Conidiophores exhibited extensive branching, with phialides that include a smooth-walled structure and truncated-base conidia. The growth of *T. longibrachiatium* on Czapek's dextrose agar medium exhibited a surface mycelium of dark green coloration and a pale greenish-yellow reverse. Conidiophores exhibited branching with elongated primary branches; phialides appeared in clusters, and conidia were green with smooth walls. *T. harzianum* and *T. longibrachiatium* had significant acid generation capabilities, as seen by the color change of phenol red in Czapek's agar medium from red to yellow with prolonged incubation periods. Acid production commenced 2 d post-inoculation for both isolates, with *T. harzianum* exhibiting 45 mm and *T. longibrachiatium* 22.5 mm. After 5 d, acid diffusion reached 90 mm, resulting in a full color change of the plate to yellow. *T. harzianum* and *T. longibrachiatium* demonstrated effective potassium solubilization on Aleksandrov solid agar medium containing mica (a natural potassium source), resulting in clear zones measuring between 22.5 and 28 mm after 4 d of inoculation.

Irrigation water applied ($m^3 \cdot ha^{-1}$)

The volume of irrigation water applied ($m^3 \cdot ha^{-1}$) is a crucial statistic in agriculture for resource management, efficiency assessment, and water supply planning based on climate, crop type, and irrigation technology. It denotes the volume of water, quantified in cubic meters, supplied to one hectare of land for agricultural irrigation. Fig. 1 illustrates that the actual irrigation water fluctuates across various potato growth stages and irrigation levels during the two growing seasons. As the plant developed and grew during the initial and development stages, a progressive increase in water usage and application was noticed. The highest irrigation water applied occurred around mid-season, with average values across two seasons of 1,413.2, 1,130.5, and 847.9 $m^3 \cdot ha^{-1}$ for Full Irrigation, Moderate Irrigation, and Stress Irrigation, respectively. In the late season phase, the volume of irrigation water utilized markedly diminished throughout both seasons at different irrigation levels. The total real water volume over two seasons was 3,986.8 $m^3 \cdot ha^{-1}$ at Full Irrigation, 3,189.4 $m^3 \cdot ha^{-1}$ at Moderate Irrigation, and 2,392 $m^3 \cdot ha^{-1}$ at Stress Irrigation.

Measurements of yield and its components

The results regarding yield and yield component parameters demonstrated that various irrigation treatments, the application of mica with or without *Trichoderma* consortium, and their interaction

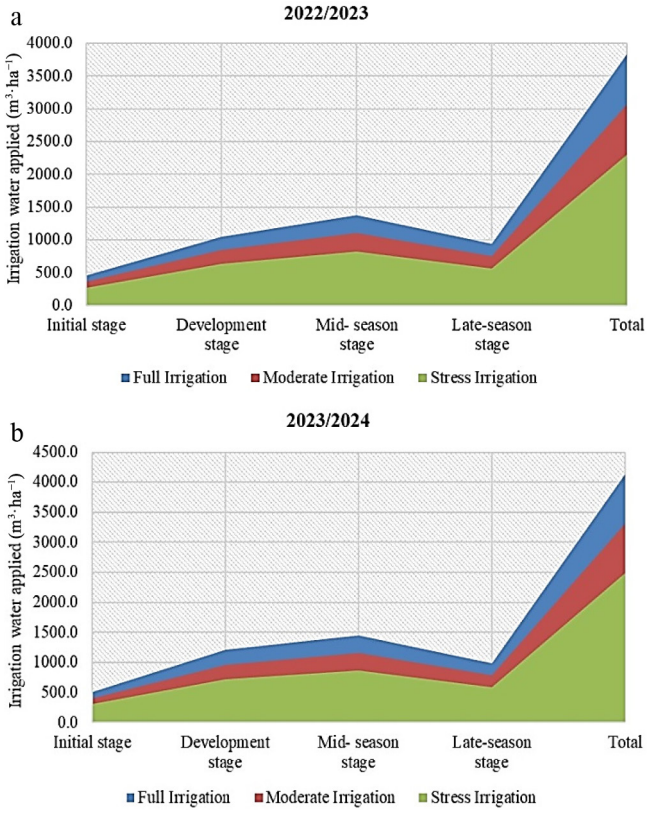

Fig. 1 Volume of irrigation water applied ($m^3 \cdot ha^{-1}$) at various growth stages of potato during the (a) 2022/2023, and (b) 2023/2024 seasons, cultivated under different irrigation regimes utilizing a drip irrigation system.

significantly influenced the outcomes. Tuber number and weight per plant (Table 3), average tuber weight, and total tuber yield (Table 4) exhibited the lowest values under water scarcity at the irrigation level of Stress Irrigation, in contrast to plants irrigated with Full Irrigation. Simultaneously, by conserving 20% of utilized irrigation water at Moderate Irrigation (797.4 $m^3 \cdot ha^{-1}$), the average reduction percentage across both seasons was 10.5%, 5.2%, 13.9%, and 28.5% for the number of tubers per plant, tuber weight per plant, average tuber weight, and total tuber yield, respectively. The application of 50% mica combined with a *Trichoderma* consortium (T3) yielded the highest value for the specified parameters compared to other treatments, including 100% chemical fertilizer (control, T1).

The maximum percentage increase, averaged over two seasons, was 20% for tuber number per plant, 34.8% for tuber weight per plant, 27.2% for average tuber weight, and 34.7% for total tuber production compared to the control treatment. The interaction effect revealed that the maximum values for potassium ore, tuber weight per plant, average tuber weight, and total tuber yield were seen with the application of 50% mica combined with a *Trichoderma* consortium under full irrigation. No significant difference was seen in the number of tubers per plant, tuber weight per plant, average tuber weight, and total tuber yield when comparing the control treatment at Full Irrigation with the treatment of 50% mica plus *Trichoderma* consortium under an irrigation level of Moderate Irrigation. Moreover, a 40% reduction in water consumption (1,594.7 $m^3 \cdot ha^{-1}$) at Stress Irrigation, combined with the addition of 50% potassium ore to the soil and inoculation with a *Trichoderma* consortium, resulted in a comparative analysis against chemical fertilizer at Full Irrigation. Over two seasons, a reduction of 17.3% in tuber number per plant, 23.3% in tuber weight per plant, 27.5% in average tuber weight, and 26.0% in total tuber yield were recorded.

The percentage of marketable tubers, marketable tuber weight per plant (Table 5), along with the total marketable tuber yield (Table 6), were assessed to clarify the influence of the examined factors in this study. A substantial effect of different irrigation levels on the marketable tuber percentage per plant was observed; however, no notable difference was detected regarding mica with or without *Trichoderma* consortium, nor for their interaction. The weight of marketable tubers per plant and total marketable tuber yield were significantly affected by the experimental variables and their interaction. Water scarcity diminished the marketable tuber weight per plant and total marketable yield by 31.8% and 31.7% at 80% of ETc and by 49.6% and 49.5% at Stress Irrigation across two seasons, respectively. The results from the soil application of *Trichoderma* consortium inoculation and mica indicated that the combination of 50% mica and *Trichoderma* consortium (T3) achieved a 32.7/% increase in marketable tuber weight per plant and a 33.7% increase in total marketable yield, averaged over two seasons, in comparison to chemical fertilizer (T1). In light of the interaction impacts, soil application of 50% potassium ore combined with *Trichoderma* consortium, as opposed to chemical fertilizer, enhanced the marketable tuber weight per plant and total

Table 3. Influence of varying irrigation levels, application of *Trichoderma* consortium with potassium ore, and their interaction on tuber number and weight (g) per plant during growing seasons of 2022/2023 and 2023/2024.

	Treatment	Tuber number per plant				Tuber weight per plant (kg)			
		Full irrigation	Moderate irrigation	Stress irrigation	Mean	Full irrigation	Moderate irrigation	Stress irrigation	Mean
2022/2023	T1	6.00 ± 0.10^{ab}	5.00 ± 0.12^{c}	4.00 ± 0.10^{d}	5.00^{b}	0.409 ± 0.01^{c}	0.322 ± 0.01^{de}	0.211 ± 0.00^{g}	0.314^{d}
	T2	6.00 ± 0.10^{ab}	5.67 ± 0.12^{bc}	4.00 ± 0.10^{d}	5.22^{b}	0.523 ± 0.01^{b}	0.339 ± 0.00^{d}	0.257 ± 0.00^{f}	0.373^{b}
	T3	6.67 ± 0.20^{a}	6.00 ± 0.12^{ab}	5.00 ± 0.10^{c}	5.89^{a}	0.608 ± 0.00^{a}	0.420 ± 0.01^{c}	0.314 ± 0.01^{e}	0.447^{a}
	T4	5.67 ± 0.10^{bc}	5.00 ± 0.12^{c}	4.00 ± 0.10^{d}	4.89^{b}	0.415 ± 0.01^{c}	0.315 ± 0.00^{e}	0.250 ± 0.01^{f}	0.327^{c}
	Mean	6.08^{a}	5.42^{b}	4.25^{c}		0.489^{a}	0.349^{b}	0.258^{c}	
2023/2024	T1	6.05 ± 0.11^{cd}	5.37 ± 0.15^{ef}	3.55 ± 0.12^{i}	4.99^{c}	0.433 ± 0.00^{c}	0.339 ± 0.01^{e}	0.220 ± 0.00^{g}	0.331^{d}
	T2	6.49 ± 0.20^{bc}	5.81 ± 0.12^{de}	4.52 ± 0.11^{gh}	5.61^{b}	0.548 ± 0.01^{b}	0.355 ± 0.00^{d}	0.267 ± 0.00^{f}	0.390^{b}
	T3	7.40 ± 0.13^{a}	6.70 ± 0.17^{b}	4.97 ± 0.20^{fg}	6.36^{a}	0.639 ± 0.00^{a}	0.441 ± 0.01^{c}	0.332 ± 0.00^{e}	0.471^{a}
	T4	5.86 ± 0.11^{de}	5.24 ± 0.23^{f}	4.20 ± 0.20^{h}	5.10^{c}	0.432 ± 0.00^{c}	0.334 ± 0.00^{e}	0.261 ± 0.00^{f}	0.342^{c}
	Mean	6.45^{a}	5.78^{b}	4.31^{c}		0.513^{a}	0.367^{b}	0.270^{c}	

Values are expressed as the mean of three replicates ± SD, with different superscript letters indicating significant differences at the $p \leq 0.05$ level according to Tukey's test. T1 = Chemical Fertilizers (CF), T2 = 50% CF + *Trichoderma* consortium, T3 = 50% mica + *Trichoderma* consortium, T4 = *Trichoderma* consortium.

Table 4. Changes in average tuber weight (kg) and total tuber yield ($ton \cdot ha^{-1}$) as affected by varying irrigation levels, application of *Trichoderma* consortium with potassium ore, and their interaction during growing seasons of 2022/2023 and 2023/2024.

	Treatment	Average tuber weight (kg)				Total tuber yield ($ton \cdot ha^{-1}$)			
		Full irrigation	Moderate irrigation	Stress irrigation	Mean	Full irrigation	Moderate irrigation	Stress irrigation	Mean
2022/2023	T1	0.155 ± 0.00^{bc}	0.127 ± 0.00^{e}	0.081 ± 0.00^{g}	0.121^{c}	26.726 ± 0.40^{c}	21.037 ± 0.82^{de}	13.778 ± 0.23^{g}	20.514^{d}
	T2	0.156 ± 0.00^{bc}	0.147 ± 0.00^{cd}	0.087 ± 0.00^{g}	0.130^{b}	34.147 ± 0.38^{b}	22.121 ± 0.11^{d}	16.751 ± 0.21^{f}	24.340^{b}
	T3	0.184 ± 0.00^{a}	0.161 ± 0.00^{b}	0.113 ± 0.00^{f}	0.153^{a}	39.676 ± 0.19^{a}	27.409 ± 0.85^{c}	20.507 ± 0.34^{e}	29.197^{a}
	T4	0.144 ± 0.00^{d}	0.116 ± 0.00^{f}	0.084 ± 0.00^{g}	0.115^{d}	27.091 ± 0.53^{c}	20.590 ± 0.26^{e}	16.323 ± 0.35^{f}	21.334^{c}
	Mean	0.160^{a}	0.138^{b}	0.091^{c}		31.910^{a}	22.789^{b}	16.840^{c}	
2023/2024	T1	0.164 ± 0.00^{b}	0.132 ± 0.00^{d}	0.083 ± 0.00^{g}	0.126^{c}	28.283 ± 0.19^{c}	22.177 ± 0.48^{e}	14.380 ± 0.12^{g}	21.613^{d}
	T2	0.165 ± 0.00^{b}	0.155 ± 0.00^{c}	0.090 ± 0.00^{f}	0.137^{b}	35.767 ± 0.33^{b}	23.183 ± 0.19^{c}	17.417 ± 0.12^{f}	25.456^{b}
	T3	0.196 ± 0.00^{a}	0.172 ± 0.00^{b}	0.119 ± 0.00^{e}	0.162^{a}	41.747 ± 0.11^{a}	28.820 ± 0.42^{c}	21.663 ± 0.14^{e}	30.743^{a}
	T4	0.152 ± 0.00^{c}	0.123 ± 0.00^{e}	0.088 ± 0.00^{fg}	0.121^{d}	28.230 ± 0.23^{c}	21.840 ± 0.25^{e}	17.053 ± 0.13^{f}	22.374^{c}
	Mean	0.169^{a}	0.146^{b}	0.095^{c}		33.507^{a}	24.005^{b}	17.628^{c}	

Values are expressed as the mean of three replicates ± SD, with different superscript letters indicating significant differences at the $p \leq 0.05$ level according to Tukey's test.

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marketable yield by 41.2% and 41.0%, respectively, across both seasons at Full Irrigation. Nonetheless, with water savings of 20% and 40% at Moderate Irrigation and Stress Irrigation, the reduction percentage for marketable tuber weight per plant was 7.6% and 31.1%, respectively, and for total marketable yield, they were 7.4% and 31.0%, respectively.

Irrigation water productivity ($m^3 \cdot ha^{-1}$)

Irrigation water productivity (IWP) denotes the correlation between total tuber production and the volume of water utilized (Table 6). Irrigation water productivity helps elucidate the effects of irrigation regimes on crop productivity. The reduction percentage due to water scarcity at Moderate Irrigation was 28.5%, while the average reduction percentage in IWP over two seasons compared to Full Irrigation was 10.6%. Furthermore, the deficit irrigation treatment at Stress Irrigation exhibited a 12.2% drop in IWP compared to Full Irrigation. The combination of potassium ore (50%) and microorganism inoculation increased water productivity by 42.3% over two seasons compared to chemical fertilizer. The interaction effect results indicated that T3 (50% mica + *Trichoderma* consortium) exhibited the largest percentage growth (48.1% over two seasons) in comparison to chemical fertilizer at Full Irrigation. No significant difference was observed between Moderate Irrigation and Stress Irrigation while applying 50% mica and *Trichoderma* consortium inoculation, with a percentage increase of 27.8% compared to the control treatment under Full Irrigation level.

Chemical composition of potato tuber

The variations in nitrogen (N), phosphorus (P), potassium (K), and protein levels in potato tuber, associated with distinct irrigation levels (Full Irrigation, Moderate Irrigation, and Stress Irrigation), soil application with or without potassium ore, and the interactive effects of both factors, are detailed in Tables 7 and 8. A reduction in irrigation water supply, along with a drop in N, P, K, and protein levels, was noted. The reduction percentage in water deficit, compared to fully irrigated conditions during both seasons, was 28.7% for nitrogen, 34.7% for phosphorus, 31% for potassium, and 29% for protein content. The utilization of mica and *Trichoderma* consortium inoculation enhanced the nitrogen, phosphorus, potassium, and protein levels in potato tubers relative to chemical fertilizer. The percentage increase of 50% mica + *Trichoderma* consortium (T3) application relative to chemical fertilizer treatment, averaged over two seasons, was 20.6% for nitrogen, 42.4% for phosphorus, 7.6% for potassium, and 20.8% for protein, respectively. The interaction effect of applying 50% mica + micro under Full Irrigation resulted in an increase of 13.7% in nitrogen, 28.6% in phosphorus, 8% in potassium, and 17.1% in protein compared to the control treatment. At the same time, the identical treatment at Moderate Irrigation resulted in an increase of 5.6% in nitrogen content and 8.5% in protein content across two seasons. No substantial variation was observed in phosphorus and potassium levels between the two regimens. Furthermore, a 40% reduction in water usage at an irrigation level of Stress Irrigation, compared to chemical fertilizer at Full

Table 5. Marketable tuber per plant (%) and marketable tuber weight per plant (kg) as influenced by varying irrigation levels, application of *Trichoderma* consortium with potassium ore, and their interaction during growing seasons of 2022/2023 and 2023/2024.

	Treatment	Marketable tuber per plant (%)				Marketable tuber weight per plant (kg)			
		Full irrigation	Moderate irrigation	Stress irrigation	Mean	Full irrigation	Moderate irrigation	Stress irrigation	Mean
2022/2023	T1	71.78 ± 0.70^{bc}	58.21 ± 0.90^{e}	70.98 ± 2.66^{abc}	66.99^{a}	0.384 ± 0.01^{c}	0.296 ± 0.01^{ef}	0.193 ± 0.00^{i}	0.291^{c}
	T2	76.24 ± 1.66^{a}	60.27 ± 2.93^{de}	68.22 ± 3.81^{abcd}	68.24^{a}	0.528 ± 0.00^{b}	0.307 ± 0.01^{e}	0.236 ± 0.00^{h}	0.357^{b}
	T3	75.00 ± 2.71^{ab}	60.46 ± 2.67^{de}	68.09 ± 4.01^{bcd}	67.85^{a}	0.544 ± 0.00^{a}	0.355 ± 0.00^{d}	0.265 ± 0.00^{g}	0.388^{a}
	T4	66.95 ± 0.82^{cd}	60.51 ± 0.89^{de}	69.57 ± 2.42^{abc}	65.68^{a}	0.360 ± 0.00^{d}	0.283 ± 0.01^{fg}	0.228 ± 0.01^{h}	0.290^{c}
	Mean	72.49^{a}	59.87^{c}	69.21^{b}		0.454^{a}	0.310^{b}	0.231^{c}	
2023/2024	T1	71.78 ± 0.70^{ab}	60.00 ± 4.00^{e}	67.74 ± 2.30^{abcde}	66.51^{a}	0.405 ± 0.00^{c}	0.311 ± 0.00^{ef}	0.197 ± 0.00^{i}	0.304^{c}
	T2	$75.50 \pm 2.-91^{a}$	60.27 ± 2.93^{de}	68.22 ± 3.81^{abcde}	67.90^{a}	0.556 ± 0.00^{b}	0.321 ± 0.00^{d}	0.244 ± 0.00^{h}	0.374^{b}
	T3	69.96 ± 0.87^{abc}	64.69 ± 2.91^{bcde}	69.50 ± 5.98^{abcd}	68.05^{a}	0.570 ± 0.00^{a}	0.375 ± 0.00^{d}	0.279 ± 0.00^{g}	0.408^{a}
	T4	66.95 ± 0.82^{abcde}	61.51 ± 1.50^{cde}	71.76 ± 4.21^{ab}	66.74^{a}	0.378 ± 0.00^{d}	0.297 ± 0.00^{f}	0.238 ± 0.01^{h}	0.304^{c}
	Mean	71.05^{a}	61.62^{c}	69.30^{b}		0.477^{a}	0.326^{b}	0.239^{c}	

Each value represents a mean of three replicates ± standard deviation, with different superscript letters indicate significant differences at the $p \leq 0.05$ level according to Tukey's test.

Table 6. Mean of total marketable tuber yield ($ton \cdot ha^{-1}$) and irrigation water productivity ($kg \cdot m^{-1}$) as affected by varying irrigation levels, application of *Trichoderma* consortium with potassium ore, and their interaction during growing seasons of 2022/2023 and 2023/2024.

	Treatment	Total marketable tuber yield ($ton \cdot ha^{-1}$)				Irrigation water productivity ($kg \cdot m^{-1}$)			
		Full irrigation	Moderate irrigation	Stress irrigation	Mean	Full irrigation	Moderate irrigation	Stress irrigation	Mean
2022/2023	T1	25.08 ± 0.42^{b}	19.32 ± 0.35^{de}	12.59 ± 0.26^{h}	18.996^{c}	6.97 ± 0.10^{cd}	6.86 ± 0.27^{cd}	5.99 ± 0.10^{e}	6.61^{d}
	T2	34.47 ± 0.29^{a}	20.03 ± 0.44^{d}	15.39 ± 0.28^{g}	23.296^{b}	8.90 ± 0.10^{b}	7.21 ± 0.04^{c}	7.28 ± 0.09^{c}	7.80^{b}
	T3	35.53 ± 0.32^{a}	23.19 ± 0.17^{c}	17.33 ± 0.29^{f}	25.351^{a}	10.35 ± 0.05^{a}	8.93 ± 0.28^{b}	8.91 ± 0.15^{b}	9.40^{a}
	T4	23.53 ± 0.32^{c}	18.44 ± 0.36^{ef}	14.89 ± 0.79^{g}	18.952^{c}	7.07 ± 0.14^{cd}	6.71 ± 0.08^{d}	7.09 ± 0.15^{cd}	6.96^{c}
	Mean	29.65^{a}	20.24^{b}	15.05^{c}		8.32^{a}	7.43^{b}	7.32^{b}	
2023/2024	T1	26.42 ± 0.30^{c}	20.28 ± 0.10^{e}	12.87 ± 0.10^{i}	19.86^{c}	6.83 ± 0.04^{cde}	6.70 ± 0.15^{de}	5.79 ± 0.05^{f}	6.44^{d}
	T2	36.33 ± 0.22^{b}	20.99 ± 0.26^{e}	15.94 ± 0.10^{h}	24.42^{b}	8.64 ± 0.08^{b}	7.00 ± 0.06^{c}	7.01 ± 0.05^{c}	7.55^{b}
	T3	37.21 ± 0.19^{a}	24.48 ± 0.14^{d}	18.20 ± 0.18^{g}	26.63^{a}	10.09 ± 0.03^{a}	8.70 ± 0.13^{b}	8.72 ± 0.06^{b}	9.17^{a}
	T4	24.66 ± 0.28^{d}	19.41 ± 0.18^{f}	15.54 ± 0.76^{h}	19.87^{c}	6.82 ± 0.06^{cde}	6.59 ± 0.08^{e}	6.87 ± 0.05^{cd}	6.76^{c}
	Mean	31.156^{a}	21.290^{b}	15.638^{c}		8.10^{a}	7.25^{b}	7.10^{c}	

Each value represents a mean of three replicates ± standard deviation, with different superscript letters indicate significant differences at the $p \leq 0.05$ level according to Tukey's test.

Table 7. Nitrogen and phosphorus percentages in tuber tissues of potato plants as influenced by varying irrigation levels, application of *Trichoderma* consortium with potassium ore, and their interaction during growing seasons of 2022/2023 and 2023/2024.

	Treatment	Nitrogen (%)				Phosphorus (%)			
		Full irrigation	Moderate irrigation	Stress irrigation	Mean	Full irrigation	Moderate irrigation	Stress irrigation	Mean
2022/2023	T1	1.57 ± 0.01^{c}	1.28 ± 0.00^{g}	1.11 ± 0.00^{h}	1.32^{c}	0.41 ± 0.01^{e}	0.35 ± 0.00^{fg}	0.21 ± 0.01^{i}	0.32^{d}
	T2	1.63 ± 0.02^{b}	1.48 ± 0.01^{e}	1.27 ± 0.01^{g}	1.46^{b}	0.49 ± 0.01^{b}	0.43 ± 0.00^{d}	0.34 ± 0.00^{g}	0.42^{b}
	T3	1.78 ± 0.01^{a}	1.65 ± 0.01^{b}	1.35 ± 0.00^{f}	1.59^{a}	0.52 ± 0.00^{a}	0.46 ± 0.01^{c}	0.36 ± 0.01^{f}	0.45^{a}
	T4	1.53 ± 0.01^{d}	1.11 ± 0.02^{h}	0.88 ± 0.01^{i}	1.17^{d}	0.47 ± 0.01^{bc}	0.41 ± 0.00^{de}	0.31 ± 0.01^{h}	0.40^{c}
	Mean	1.63^{a}	1.38^{b}	1.15^{c}		0.47^{a}	0.42^{b}	0.31^{c}	
2023/2024	T1	1.65 ± 0.01^{c}	1.35 ± 0.01^{g}	1.19 ± 0.01^{h}	1.39^{c}	0.43 ± 0.01^{e}	0.37 ± 0.01^{g}	0.23 ± 0.01^{i}	0.34^{d}
	T2	1.72 ± 0.01^{b}	1.56 ± 0.01^{e}	1.34 ± 0.01^{g}	1.54^{b}	0.52 ± 0.01^{b}	0.46 ± 0.01^{d}	0.35 ± 0.01^{g}	0.45^{b}
	T3	1.87 ± 0.01^{a}	1.74 ± 0.01^{b}	1.43 ± 0.01^{f}	1.68^{a}	0.56 ± 0.01^{a}	0.48 ± 0.01^{c}	0.40 ± 0.01^{f}	0.48^{a}
	T4	1.62 ± 0.01^{d}	1.16 ± 0.01^{i}	0.94 ± 0.00^{j}	1.24^{d}	0.51 ± 0.00^{b}	0.44 ± 0.01^{de}	0.32 ± 0.01^{h}	0.42^{c}
	Mean	1.71^{a}	1.45^{b}	1.22^{c}		0.51^{a}	0.44^{b}	0.33^{c}	

Data are expressed as averages ± standard deviation (n = 3), with different superscript letters indicating significant differences at the $p \leq 0.05$ level according to Tukey's test.

Table 8. The contents of potassium and protein in tuber tissues of potato plants as affected by varying irrigation levels, application of *Trichoderma* consortium with potassium ore, and their interaction during growing seasons of 2022/2023 and 2023/2024.

	Treatment	Potassium (%)				Protein (%)			
		Full irrigation	Moderate irrigation	Stress irrigation	Mean	Full irrigation	Moderate irrigation	Stress irrigation	Mean
2022/2023	T1	1.72 ± 0.02^{b}	1.61 ± 0.01^{c}	1.30 ± 0.00^{g}	1.55^{b}	9.18 ± 0.08^{c}	7.99 ± 0.03^{g}	6.94 ± 0.03^{h}	8.25^{c}
	T2	1.51 ± 0.01^{d}	1.39 ± 0.00^{f}	1.10 ± 0.01^{i}	1.33^{c}	10.17 ± 0.11^{b}	9.25 ± 0.03^{e}	7.97 ± 0.03^{g}	9.13^{b}
	T3	1.85 ± 0.00^{a}	1.72 ± 0.01^{b}	1.41 ± 0.00^{f}	1.66^{a}	11.14 ± 0.06^{a}	10.30 ± 0.06^{b}	8.47 ± 0.02^{f}	9.97^{a}
	T4	1.46 ± 0.01^{e}	1.19 ± 0.00^{h}	0.73 ± 0.00^{j}	1.26^{d}	9.59 ± 0.05^{d}	6.92 ± 0.12^{h}	5.52 ± 0.04^{i}	7.34^{d}
	Mean	1.63^{a}	1.47^{b}	1.13^{c}		10.18^{a}	8.61^{b}	7.23^{c}	
2023/2024	T1	1.80 ± 0.01^{b}	1.70 ± 0.01^{c}	1.36 ± 0.00^{h}	1.62^{b}	10.33 ± 0.07^{c}	8.42 ± 0.05^{g}	7.39 ± 0.05^{h}	8.71^{c}
	T2	1.58 ± 0.01^{d}	1.46 ± 0.01^{g}	1.16 ± 0.00^{j}	1.40^{c}	10.75 ± 0.03^{b}	9.75 ± 0.04^{e}	8.37 ± 0.04^{g}	9.62^{b}
	T3	1.95 ± 0.01^{a}	1.81 ± 0.01^{b}	1.49 ± 0.01^{f}	1.75^{a}	11.72 ± 0.04^{a}	10.87 ± 0.04^{b}	8.91 ± 0.03^{f}	10.50^{a}
	T4	1.54 ± 0.01^{e}	1.24 ± 0.01^{i}	0.77 ± 0.01^{k}	1.18^{d}	10.11 ± 0.04^{d}	7.26 ± 0.06^{h}	5.84 ± 0.01^{i}	7.74^{d}
	Mean	1.72^{a}	1.55^{b}	1.19^{c}		10.73^{a}	9.08^{b}	7.63^{c}	

Data are expressed as averages ± standard deviation (n = 3), with different superscript letters indicating significant differences at the $p \leq 0.05$ level according to Tukey's test.

Irrigation, resulted in decreases of 4.4%, 9.5%, 17.6%, and 11% in nitrogen, phosphorus, potassium, and protein content of potato tubers, respectively.

Quality characteristics of potato tubers

The percentage of dry matter and starch yield (ton·ha^{-1}) considerably decreased with increased water scarcity (Table 9). The reduction percentage peaked at Stress Irrigation, compared to Full Irrigation, registering 18.5% and 18.7% in the 1st and 2nd, season respectively. Moreover, the application of 50% mica combined with a *Trichoderma* consortium resulted in a notable boost in dry matter and starch yield compared to chemical fertilizer, with an increase of 16.2% in dry matter and 74.4% in starch yield over two seasons. The statistical analysis indicates a highly significant interaction effect on potato tuber dry matter and starch yield across the two seasons. At Full Irrigation, dry matter (%) and starch yield improved by 13.6% and 73.3%, respectively, with the application of mica combined with *Trichoderma* consortium inoculation (T3) in comparison to chemical fertilizer (T1). T3 at Moderate Irrigation exhibited a 5.5% rise in dry matter and a 9.3% increase in starch yield, averaged over two seasons, in comparison to chemical fertilizer at Full Irrigation. Despite achieving a 40% reduction in water consumption at Stress Irrigation, the decline in dry matter and starch yield over two seasons was merely 7.0% and 30.2%, respectively.

The results for total carbohydrates, total antioxidants, total phenols, and total flavonoids in potato tubers are displayed in Tables 10 and 11**,** which indicate substantial differences among the experimental treatments. A Stress Irrigation water deficit diminished total carbohydrate levels in potato tubers, while simultaneously increasing total antioxidants, total phenols, and total flavonoids content. The average reduction percentage in total carbohydrates was 44.7% over two seasons. Total antioxidants, total phenols, and total flavonoids increased by 28.2%, 28.9%, and 71.5% during two seasons, respectively. The organic treatments yielded results contrary to the yield trait, with T3 (50% mica + *Trichoderma* consortium) exhibiting the lowest values for total antioxidants, total phenols, and total flavonoids, while T4 (*Trichoderma* consortium) demonstrated the highest values, followed by the chemical fertilizer treatment, due to water stress. Nevertheless, T3 recorded the greatest total carbohydrate value, followed by T2 (50% CF + *Trichoderma* consortium). The interaction effect indicated that the total carbohydrate content in potato tubers was elevated under Full Irrigation with the application of 50% mica + *Trichoderma* consortium. Simultaneously, the identical treatment at Moderate Irrigation surpassed the control treatment at Full Irrigation, exhibiting an increase of 24.9% in the 2022/2023 season and 24.5% in the 2023/2024 season. Nevertheless, total antioxidants, total phenols, and total flavonoids exhibited higher levels under water deficit with *Trichoderma* consortium inoculation compared to other treatments, with percentage increases of 35.3%, 35.5%, and 82.8% across both seasons, respectively, in comparison to chemical fertilizer.

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Table 9. Influence of varying irrigation levels, application of *Trichoderma* consortium with potassium ore, and their interaction on dry matter percentage and starch yield (ton·ha^{-1}) during growing seasons of 2022/2023 and 2023/2024.

	Treatment	Dry matter (%)				Starch yield (ton·ha^{-1})			
		Full irrigation	Moderate irrigation	Stress irrigation	Mean	Full irrigation	Moderate irrigation	Stress irrigation	Mean
2022/2023	T1	21.31 ± 0.61^{cd}	19.82 ± 0.28^{efg}	16.21 ± 0.08^{i}	19.11^{c}	3.98 ± 0.10^{cd}	2.86 ± 0.16^{ef}	1.43 ± 0.03^{h}	2.75^{c}
	T2	22.99 ± 0.47^{ab}	21.05 ± 0.64^{cde}	18.55 ± 0.50^{gh}	20.86^{b}	5.60 ± 0.20^{b}	3.24 ± 0.14^{e}	2.08 ± 0.08^{g}	3.64^{b}
	T3	24.29 ± 0.28^{a}	22.36 ± 0.33^{bc}	19.71 ± 0.46^{fg}	22.12^{a}	6.96 ± 0.06^{a}	4.34 ± 0.16^{c}	2.76 ± 0.12^{f}	4.89^{a}
	T4	20.10 ± 0.53^{def}	18.31 ± 0.21^{h}	17.78 ± 0.23^{h}	18.73^{c}	3.75 ± 0.18^{d}	2.52 ± 0.03^{f}	1.92 ± 0.07^{g}	2.73^{c}
	Mean	22.17^{a}	20.38^{b}	18.06^{c}		5.01^{a}	3.24^{b}	2.05^{c}	
2023/2024	T1	22.08 ± 0.40^{c}	20.42 ± 0.29^{e}	16.76 ± 0.05^{g}	19.75^{c}	4.41 ± 0.08^{d}	3.13 ± 0.12^{g}	1.56 ± 0.01^{j}	3.03^{c}
	T2	23.78 ± 0.34^{b}	21.91 ± 0.40^{cd}	18.94 ± 0.73^{f}	21.54^{b}	6.12 ± 0.15^{b}	3.58 ± 0.11^{f}	2.23 ± 0.13^{i}	3.97^{b}
	T3	25.01 ± 0.19^{a}	23.43 ± 0.23^{b}	20.64 ± 0.16^{e}	23.03^{a}	7.60 ± 0.06^{a}	4.84 ± 0.03^{c}	3.10 ± 0.01^{g}	5.18^{a}
	T4	21.04 ± 0.09^{de}	18.92 ± 0.15^{f}	18.38 ± 0.13^{f}	19.45^{c}	4.14 ± 0.03^{e}	2.79 ± 0.00^{h}	2.10 ± 0.03^{i}	3.01^{c}
	Mean	22.98^{a}	21.17^{b}	18.68^{c}		5.56^{a}	3.58^{b}	2.24^{c}	

Values are expressed as the mean of three replicates ± SD, with different superscript letters indicating significant differences at the $p \leq 0.05$ level according to Tukey's test.

Table 10. Mean of total carbohydrate and total antioxidants influenced by varying irrigation levels, application of *Trichoderma* consortium with potassium ore, and their interaction.

	Treatment	Total carbohydrate (mg·g^{-1} fresh weight)				Total antioxidants (mg·g^{-1} fresh weight)			
		Full Irrigation	Moderate Irrigation	Stress Irrigation	Mean	Full Irrigation	Moderate Irrigation	Stress Irrigation	Mean
2022/2023	T1	42.21 ± 0.59^{d}	36.20 ± 0.57^{e}	20.31 ± 0.16^{g}	32.91^{c}	89.24 ± 1.17^{e}	96.12 ± 0.21^{cd}	112.05 ± 1.09^{b}	99.14^{b}
	T2	48.40 ± 0.96^{c}	43.32 ± 0.51^{d}	29.06 ± 0.44^{f}	40.26^{b}	79.03 ± 0.32^{f}	85.99 ± 0.37^{e}	95.11 ± 0.77^{d}	86.71^{c}
	T3	62.88 ± 1.22^{a}	52.73 ± 0.43^{b}	38.23 ± 0.43^{e}	51.28^{a}	61.29 ± 0.47^{h}	73.29 ± 0.45^{g}	87.99 ± 0.74^{e}	74.19^{d}
	T4	36.100 ± 0.30^{e}	26.97 ± 0.60^{f}	17.58 ± 0.50^{h}	26.88^{d}	95.02 ± 0.93^{d}	99.31 ± 1.15^{c}	120.99 ± 2.87^{a}	105.11^{a}
	Mean	47.40^{a}	39.81^{b}	26.30^{c}		81.15^{c}	88.68^{b}	104.04^{a}	
2023/2024	T1	44.99 ± 0.89^{d}	38.38 ± 1.14^{e}	21.66 ± 0.44^{g}	35.00^{c}	85.32 ± 0.87^{e}	91.87 ± 0.42^{d}	107.06 ± 0.46^{b}	94.75^{b}
	T2	51.48 ± 0.88^{c}	45.81 ± 0.95^{d}	30.84 ± 0.85^{f}	42.71^{b}	75.94 ± 0.89^{f}	82.23 ± 0.92^{e}	91.25 ± 0.47^{d}	83.14^{c}
	T3	67.36 ± 1.14^{a}	56.03 ± 0.80^{b}	40.47 ± 0.83^{e}	54.62^{a}	58.70 ± 0.86^{h}	70.13 ± 0.92^{g}	84.13 ± 0.15^{e}	70.99^{d}
	T4	38.79 ± 0.90^{h}	28.98 ± 0.58^{f}	38.57 ± 0.78^{e}	28.78^{d}	91.17 ± 0.47^{d}	95.25 ± 0.59^{c}	116.23 ± 1.84^{a}	100.88^{a}
	Mean	50.60^{a}	42.29^{b}	27.94^{c}		77.78^{c}	84.87^{b}	99.67^{a}	

Data are expressed as averages ± standard deviation ($n = 3$), with different superscript letters indicating significant differences at the $p \leq 0.05$ level according to Tukey's test.

Table 11. Total phenols and flavonoids contents in response to varying irrigation levels, application of *Trichoderma* consortium with potassium ore, and their interaction.

	Treatment	Total phenols (mg·g^{-1} fresh weight)				Total flavonoids (mg·g^{-1} fresh weight)			
		Full Irrigation	Moderate Irrigation	Stress Irrigation	Mean	Full Irrigation	Moderate Irrigation	Stress Irrigation	Mean
2022/2023	T1	55.20 ± 0.80^{f}	64.69 ± 0.82^{d}	70.82 ± 0.54^{b}	63.57^{b}	3.86 ± 0.05^{f}	5.17 ± 0.03^{d}	6.61 ± 0.05^{b}	5.21^{b}
	T2	47.53 ± 0.33^{g}	54.23 ± 1.12^{f}	64.19 ± 0.87^{d}	55.31^{c}	3.05 ± 0.03^{g}	4.44 ± 0.04^{e}	5.55 ± 0.03^{c}	4.36^{c}
	T3	41.98 ± 0.65^{i}	44.69 ± 0.87^{h}	53.03 ± 0.88^{f}	46.56^{d}	2.21 ± 0.02^{h}	3.69 ± 0.02^{f}	4.50 ± 0.04^{e}	3.47^{d}
	T4	59.03 ± 0.90^{e}	68.28 ± 0.65^{c}	74.82 ± 0.58^{a}	67.37^{a}	4.57 ± 0.24^{e}	5.49 ± 0.03^{c}	7.06 ± 0.07^{a}	5.71^{a}
	Mean	50.93^{c}	57.97^{b}	65.71^{a}		3.42^{c}	4.70^{b}	5.93^{a}	
2023/2024	T1	52.90 ± 0.21^{f}	61.95 ± 0.27^{d}	67.78 ± 0.77^{b}	60.87^{b}	3.68 ± 0.03^{g}	4.93 ± 0.01^{d}	6.26 ± 0.04^{b}	4.96^{b}
	T2	45.59 ± 0.66^{h}	51.98 ± 0.72^{fg}	61.80 ± 0.34^{d}	53.13^{c}	2.90 ± 0.01^{i}	4.24 ± 0.02^{f}	5.29 ± 0.02^{c}	4.14^{c}
	T3	40.32 ± 0.34^{j}	43.23 ± 0.34^{i}	50.83 ± 0.29^{g}	44.79^{d}	2.12 ± 0.02^{j}	3.52 ± 0.01^{h}	4.26 ± 0.03^{f}	3.30^{d}
	T4	56.88 ± 0.41^{e}	65.36 ± 0.57^{c}	71.59 ± 0.53^{a}	64.61^{a}	4.52 ± 0.06^{e}	5.24 ± 0.02^{c}	6.72 ± 0.03^{a}	5.49^{a}
	Mean	48.92^{c}	55.63^{b}	63.00^{a}		3.31^{c}	4.48^{b}	5.63^{a}	

Data are expressed as averages ± standard deviation ($n = 3$), with different superscript letters indicating significant differences at the $p \leq 0.05$ level according to Tukey's test.

Cluster analysis

Cluster analysis in this investigation was utilized to examine the data collected to identify all potential positive and negative correlations between the plant responses to treatments and potato tuber characteristics, yield, and physiological and biochemical parameters. The first dendrograms (Fig. 2a) illustrate the impacts of several irrigation levels on potato productivity, tuber attributes, and physiological and biochemical assessments. The similarity coefficient among irrigation levels varied from 0.87 to 0.99, resulting in the formation of two clusters at a similarity threshold of 0.90. The irrigation regimes of Full Irrigation and Moderate Irrigation were categorized together in cluster I, while Stress Irrigation was classified separately in cluster II. Fig. 2b illustrated the cluster resulting from the organic treatments, classified into two primary groups. Cluster I consisted of a combination of *Trichoderma* consortium inoculation with 50% chemical fertilizer or 50% mica. Cluster II

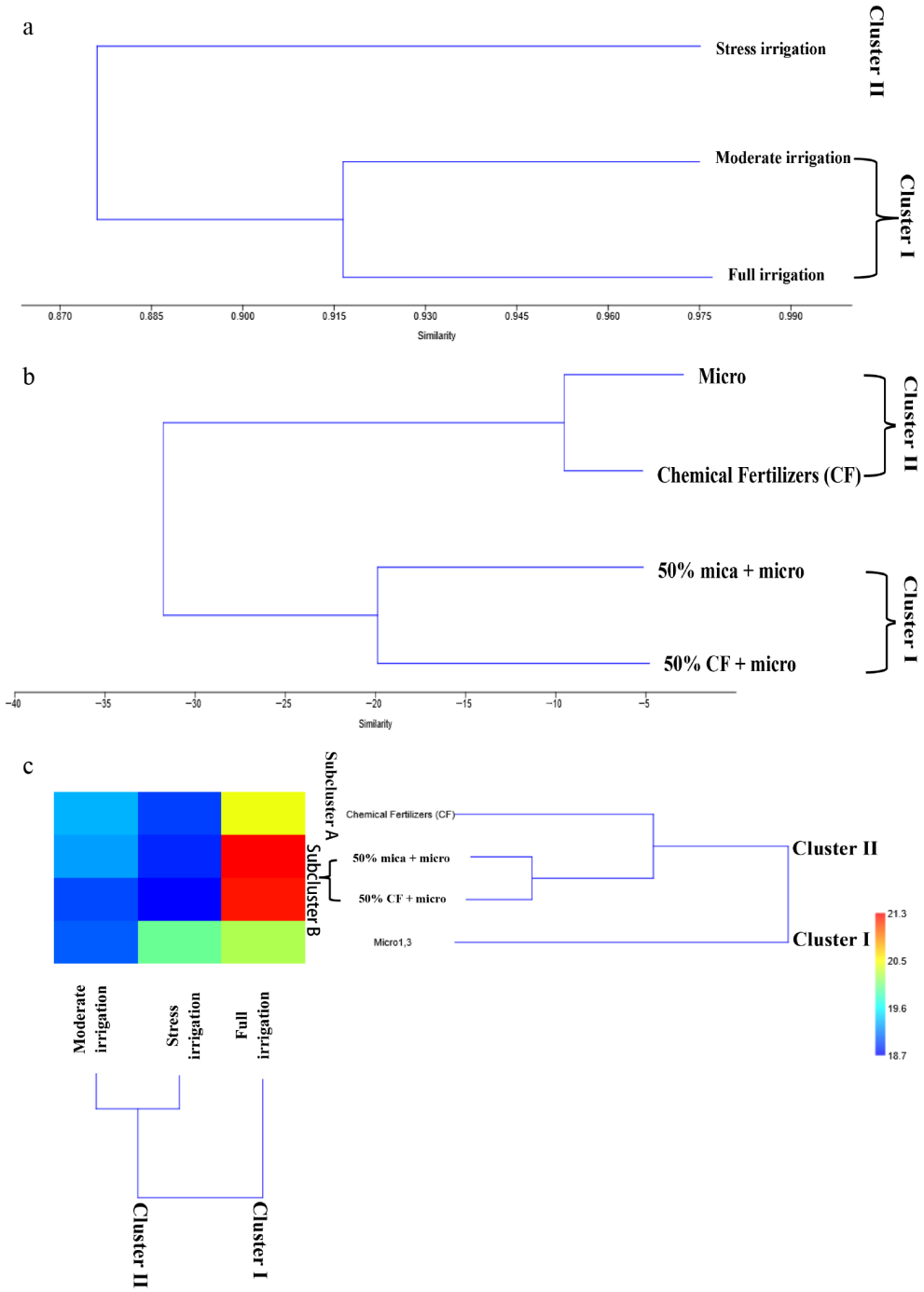

Fig. 2 Cluster analysis of (a) diverse irrigation regimes, with or without (b) *Trichoderma* consortium inoculation (micro) and potassium ore (mica), and (c) their interaction based on yield and yield components, irrigation water productivity, and potato tuber chemical composition, utilizing paired-group UPGMA and Bray-Curtis similarity index.

comprised the chemical fertilizer treatment (control) and a sole application of *Trichoderma* consortium inoculation. The interaction between experimental components (different irrigation regimes and chemical or organic treatments) demonstrated that the resulting cluster illustrated in Fig. 2c does not correspond precisely with the individual effects of the research factors shown in Fig. 2a, b. The use of a *Trichoderma* consortium inoculation is isolated within an individual group (cluster I), as opposed to dendrograms created in Fig. 2b. Meanwhile, other treatments classified within the same group (cluster II) are subdivided into two sub-groups. Sub-group A comprises chemical fertilizer treatment (control), whereas sub-group B involves *Trichoderma* consortium inoculation in combination with either 50% chemical fertilizer or with 50% mica. Simultaneously, the irrigation level of Full Irrigation was categorized in a distinct group (cluster I), while Moderate Irrigation and Stress Irrigation were grouped together in cluster II.

Discussion

The utilization of irrigation water differs among various crops and water management systems, highlighting the significant impact of

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efficient irrigation techniques like drip irrigation. Irrigation levels significantly affect potato productivity, as optimal or near-optimal water supply generally maximizes tuber production, although moderate deficiencies may diminish yields yet improve water use efficiency in arid environments[42]. Research indicates that yield grows linearly with applied water until reaching ideal levels, after which additional water yields diminishing returns. Deficit irrigation frequently reduces yields by 7%–35%, contingent upon severity and soil type[43]. Full irrigation yields range from 46–57 t·ha^{-1} in trials, decreasing by 6%–14% under 25%–40% deficiencies. In sandy soils, 90% of the evapotranspiration (ETo) resulted in optimal yields with drip irrigation systems, highlighting uniform moisture distribution in the root zone. In the arid regions, optimal yields reached 46.8 t·ha^{-1} with a total of 180 mm of water (20 mm every 7 d), achieving a water use efficiency of up to 15.7 kg·m^{-3}[44]. Irrigation levels markedly enhance average tuber weight. This contrasts with Wenzel et al.[45], who showed no direct correlation between irrigation amount and the mean tuber weight. Improving potato yield may result from the consortium of *Trichoderma*, which boosts the physical characteristics of sandy calcareous soil by facilitating organic matter decomposition, augmenting porosity, and fostering superior root development.

Irrigation treatments substantially influence NPK content in potato tubers, with complete or near-complete irrigation typically optimizing nutrient absorption, whereas moderate deficits may occasionally elevate specific nutrient concentrations but diminish overall yields[43,46,47]. Complete irrigation at 100% evapotranspiration or similar levels boosts NPK uptake in tubers by optimizing soil moisture, hence improving nutrient availability and root absorption. Research indicates that 100% ET irrigation yields superior tuber NPK concentrations compared to deficit irrigation, corresponding with trends observed in sandy soils where sustained moisture mitigates stress-induced nutrient uptake limitations[43,46,48]. Moderate deficit irrigation (e.g., 75% or 66% field capacity) may sustain or marginally increase NPK concentrations by concentrating dry matter; however, severe deficits diminish overall uptake and tuber yields by 12%–42%. Drip irrigation at 0.4–0.8 pan evaporation (PE) demonstrates no significant alteration in tuber NPK, whereas overall plant absorption increases with elevated water levels[43,46,47]. The integration of irrigation with organic amendments or nitrogen fertilization enhances NPK benefits, as demonstrated in trials where complete irrigation alongside soil conditioners increased marketable tuber yields and nutritional composition. In environments such as Egypt's sandy calcareous soils, comprehensive drip irrigation enhances NPK levels, as in a previous study on cabbage and maize. Potassium application rates of 200–400 kg·ha^{-1}, combined with 500 mm of water input, enhance tuber quality[46,49,50]. *Trichoderma* species, functioning as potassium-solubilizing microorganisms, release potassium and phosphorus from natural mineral sources (like mica), converting them into forms accessible to plants. The findings indicated that the application of mica and *Trichoderma* consortium inoculation improved nitrogen, phosphorus, potassium, and protein concentrations in potato tubers compared to chemical fertilizers under conditions of water shortage. The fungi enhance plant resilience to abiotic challenges prevalent in sandy soils, including low water retention and high alkalinity, by promoting root stimulation and nutrient absorption.

The findings indicated that starch yield diminished due to the imposition of water deficit, whereas it was augmented by the application of potassium roe and *Trichoderma* consortium inoculation. Prior research has demonstrated that starch content, the primary quality criterion in starch potato food production, is genetically determined and influenced by several subordinate external factors, such as climatic conditions, water availability, soil characteristics, and fertilization[45,51–53]. Furthermore, the obtained data demonstrated a positive correlation between total yield and starch yield, while drought stress resulted in yield reduction, thereby decreasing starch yield[45]. Irrigation levels significantly affect the total carbohydrate content in potato tubers, with complete irrigation (100% ETc) often optimizing accumulation in contrast to deficiency situations. Water stress diminishes photosynthesis and the transfer of assimilates, resulting in decreased total carbohydrates, while several studies indicate a shift toward soluble sugars. Research regularly demonstrates elevated total carbohydrates with sufficient irrigation. For example, an increase from 50% to 100% ETo elevated total carbohydrates in tubers by 27.7% over two seasons. Complete irrigation (100% ET) produced a maximum of 63.8% total carbohydrates, decreasing to 50% at 50% ET[54]. Water deficiencies diminish total carbohydrates by lowering chlorophyll levels, photosynthetic activity, and the conversion of starch into sugars. Conventional farming with full water supply achieved 86.2% total carbohydrates, whereas 80% water stress reduced it to 78.2%; organic systems exhibited analogous patterns, peaking at 82.8% under extreme stress (50% ETc). Zahran et al.[55] shown that the utilization of soil conditioner markedly improved the protein, carbohydrates, vitamin C, and total phenolic content of pea seeds in comparison to chemical fertilizer. Certain reports suggest elevated levels of soluble sugars during deficits, partially offsetting overall losses[46,54,56].

Fungal potassium solubilization improves soil fertility by transforming insoluble minerals into forms accessible to plants. This method facilitates sustainable agriculture, especially in potassium-deficient soils, in accordance with bioremediation and plant growth enhancement strategies[8,57]. Fungi solubilize potassium by acidifying the environment through the generation of organic acids, including gluconic, citric, and oxalic acids, which decrease pH and dissolve minerals such as feldspar or biotite. Chelation and complexation by fungal metabolites destabilize mineral structures, whereas certain strains demonstrate redox activity to promote ion release. The synthesis of polysaccharides facilitates mineral aggregation and decomposition, hence improving efficiency[15,16,58]. These fungi enhance nutrient absorption, seed germination, and crop productivity (e.g., maize growth enhancement), hence diminishing the use of chemical fertilizers. In potassium-deficient areas, bioinoculants integrate solubilization with biocontrol, thereby reducing environmental contamination. Subsequent investigation ought to enhance strain consortia for field effectiveness[16,57,59].

Research indicated that microbial consortia containing *Trichoderma* had significantly enhanced efficacy in diverse agricultural applications[60]. Furthermore, the innovation of biofertilizers utilizing *Trichoderma*-based microbiomes not only promotes plant growth but also rehabilitates healthy soil microbiota, particularly in impoverished and degraded agricultural regions[61]. The genus *Trichoderma* (*T. koningii, T. harzianum, T. citrinoviride,* and *T. viridescens*) possesses the ability to solubilize insoluble potassium from minerals such as biotite and feldspar, thereby rendering it accessible for plant absorption. *Trichoderma koningii* and *T. harzianum* significantly enhanced potassium solubility, achieving a rise of up to 123% compared to controls in media such as Altomare et al.[18]. Consortia of *T. asperellum*, *T. asperelloides*, and *T. harzianum* were observed to enhance cucumber seedling growth more effectively than the monoculture of an individual strain[20]. The application of *T. harzianum* and *T. virens* consortia in tomato plants promotes plant growth and enhances the rhizosphere microbial population[62,63]. Generally, the application of a *Trichoderma* consortium in

conjunction with natural potassium sources (e.g., mica) considerably enhances potato growth, tuber production, and nutrient absorption in sandy calcareous soil. *Trichoderma* enhances soil structure and solubilizes mineral-bound minerals, offsetting the low nutrient retention of sandy soils and improving the efficacy of natural fertilizers. Future research under diverse soil and climatic conditions is advised to confirm the reliability of the synergistic effects of *Trichoderma* and potassium ore, as well as their long-term implications for soil fertility, rhizosphere microbial communities, and postharvest tuber quality, thereby enhancing their integration into sustainable potato production systems.

Conclusions

This study demonstrated that the combined application of *T. harzianum* and *T. longibrachiatum* as a microbial consortium is a compatible and effective biofertilization strategy. Both isolates exhibited strong capabilities for organic acid production and potassium solubilization, particularly from mica as a natural potassium source. The consortium significantly enhanced potato growth, yield components, and tuber quality compared to conventional chemical fertilization. Importantly, the integration of 50% mica with the *Trichoderma* consortium improved irrigation water productivity and maintained competitive yields under moderate water deficit, highlighting its potential in sustainable and water-efficient agriculture. Additionally, the treatment positively influenced tuber nutritional composition and quality attributes, while mitigating the adverse effects of water stress. Furthermore, it enhanced the chemical and qualitative content of tubers, including nitrogen, phosphorus, potassium, protein, starch, total carbohydrates, total antioxidants, total phenols, and total flavonoids. These findings confirm that the *Trichoderma* consortium can serve as an eco-friendly alternative to reduce chemical fertilizer inputs and optimize crop performance under varying irrigation conditions. Future research should focus on large-scale field validation of the *Trichoderma* consortium across different soil types, climatic conditions, and crop systems to confirm its broader applicability. The development of stable, cost-effective bioformulations and carrier systems for long-term storage and field application is also essential. Additionally, integrating the consortium with other beneficial microorganisms could further enhance nutrient availability and stress tolerance. Exploring its role in improving plant resilience to multiple abiotic stresses, such as salinity and drought, will be valuable. Finally, long-term studies assessing soil health, microbial diversity, and environmental impacts will support the adoption of this approach as a cornerstone of sustainable and climate-smart agricultural practices.

Author contributions

The authors confirm their contributions to the paper as follows: study conception and design: Mostafa HHA, Mahmoud GAE, Hefzy M; experimental work: Mostafa HHA, Mahmoud GAE, Hefzy M; data analysis: Mostafa HHA, Mahmoud GAE, Hefzy M; draft manuscript preparation: Mostafa HHA, Mahmoud GAE, Hefzy M. All authors reviewed the results and approved the final version of the manuscript.

Data availability

The datasets generated during and/or analyzed in the current study are available from the corresponding author upon reasonable request.

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Conflict of interest

The authors declare that they have no conflict of interest.

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