Using phosphorus-dissolving microorganisms for quinoa quality enhancement: effects on root and leaf traits and nutrient composition of quinoa seedlings in coastal wetlands

Yanan Hou[1], Deliang Xu[1], Yan Xu[1], Shan Cong[2], Xiaohong Guo[1], Nan Wu[1]*

[1]School of Resources and Environmental Engineering, Ludong University, Yantai, Shandong, China; [2]Yantai Agriculture Technology Extension Center, Yantai, Shandong, China

***Corresponding Author:** Nan Wu, School of Resources and Environmental Engineering, Ludong University, Yantai, Shandong, China. Email: 38019113@qq.com

Academic Editor: Jelena Popović-Djordjević, PhD, Department for Food Technology and Biochemistry, Faculty of Agriculture, University of Belgrade, Belgrade, Serbia

Received: 15 July 2024; Accepted: 20 March 2025; Published: 27 May 2025

ORIGINAL ARTICLE

Abstract

Quinoa (*Chenopodium quinoa* Willd) is rich in protein and dietary fiber, both of which are safe and healthy. In-depth research is being conducted on the nutritional components of quinoa. We explore the effects of phosphorus-solubilizing microorganisms on the root and leaf traits, protein content, biomass, and nutritional elements of quinoa. This study added different phosphorus-solubilizing microbial agents to quinoa grown in saline alkali soil (blank control, CK group; Kaiduo explosive root (arbuscular mycorrhizal fungi, AMF) was applied alone, K group; and compound application of Kaiduo explosive root and dephosphorizing bacteria (KJ group), analyzing their effects on the root and leaf traits, protein content, biomass, and nutritional elements of quinoa. The results revealed that the combined application of AMF and dephosphorylating bacteria can (a) promote the root and leaf development of quinoa, (b) increase the fresh weight and dry weight of quinoa, and (c) increase the protein content and nutrient elements such as iron and potassium in quinoa. The conclusion is that the addition of dephosphorylating microorganisms can improve the quality of quinoa and popularize the cultivation of quinoa in coastal wetlands.

Keywords: Arbuscular mycorrhizal fungi; Leaf traits; Nutrient elements; Phosphate-solubilizing bacteria; Quinoa; Root traits

Introduction

Quinoa (*Chenopodium quinoa* Willd) is an annual herbaceous dicotyledonous plant of the Amaranthaceae family, native to the Andean region of South America. It is highly resistant to environmental stresses and has the advantage of being tolerant to cold, drought, and salinity (Huang *et al*., 2021; Yasui *et al*., 2016). Quinoa is rich in protein, dietary fiber, and other nutrients, which makes it a safe and healthy food (Ray *et al*., 2023). In recent years, numerous studies have been done on the nutrient composition of quinoa. With the extremely high nutritional and economic value of quinoa, its cultivation and promotion have become particularly important (Jaiswal *et al*., 2022). However, there is an obvious lack of research on whether phosphate-solubilizing microorganisms have an effect on root and leaf traits, biomass, protein content, and nutrients in quinoa seedlings.

ISSN 1757-837X online, DOI 10.15586/qas.v17i2.1552

Arbuscular mycorrhizal fungi (AMF) are inter-root microorganisms that are widely present in the soil and can form symbiotic relationships with the root systems of more than 80% of terrestrial plants on earth, which can enhance the uptake of nutrients in the soil and improve the resistance characteristics of plants (Wang *et al.*, 2024; Lee *et al.*, 2023; Patel *et al.*, 2016). When AMF are symbiotic with plant roots, the mycorrhizal fungi are able to absorb nitrogen and phosphorus in the soil and convert them into forms that can be directly absorbed and utilized by the plants (Fan *et al.*, 2024). It was found that AMF enhanced the activities of acid phosphatase, phytase, and alkaline phosphatase in the soil; enhanced the mineralization of organic phosphorus in the soil; and lowered the content of organic phosphorus in the soil. It was found that the AMF could significantly enhance the root vigor of Dianchonglou (*Paris polyphylla var. yunnanensis*) and encourage the root system to take up more nutrients from the soil such as nitrogen, phosphorus, and potassium (Li *et al.*, 2023). It was founded that AMF could effectively inhibit the transport of Na^+ in the stem of sorghum (*Sorghum halepense L.*) plants under salt stress, reducing the toxic effect of Na^+ on the plant and improving the ability of sorghum to resist salt stress (Yamato *et al.*, 2008). However, further research is required to assess the effects of AMF on the root and leaf traits, biomass, protein content, and nutritional elements of quinoa.

Phosphate-solubilizing bacteria (PSB) can colonize in the inter-roots of plants and form symbiotic relationships with plants, and they play a role in the growth and development of plants (Koczorski *et al.*, 2023; Wang *et al.*, 2023). PSB can efficiently convert insoluble phosphorus in the soil into phosphorus available in the inter-roots of plants, so as to increase the uptake of phosphorus in the plant root system (Tian *et al.*, 2021; Turan *et al.*, 2023; Ullah *et al.*, 2023). It is inoculated sprouted walnuts with inter-root PSB and found that the photosynthetic rate and inter-cellular CO_2 concentration of walnuts in the experimental group increased significantly compared with that of the control group, thus verifying the growth-promoting effect of inter-root PSB on walnuts. Wang *et al.* (2022) screened out PSB with very high phosphorus-solubilizing ability and IAA production, and inoculated wheat with PSB. The results of the study showed that the yield of wheat inoculated with PSB was significantly increased by 14.42%; it also proved that the active phosphorus fraction of the soil inoculated with PSB was significantly increased by 122.04% compared with that of the uninoculated soil; and PSB promoted the growth and development of wheat and increased the yield by increasing the active phosphorus ratio and the content of IAA in the soil (Wang *et al.*, 2022). Quinoa is an excellent crop that is rich in a variety of nutrients (Le *et al.*, 2021). Through previous studies, it was found that there is a lack of research on the effect of dephosphorylating bacteria on the growth and development of quinoa; especially, the effect on quinoa's root and leaf traits, biomass, protein content, and nutrient elements needs to be studied in depth.

In order to investigate whether dephosphorylating microorganisms can promote the growth and development of quinoa in saline–alkaline soils, the main objectives of the present work were to explore the effects of dephosphorylating microorganisms on the growth of quinoa seedlings by setting up conditions for the addition of different microbial agents, so as to provide new research ideas and directions for the promotion and cultivation of quinoa in coastal wetlands.

Materials and Methods

Materials

Soil for testing was taken from the coastal wetland of the Yellow River Delta (37°38′N, 118°54′E). The basic soil properties are shown in Table 1; 9 pots: 16 cm (upper diameter) × 9 cm (lower diameter) × 16 cm (height); nine markers; PSB (PSBDYJP *Pseudomonas*; patent name: a strain of broadly adapted pH salt-tolerant PSB and its application; patent no.: ZL 2021 1 1415216.0; patent filing date: 2021/11/25; patentee: Ludong University Yantai, Shandong Province); Kaiduo explosive root microbial agent (Produced by Yantai Gutri Bio-technology Co.; Main technical indexes: effective number of live bacteria ≥ 1 billion/g, mycorrhizal fungi ≥ 200 million/g, humic acid of mineral origin ≥ 80%, small-molecule organic carbon ≥ 60%, B, Zn, Fe ≥ 0.1%); 270 seeds of quinoa (From Shandong Sericulture Research Institute).

Experimental design

Ratio of Kaiduo explosive root microbial agent: dissolve 0.5 g Kaiduo explosive root in 100 mL distilled water.

Table 1. Basic properties of saline soils in coastal wetlands of the Yellow River delta.

Indicators	Nitrogen content	Phosphorus content	Carbon content	EC	pH	Salinity
Quantity contained	100 mg•Kg^{-1}	5230 mg•Kg^{-1}	2600 mg•Kg^{-1}	2.150 mS/cm	7.453	1700 mg•Kg^{-1}

Set up three treatment groups: CK group—blank control group with 75 mL distilled water; K group—with a separate application of 50 mL Kaiduo explosive root microbial agent and 25 mL distilled water; KJ group—this composite application group consisted of 50 mL Kaiduo explosive root microbial agent and 25 mL phosphate solubilizing bacterial agent (10%). Each treatment consisted of three independent replications, for a total of nine pots.

Add an equal volume of saline–alkali soil (approximately 3/4 of the pot volume) to each pot, and apply Kaiduo explosive root microbial agent and phosphate-solubilizing bacterial agent to the soil according to the treatment groups. Select quinoa seeds (Qingli No. 2, 1000-seed weight: 3.78 g) of uniform size and full grains; soak the seeds for 1 h and then sow them. Evenly sow 30 quinoa seeds in each pot and then cover the soil with 1 cm of soil, room temperature should be approximately 25°C, humidity should be 80%. After sowing, water every 2 days to ensure 60% of the water holding capacity (WHC) in the field. Every week, apply Kaiduo explosive root microbial agent and phosphorus-solubilizing bacterial agent to the soil according to the treatment groups. Regular application of microbial agents during the growth period of quinoa can effectively promote the growth of quinoa. When the quinoa seedlings grow to four leaves and one center, the seedlings are fixed. When thinning, 20 evenly growing plants are kept in each pot. Measure data after 130 days of planting.

Indicator measurement

Root trait detection

Take one plant from each pot. When sampling, remove the root system and soil from the pot. Slowly and carefully shake off the soil from the root system to ensure the integrity of the root system structure, and clean the root system with flowing water. Use a root scanner (Microtek Scan Wizard EZ; Microtek International Inc., Taiwan) to scan the roots of quinoa seedlings cultured in soil for 130 days, save the data in an Excel spreadsheet, and save the scanned images.

Leaf trait detection

Take one plant from each pot, randomly select five leaves, separate them from the stem of the plant, and ensure the integrity of the petiole. Use a leaf scanner (F800A3 Jieyu Technology Video Display Platform; Jieyu Technology, Shenzhen, China) to scan the leaves of quinoa seedlings cultured in soil for 130 days. After connecting the computer to the leaf scanner and calibrating it, place five leaves of each plant on a whiteboard and flatten them with a plastic cover plate. After scanning, select all blades from the image for analysis, save the data in an Excel spreadsheet, and also save the scanned image.

Biomass detection

Take a plant with uniform growth in each group; separate the roots, stems, and leaves; and use an electronic balance (precision 0.0001g) to measure the fresh weight of the roots, stems, and leaves, respectively. After measurement, put them into a petri dish, mark well, bake at 105°C for 30 min to kill, then dry at 65°C to constant weight, and use an electronic balance (precision 0.0001g) to measure the dry weight of roots, stems, and leaves, respectively. Organize data in an Excel spreadsheet.

Protein content detection

Weigh 0.3 g of the sample and grind it using a mortar. Firstly, digest the sample by sequentially adding 0.5 g of copper sulfate, 5 g of potassium sulfate, 10 mL of concentrated sulfuric acid, and 2 mL of hydrogen peroxide into the digestion tube containing the sample. Use the program of formula 1 in the digestion instrument for digestion. After digestion is complete, wait for the digestive tract to cool completely before removing the tube for distillation and titration using an automatic Kjeldahl nitrogen analyzer (Kjeltec; FOSS, Denmark). Firstly, prepare 40% sodium hydroxide solution, 1% boric acid solution, and indicators of 0.1% bromocresol green and 0.1% methyl red; mix the prepared reagents (1 L 1% boric acid + 10 mL 0.1% bromocresol green + 7 mL 0.1% methyl red). Then, prepare and calibrate 0.1mol/L standard hydrochloric acid. The specific steps for calibration are to take anhydrous sodium carbonate and burn it in a high-temperature furnace at 270°C–300°C until it reaches a constant weight. Weigh 0.2 g of anhydrous sodium carbonate and dissolve it in 50 mL of water, add 10 drops of indicator solution, and titrate with the prepared 0.1mol/L standard hydrochloric acid solution until the solution changes color. Then, take 20 mL of 0.1% methyl red ethanol solution and 30 mL of 0.2% bromocresol green ethanol solution, shake well, and prepare the indicator. Create a new program on the automatic Kjeldahl nitrogen analyzer, with a diluent volume of 80, an alkali volume of 60, and a receiver volume of 30, and then empty the sample tube (Gonçalves *et al*., 2023). Connect the sample tube to the instrument, modify the sample quality, and start testing. To reduce errors, repeat the measurement three times.

Nutrient element detection

The detection instrument chosen is an inductively coupled plasma emission spectrometer (Prodigy-plus; Teledyne Tekmar, USA), which is mainly used to detect the concentration of nutrients such as Zn, B, Fe, Al, Mn, K, Na, P, Ca, Mg, and so on. The specific process is as follows: weigh 0.2 g of the sample in a 25 mL beaker, add 2 mL–5 mL of nitric acid, soak it overnight, and place it on an electric heating plate. Heat it at about 100°C until the solid sample is digested. Then, add 0.5 mL of perchloric acid and heat it to dissipate at about 140°C until the

white smoke is emitted. If the residue is not white, add nitric acid and perchloric acid to repeat the digestion, and finally extract with 7% hydrochloric acid solution. Measure on the machine after adjusting the content of the element to an appropriate volume (Lu *et al*., 2020). To reduce errors, each treatment group repeats the measurement three times.

Data processing and analysis

Use Microsoft Excel 2019 data analysis software to record the data obtained from the root and leaf scanner of quinoa seedlings, as well as data on plant biomass and nutrient content and calculate the mean and deviation. Use SPSS.26 data analysis software to test the normality of the data. Use SPSS.26 to perform one-way ANOVA at the 0.05 level, perform multiple comparisons using LSD and Duncan methods, and plot using Origin.2022.

Results and Analysis

Effects of phosphorus-solubilizing microorganisms on root and leaf traits of quinoa seedlings

Data on the root system of quinoa seedlings treated with different microbial agents are summarized in Table 2. The root length, number of connections, number of nodes, number of forks, and other root traits in the KJ group were higher than those in the K and CK groups. The root length of the KJ group increased by 26.23%, the number of root connections increased by 38.17%, the number of root nodes increased by 9.58%, and the number of root forks increased by 97.06% compared to the K group, which showed that compared with the application of AFM alone, the combined application of AFM and dephosphorylating bacteria could effectively promote the development of the root system of quinoa.

The leaf data of quinoa seedlings under different microbial agents are shown in Figures 1 and 2. The leaf area of the KJ group was significantly increased by 85.51% compared with the K group, which was twice as much as that of the CK group, and the perimeter of the leaves of the KJ group was significantly increased by 27.33% and 38.11% compared with that of the K and CK groups, which was in agreement with the results of the promotion of the root traits. The combination of arbuscular mycorrhizal fungus and phosphorus-solubilizing bacteria was more effective in the promotion of the leaf traits compared with the application of arbuscular mycorrhizal fungus alone.

Effect of phosphorus-solubilizing microorganisms on the biomass of quinoa seedlings

The biomass data of quinoa seedlings under different microbial agents are shown in Figures 3 and 4. The fresh weight and dry weight of the whole plant in the KJ group increased by 54.27% and 65.26% compared with that of the K group, and the fresh weight and dry weight of the whole plant in the K group increased by 19.60% and 41.79% compared with that of the CK group, respectively. The fresh weight and dry weight of the aboveground part in the KJ group increased by 53.96% and 64.37% compared with that of the K group, and the fresh weight and dry weight of the aboveground part in the K group increased by 20.09% and 50.00% compared with that of the CK group, respectively. The fresh weight and dry weight of the underground part in the KJ group increased by 54.31% and 75.00% compared with that of the K group, and the fresh weight and dry weight of the underground part in the K group did not differ much from that of the CK group. It proved that the effect of dephosphorylating microorganisms on the biomass of quinoa was basically the same as that of the root and leaf traits, and the combined application of AFM and dephosphorylating bacteria could increase the biomass of quinoa compared with the application of AFM alone.

Table 2. Root length, number of connections, number of nodes, and number of forks of quinoa seedlings treated with different microbial agents.

Index	CK	K	KJ
Root length (cm)	4.988±2.552[a]	5.517±1.003[a]	6.964±1.186[a]
Number of connections	30.000±20.396[a]	43.667±13.671[a]	60.333±21.700[a]
Number of nodes	36.333±26.386[a]	55.667±14.817[a]	61.000±16.310[a]
Number of forks	9.333±4.110[a]	11.333±4.989[a]	22.333±8.498[a]

Different lowercase letters indicate significant differences between processing groups (P<0.05). Significance test was performed using the LSD method. The analysis of variance showed that the effect of different treatment groups on the root length of quinoa was not significant, F(2, 6)=0.703, P=0.532; the effect of different treatment groups on the number of root connections in quinoa was not significant, F(2, 6)=1.290, P=0.342; the effect of different treatment groups on the number of root nodes in quinoa was not significant, F(2, 6)=0.855, P=0.471; the effect of different treatment groups on the number of root forks in quinoa was not significant, F(2, 6)=2.579, P=0.155. CK is the control group, K is the application of Kaiduo explosive root microbial agent, KJ is the application of Kaiduo explosive root microbial agent and PSB.

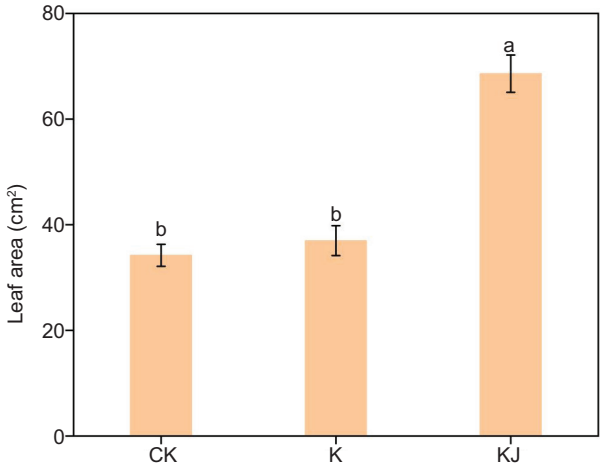

Figure 1. Leaf area of quinoa seedlings treated with different microbial agents. Different lowercase letters indicate significant differences between processing groups (*P*<0.05). CK is the control group, K is the application of Kaiduo explosive root microbial agent, KJ is the compound application of Kaiduo explosive root microbial agent and phosphate-solubilizing bacteria.

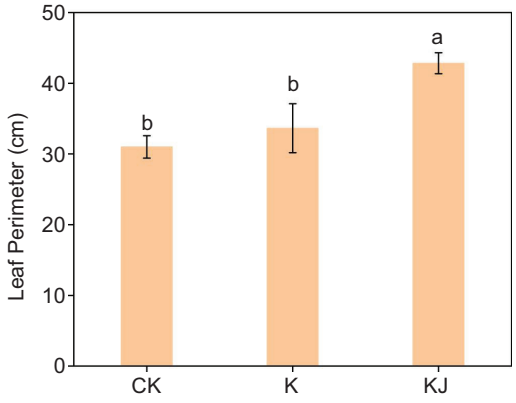

Figure 2. Leaf perimeter of quinoa seedlings treated with different microbial agents. Different lowercase letters indicate significant differences between processing groups (*P*<0.05). CK is the control group, K is the application of Kaiduo explosive root microbial agent, KJ is the compound application of Kaiduo explosive root microbial agent and phosphate-solubilizing bacteria.

The numbers in the figure represent the mean values for each treatment group. CK is the control group, K is the application of Kaiduo explosive root microbial agent, KJ is the compound application of Kaiduo explosive root microbial agent and phosphate-solubilizing bacteria.

The numbers in the figure represent the mean values for each treatment group. CK is the control group, K is the application of Kaiduo explosive root microbial agent, KJ is the compound application of Kaiduo explosive root microbial agent and phosphate-solubilizing bacteria.

Effect of phosphate-solubilizing microorganisms on the nutrient composition of quinoa seedlings

The protein content of quinoa seedlings under different microbial agents is shown in Table 3. There was no significant difference in the protein content of quinoa seedlings in the three different treatment groups, and the protein content of the KJ group was slightly higher than that of the CK group and the K group, and the protein content of the CK group was slightly higher than that of the K group. It indicated that compound application of AFM and PSB could increase the protein content of quinoa.

Nutrient element contents of quinoa seedlings under different microbial agents are shown in Figures 5 and 6. The microelements in the leaves of quinoa seedlings were Zn, B, Fe, Al, Mn, etc. The concentrations of zinc and boron elements in the K group were 10.18% and 3.14% higher than those in the KJ group, respectively, and the KJ group was higher than the CK group. The concentrations of iron and aluminum elements in the KJ group were 55.81% and 44.04% higher than those in the K group, respectively, and the K group was higher than the CK group; the concentration of manganese element in the CK group was 35.42% higher than that in the KJ group, and the KJ group was higher than the K group. It indicated that the application of phosphorus-dissolving microorganisms can increase the concentration of the microelements zinc, boron, iron, and aluminum in quinoa leaves. The macroelements in the leaves of quinoa seedlings include K, Na, P, Ca, Mg, etc. The concentrations of potassium and sodium elements in the KJ group were 10.77% and 38.61% higher than those in the K group, respectively, and the K group was higher than the CK group; the concentration of phosphorus element in the K group was 44.58% higher than that in the KJ group, and the KJ group was higher than the CK group; the concentrations of calcium and magnesium elements in the CK group were 4.58% and 18.14% higher than those in the KJ group, respectively, with the KJ group being higher than the K group. It indicated that the application of phosphorus-dissolving microorganisms can increase the concentration of the macroelements potassium, sodium, and phosphorus in quinoa leaves.

Discussion

Effect of phosphorus-solubilizing microorganisms on root and leaf traits of quinoa

Combined application of AMF and PSB can effectively improve root and leaf traits in quinoa seedlings. AMF can form a large network of extra-root mycelium and hyphae after symbiosis with the host plant, altering root

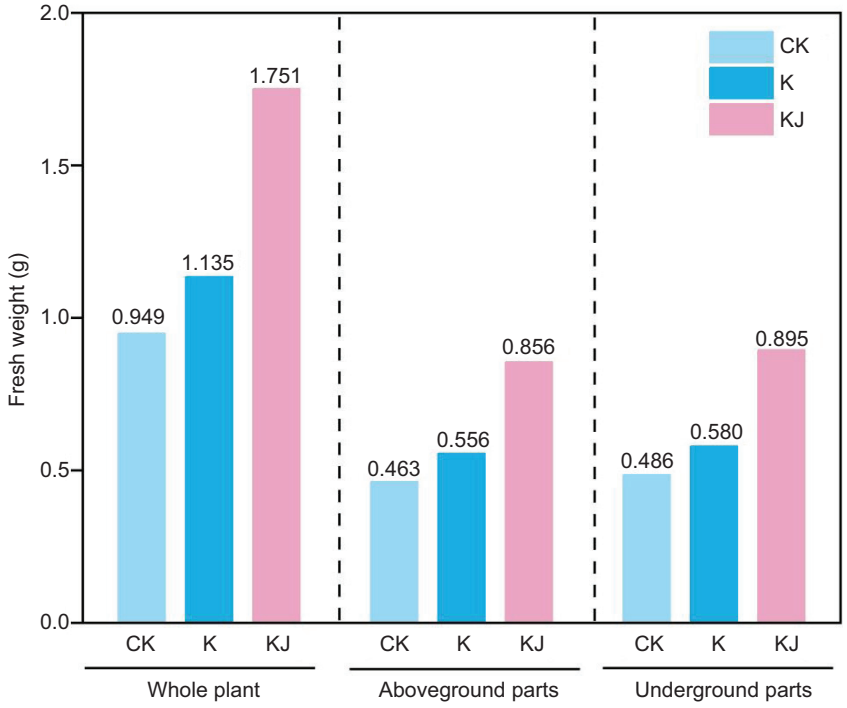

Figure 3. Whole plant fresh weight, aboveground fresh weight, and underground fresh weight of quinoa seedlings treated with different microbial agents.

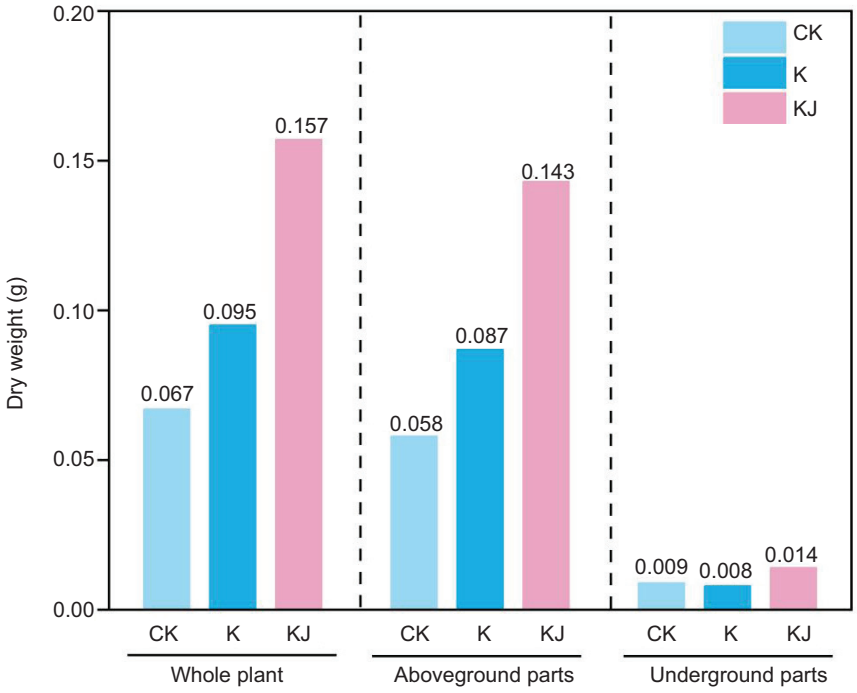

Figure 4. Whole plant dry weight, aboveground dry weight, and underground dry weight of quinoa seedlings treated with different microbial agents.

morphology and promoting root development (Bi and Zhou, 2021). In this study, root indicators, such as root length, number of connections, number of nodes, and number of forks, were higher in the K group than in the CK group, suggesting that AMF promotes the growth of fine roots, which have a larger surface area to volume ratio, thereby increasing the nutrient uptake area of the root system and improving the nutrient uptake and transport capacity of the root system (Chen *et al*., 2023; Yu *et al*., 2023). Therefore, it can promote the growth of leaves and the increase of biomass in the aboveground part of quinoa. It proves that the growth of quinoa leaves as well as the increase in biomass are closely related to the changes in the morphology of its root system. By secreting phytohormones, such as indoleacetic acid and cytokinin, the dephosphorylating bacteria promote the growth and development of the plant root system, which enables the plant to take up nutrients from a relatively wider soil area (Kshetri *et al.*, 2024; Ponce *et al*., 2021). In this study, the root length, number of connections, number of nodes, number of forks, as well as leaf area and leaf perimeter of quinoa in the KJ group were higher than those in the K group, suggesting that the compound application of AMF and PSB can combine the advantages of these two microbial agents, thus better exerting the growth-promoting performance on quinoa.

Table 3. Protein content of quinoa seedlings treated with different microbial agents.

Processing groups	CK	K	KJ
Protein (%)	6.733±0.093[a]	6.354±0.376[a]	6.928±0.408[a]

Different lowercase letters indicate significant differences between processing groups (P<0.05). The results of the analysis of variance showed that the effect of different treatment groups on the protein content of quinoa seedlings was not significant, $F(2, 6)=1.399$, P=0.329. CK is the control group, K is the application of Kaiduo explosive root microbial agent, KJ is the compound application of Kaiduo explosive root microbial agent and PSB.

Effect of phosphorus-solubilizing microorganisms on quinoa biomass

Inoculation of phosphorus-solubilizing microorganisms during the growth period of plants can promote plant growth and development. AMF firstly affects the growth function of the root system by promoting the uptake of mineral nutrients and transporting more nutrients to the aboveground part of the plant, promoting plant growth and improving plant quality (Ranjan *et al*., 2024; Zhu *et al*., 2024). Seedling roots inoculated with PSB may

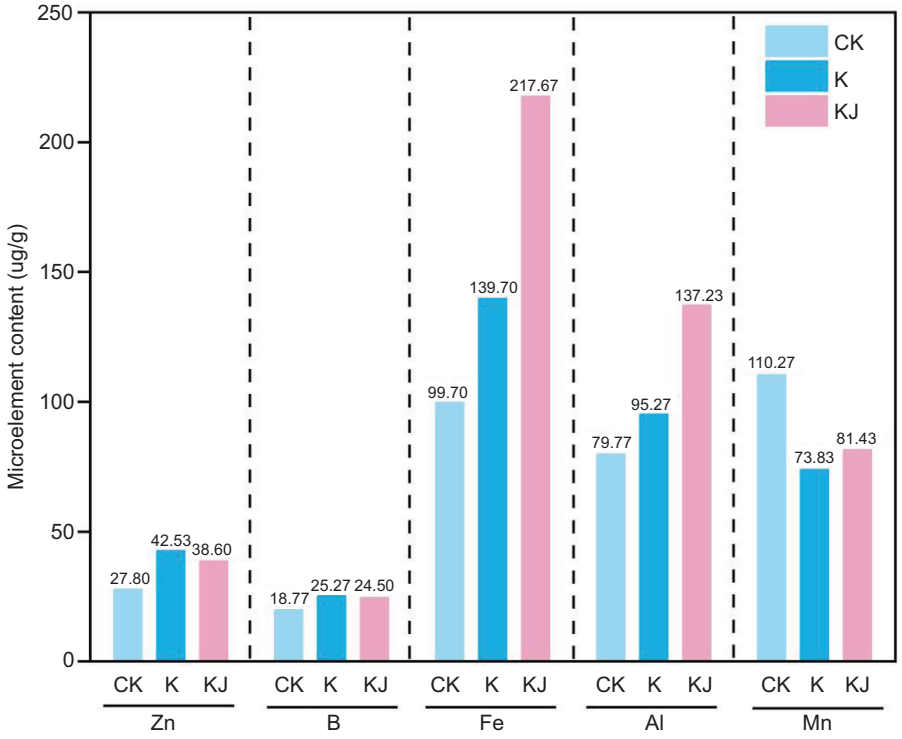

Figure 5. The microelements in quinoa seedlings of different treatment groups. The numbers in the figure represent the mean values for each treatment group. CK is the control group, K is the application of Kaiduo explosive root microbial agent, KJ is the compound application of Kaiduo explosive root microbial agent and phosphate-solubilizing bacteria.

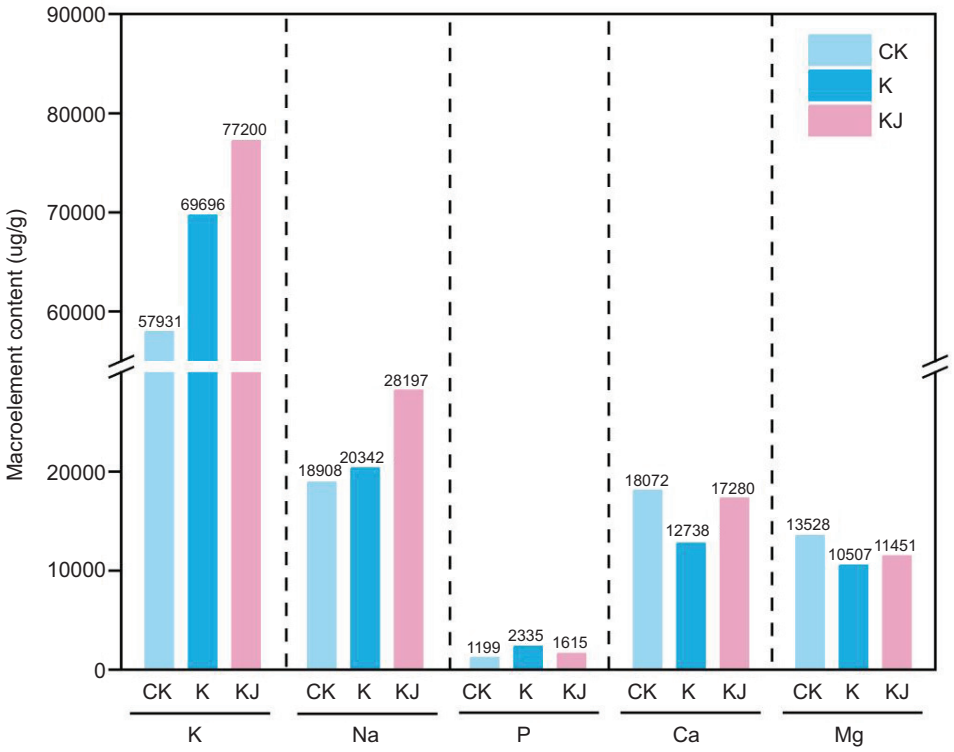

Figure 6. The macroelements in quinoa seedlings of different treatment groups. The numbers in the figure represent the mean values for each treatment group. CK is the control group, K is the application of Kaiduo explosive root microbial agent, KJ is the compound application of Kaiduo explosive root microbial agent and phosphate-solubilizing bacteria.

produce higher levels of IAA, a plant growth regulating hormone, that not only promotes growth and root elongation but also improves photosynthetic capacity, carbohydrate metabolism, and total plant yield (Elhaissoufi *et al*., 2020). Using maize as the experimental material, Huang Jianwei *et al*. (2022) found that the aboveground biomass of maize in the treatment groups of inoculation of AMF, inoculation of AMF + PSB, and inoculation of PSB were increased compared to the control by 11.9%, 11.4%, and 0.04%, respectively. Hao Jing *et al*. (2006) studied the growth-promoting effect of dephosphorylating microorganisms on pea, and the results showed that the application of dephosphorylating bacteria could significantly increase the aboveground fresh weight of pea plants as well as pea yield, which further verified the conclusion that dephosphorylating microorganisms promote the growth and development of plants. In this study, the fresh weight and dry weight of aboveground parts and whole plants of quinoa plants in KJ group were higher than those in K and CK groups, and the K group was higher than the CK group. It indicated that the compound application of PSB and AMF could combine the advantages of these two agents to further increase the biomass of quinoa, which was basically consistent with the results of previous studies.

Effect of phosphorus-solubilizing microorganisms on the nutrient composition of quinoa

Complex application of AMF and PSB increases the protein content of quinoa. Protein is not only a component that constitutes a variety of important physiological active substances in organisms but also an important guarantee for organisms to carry out life activities such as growth and development (Kalayu, 2019). Shen Ruiling *et al*. (2015) found that the protein content of quinoa was about 14.9%, while the protein content of quinoa seedling plants in this study was only 6.7%, which may be because of the fact that the experimental samples used for the detection of protein were taken from the roots, stems, and leaves of quinoa seedlings, and the experiments were carried out by potting in saline soil, which may affect the growth and development of the plants. However, the results were reliable. We found that the compound application of AMF and PSB increased the protein content of quinoa and improved the quality of quinoa.

After the application of dephosphorylating microorganisms, we found that the contents of zinc, boron, iron, aluminum, potassium, sodium, and phosphorus in quinoa plants were increased compared with the CK group,

which proved that the application of dephosphorylating microorganisms could increase the contents of many nutrients in quinoa, thus improving the quality of quinoa. This is consistent with the findings of Liu *et al.* (2020), who found that the moderate application of phosphorus and inoculation with AMF and PSB could significantly increase the mycorrhizal infestation rate, aboveground biomass, leaf chlorophyll content, and soluble sugar content of alfalfa, and significantly improve the nutritional quality of alfalfa. Coastal saline soils are not suitable for quinoa growth. However, adding dephosphorylated microbial agents can promote the cultivation of quinoa in saline soils and can improve the content of many nutrients as well as protein in quinoa.

Prospects for future applications of dephosphorylating microorganisms

Quinoa is a new type of grain crop introduced in China in recent years, and it is mostly cultivated in the mountainous areas of plateaus (Talawar and Bc, 2020). Its cultivation in low altitude areas is not that smooth at present. The phosphorus-solubilizing microorganisms in this study have an obvious growth-promoting effect on quinoa planted in saline and alkaline lands, and phosphorus-solubilizing microorganisms can be used as one of the breakthroughs for the cultivation of quinoa in the future. Application of microalgae biofertilizer may be an effective solution to alleviate the stress of saline soil on quinoa, as shown in Figure 7. The high salt concentration in saline soil produces photosynthetic inhibition and osmotic stress on quinoa plants, whereas the addition of salinity-tolerant microalgae to quinoa cultivation promotes chlorophyll production in quinoa and alleviates the effect of salinity stress on photosynthesis inhibition, improves photosynthetic efficiency, and promotes the synthesis of osmotically regulated soluble sugars and proteins in quinoa, which in turn reduces the osmotic stress of salinity on quinoa (Ma *et al.*, 2022; Mahdi *et al.*, 2021; Sangwan and Prasanna, 2021). Therefore, the addition of saline-tolerant algae when cultivating quinoa can also be one of the effective measures to promote the cultivation of quinoa in coastal wetlands.

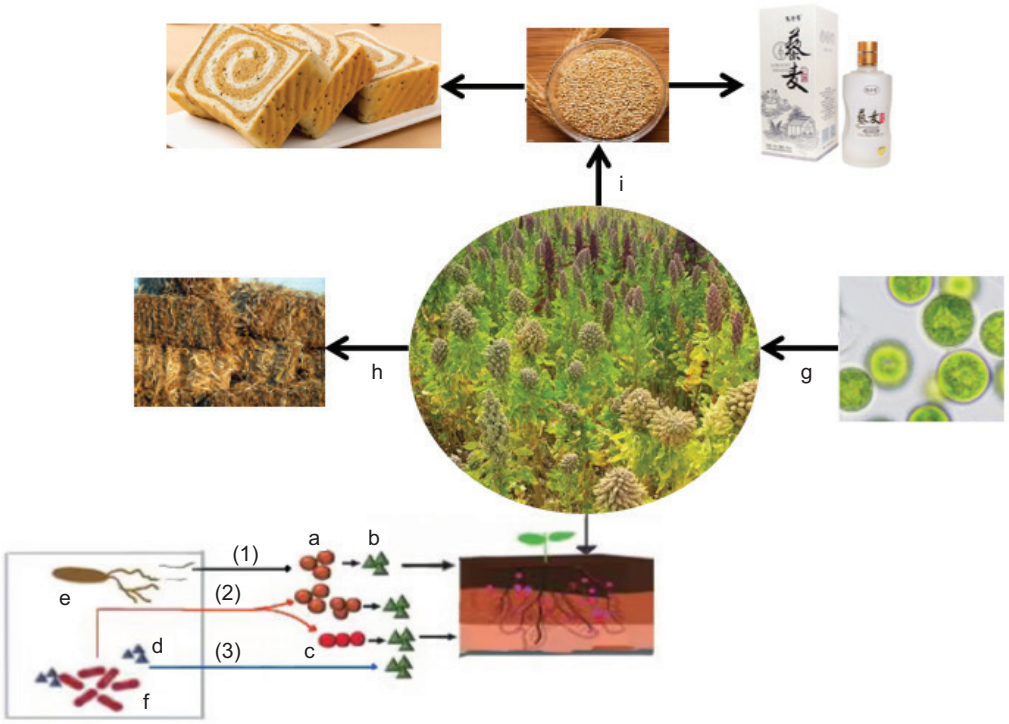

Figure 7. Mechanism of action of phosphorus-dissolving microorganisms on quinoa inter-root soil and prospects for research and development of quinoa. A is insoluble inorganic phosphorus; b is effective phosphorus; c is insoluble organic phosphorus; d is microbial biomass phosphorus; e is AMF; f is PSB; g is salinity-tolerant microalgae; h is quinoa straw that can be processed for composting; i quinoa as a food crop can be eaten directly or made into baked goods or fermented products. (1) Secretions from AMF activate insoluble inorganic phosphorus directly to effective phosphorus; (2) PSB convert insoluble phosphorus into effective phosphorus through direct activation (solubilization and mineralization) and through indirect activation (secretion of plant hormones, biocontrol agents, and nitrogen fixation); (3) PSB produce microbial biomass phosphorus through self-fixation and release effective phosphorus during the fixation-turnover process.

Currently, microbial fertilizer products are not widely used in quinoa cultivation because of technological research and development, but studies have shown that microbial application to quinoa cultivation results in significant gains with regard to quality and efficiency. Therefore, in the future, further research is needed to study the feasibility of the practical application of microbial fertilizers. Also, the combination of phosphorus-solubilizing microorganisms and saline-tolerant microalgae can be mixed and applied to the growth process of quinoa. These researches may change the difficult situation with regard to the popularization and cultivation of quinoa in coastal wetlands.

Conclusions

The root length, and the number of forks, connections, and nodes of quinoa seedlings with the composite PSB and AMF were higher than those of the single-application group and the control group; the leaf perimeter and leaf area of quinoa seedlings with the composite PSB and AMF were significantly higher than those of the single-application group and the control group. The biomass, protein content, and concentrations of various nutrients such as iron and potassium of quinoa seedlings were higher than those of the single-application group and the control group with the composite PSB and AMF. It indicated that the composite application of PSB and AMF has a better promoting effect on the growth of quinoa. This study confirmed the effectiveness of the composite microbial agent through pot control experiments, but it was not made into a product and promoted for application in quinoa cultivation. In the future, we can combine the PSB and AMF to make a composite microbial agent product, or combine phosphate-dissolving microorganisms with saline-tolerant microalgae to make a microbial fertilizer product to be applied to the growth process of the quinoa, so as to improve the nutritive and economic value of the quinoa. As a result, it can improve the growth of quinoa in coastal saline–alkaline land and assist in its ecological restoration. Farmers who rely on quinoa cultivation for a living in the future can use microbial fertilizers instead of traditional chemical fertilizers, which can produce green, organic, and pollution-free food; increase farmers' income; and reduce environmental pollution.

Data Availability Statement

Data will be made available on request.

Acknowledgments

We would like to extend our gratitude to Li Tao, a director of the Vegetable Institute of Yantai Academy of Agricultural Sciences, for his valuable contributions to this experiment.

Authors Contributions

Yanan Hou was responsible for conceptualization, data curation, methodology, formal analysis, and writing–original draft; Deliang Xu was concerned with conceptualization, data curation, methodology, formal analysis, and writing–original draft; Yan Xu looked into conceptualization, data curation, methodology, formal analysis, and writing–original draft; Shan Cong, Xiaohong Guo, and Nan Wu were responsible for writing–review & editing and supervision.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

The work was financially supported by the National Natural Science Foundation of China (41977039).

References

Bi, Y. and Zhou, H., 2021. Changes in peanut canopy structure and photosynthetic characteristics induced by an arbuscular mycorrhizal fungus in a nutrient-poor environment. Scientific Reports. 11. https://doi.org/10.1038/s41598-021-94092-w

Chen, J., Wang, L., Liang, X., Li, B., He, Y., and Zhan F., 2023. An arbuscular mycorrhizal fungus differentially regulates root traits and cadmium uptake in two maize varieties. Ecotoxicology and Environmental Safety. 264. http://doi.org/10.1016/j.ecoenv.2023.115458

Elhaissoufi, W., Khourchi, S., Ibnyasser, A., Ghoulam, C., Rchiad, Z., Zeroual, Y. and Bargaz, A., 2020. Phosphate solubilizing rhizobacteria could have a stronger influence on wheat root traits and aboveground physiology than rhizosphere p solubilization. Frontiers in Plant Science. 11. https://doi.org/10.3389/fpls.2020.00979

Fan, B., Zhao, C., Zhao, L., Wang, M., Sun, N., Li, Z. and Yang, F., 2024. Biochar application can enhance phosphorus solubilization by strengthening redox properties of humic reducing microorganisms during composting. Bioresource Technology. 395. https://doi.org/10.1016/j.biortech.2024.130329

Gonçalves, I.C., Soares, S. and Rocha, F.R.P., 2023. Exploiting microdistillation and smartphone-based digital-image colorimetry for determination of protein in foods. Microchemical Journal. 188. http://doi.org/10.1016/j.microc.2023.108461

Huang, Y., Dai, Z., Lin, J., Qi, Q., Luo, Y., Dahlgren, R.A., et al., 2021. Contrasting effects of carbon source recalcitrance on soil phosphorus availability and communities of phosphorus solubilizing

microorganisms. Journal of Environmental Management. 298. http://doi.org/10.1016/j.jenvman.2021.113426

Jaiswal, D.K., Jin, F., Hu, Q., Zhao, Y., Lin, X., Zhang, J. and Zhang, J., 2022. Enhancing quinoa growth under severe saline-alkali stress by phosphate solubilizing microorganism penicillium funicuiosum p1. Plos One. 17. https://doi.org/10.1371/journal.pone.0273459

Kshetri, L., Kotoky, R., Debnath, S., Maheshwari, D.K. and Pandey, P., 2024. Shift in the soil rhizobacterial community for enhanced solubilization and bioavailability of phosphorus in the rhizosphere of Allium hookeri Thwaites, through bioaugmentation of phosphate-solubilizing bacteria. 3 Biotech. 14. https://doi.org/10.1007/s13205-024-04026-2

Koczorski, P., Furtado, B.U., Baum, C., Weih, M., Ingvarsson, P., Hulisz, P., et al., 2023. Large effect of phosphate-solubilizing bacteria on the growth and gene expression of Salix spp. at low phosphorus levels. Frontiers in Plant Science. 14. http://doi.org/10.3389/fpls.2023.1218617

Kalayu, G., 2019. Phosphate solubilizing microorganisms: promising approach as biofertilizers. International Journal of Agronomy 2019: 1–7. https://doi.org/10.1155/2019/4917256

Lee, A., Neuberger, P., Omokanye, A., Hernandez-Ramirez, G., Kim, K. and Gorzelak, M.A., 2023. Arbuscular mycorrhizal fungi in oat-pea intercropping. Scientific Reports. 13. https://doi.org/10.1038/s41598-022-22743-7

Li, W., Wang, J., Jiang, L., Lv, G., Hu, D., Wu, D. and Yang, X., 2023. Rhizosphere effect and water constraint jointly determined the roles of microorganism in soil phosphorus cycling in arid desert regions. Catena. 222. https://doi.org/10.1016/j.catena.2022.106809

Le, L., Gong, X., An, Q., Xiang, D., Zou, L., Peng, L., et al., 2021. Quinoa sprouts as potential vegetable source: nutrient composition and functional contents of different quinoa sprout varieties. Food Chemistry. 357. http://doi.org/10.1016/j.foodchem.2021.129752

Liu, J., Liu, X., Zhang, Q., Li, S., Sun, Y., Lu, W. and Ma, C., 2020. Response of alfalfa growth to arbuscular mycorrhizal fungi and phosphate-solubilizing bacteria under different phosphorus application levels. AMB Express. 10. https://doi.org/10.1186/s13568-020-01137-w

Lu, Y., Gong, C., Wu, L., Liu, H. and Guo, G., 2020. Determination of Fe in graphene by inductively coupled plasma optical emission spectrometer. Journal of Physics: Conference Series. 1637. http://doi.org/10.1088/1742-6596/1637/1/012005

Ma, C., Lei, C.Y., Zhu, X.L., Ren, C.G., Liu, N., Liu, Z.Y., et al., 2022. Saline-alkali land amendment and value development: microalgal biofertilizer for efficient production of a halophytic crop–Chenopodium quinoa. Land Degradation & Development 34: 956–968. http://doi.org/10.1002/ldr.4508

Mahdi, I., Fahsi, N., Hafidi, M., Benjelloun, S., Allaoui, A. and Biskri, L., 2021. Rhizospheric phosphate solubilizing bacillus atrophaeus gqjk17 s8 increases quinoa seedling, withstands heavy metals, and mitigates salt stress. Sustainability. 13. https://doi.org/10.3390/su13063307

Ponce, G.E., Fuse, M., Chan, A. and Connor, E.F., 2021. The localization of phytohormones within the gall-inducing insect Eurosta solidaginis (Diptera: Tephritidae). Arthropod-Plant Interactions 15: 375–385. http://doi.org/10.1007/s11829-021-09817-5

Patel, H.D., Krishnamurthy, R. and Azeez, M.A., 2016. Effect of biofertilizer on growth, yield and bioactive component of plumbago zeylanica (Lead Wort). Journal of Agricultural Science. 8. http://doi.org/10.5539/jas.v8n5p141

Ranjan, A., Rajput, V.D., Prazdnova, E.V., Gurnani, M., Sharma, S., Bhardwaj, P., et al., 2024. Augmenting abiotic stress tolerance and root architecture: the function of phytohormone-producing PGPR and their interaction with nanoparticles. South African Journal of Botany 167: 612–629. http://doi.org/10.1016/j.sajb.2024.02.041

Ray, A., Sakhare, S.D. and Srivastava, A.K., 2023. Novel nutrient dense quinoa fractions: physical, functional, thermal and rheological characterisation for potential industry application. International Journal of Food Science & Technology 58: 6530–6540. http://doi.org/10.1111/ijfs.16766

Sangwan, S. and Prasanna, R., 2021. Mycorrhizae helper bacteria: unlocking their potential as bioenhancers of plant–arbuscular mycorrhizal fungal associations. Microbial Ecology 84: 1–10. http://doi.org/10.1007/s00248-021-01831-7

Turan, M., Kocaman, A., Tüfenkçi, Ş., Katırcıoğlu, H., Güneş, A., Kıtır, N., et al., 2023. Development of organic phosphorus vermicompost from raw phosphate rock using microorganisms and enzymes and its effect on tomato yield. Scientia Horticulturae. 321. http://doi.org/10.1016/j.scienta.2023.112323

Tian, X.Y., He, D.D., Bai, S., Zeng, W.Z., Wang, Z., Wang, M., Chen, Z.C., 2021. Physiological and molecular advances in magnesium nutrition of plants. Plant and Soil 468: 1–17. https://doi.org/10.1007/s11104-021-05139-w

Talawar, S. and Bc, D., 2020. Effect of different levels of phosphorus and phosphorus solubilizers on phosphorus fractions in soil at different stages of paddy. International Journal of Chemical Studies 8: 1100–1104. https://doi.org/10.22271/chemi.2020.v8.i1o.8396

Ullah, M., Daur, I., Khan, B., Mehran Anjum, M. and Ali, N., 2023. Rock phosphate and phosphorus solubilizing bacteria effect on yield and yield components of chickpea. Gesunde Pflanzen 75: 2889–2898. http://doi.org/10.1007/s10343-023-00866-9

Wang, X., Yan, B., Shi, L., Zhao, G. and Liu, G., 2024. Effects of native and non-native arbuscular mycorrhizal fungi on the growth of dodonaea viscosa under drought stress conditions. Journal of Soil Science and Plant Nutrition 24: 2648–2664. http://doi.org/10.1007/s42729-024-01686-0

Wang, C., Pan, G., Lu, X. and W, Qi., 2023. Phosphorus solubilizing microorganisms: potential promoters of agricultural and environmental engineering. Frontiers in Bioengineering and Biotechnology. 11. http://doi.org/10.3389/fbioe.2023.1181078

Wang, Z., Zhang, H., Liu, L., Li, S., Xie, J., Xue, X. and Jiang, Y., 2022. Screening of phosphate-solubilizing bacteria and their abilities of phosphorus solubilization and wheat growth promotion. BMC Microbiology. 22. https://doi.org/10.1186/s12866-022-02715-7

Yu, L., Zhang, H., Zhang, W., Han, B., Zhou, H., Lu, X., et al., 2023. Arbuscular mycorrhizal fungi alter the interaction effects between bacillus and rhizobium on root morphological

traits of medicago ruthenica L. Journal of Soil Science and Plant Nutrition 23: 2868–2877. http://doi.org/10.1007/s42729-023-01242-2

Yasui, Y., Hirakawa, H., Oikawa, T., Toyoshima, M., Matsuzaki, C., Ueno, M., et al., 2016. Draft genome sequence of an inbred line of chenopodium quinoa, an allotetraploid crop with great environmental adaptability and outstanding nutritional properties. DNA Research 23: 535–546. http://doi.org/10.1093/dnares/dsw037

Yamato, M., Ikeda, S. and Iwase, K., 2008. Community of arbuscular mycorrhizal fungi in a coastal vegetation on okinawa island and effect of the isolated fungi on growth of sorghum under salt-treated conditions. Mycorrhiza 18: 241–249. https://doi.org/10.1007/s00572-008-0177-2

Zhu, S., Sun, S., Zhao, W., Sheng, L., Mao, H. and Yang, X., 2024. Arbuscular mycorrhizal fungi alleviated the effects of Cd stress on Passiflora edulis growth by regulating the rhizosphere microenvironment and microbial community structure at the seedling stage. Scientia Horticulturae. 328. https://doi.org/10.1016/j.scienta.2024.112879