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# Enhancing sustainable solutions for food security in Jordan: using bacterial biofertilizer to promote plant growth and crop yield

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**Introduction:** Jordan suffers from agricultural land degradation, water scarcity, increasing in population, and the huge gap between production and consumption. Boosting of food production to meet the demand is one of the solutions. Biofertilizers are substances include beneficial microorganisms (e.g., bacteria) that are important in agricultural soil to improve yield through different mechanisms. The aim of this experiment is to study the impact of using locally produced-microorganisms along with chemical fertilizers to improve the yield of cucumber planting.

**Methods:** The experiment was carried out in a greenhouse equipped with all requirements for planting. The planting process of cucumber seedling was implemented using pots filled with soil collected from an agricultural land in the Jordan Valley, and mixed with manure, and categorized in three plots. Mixture of three types of microorganisms (STIMULANT A and B, and PHYTO-EM) along with chemical fertilizers were applied to the soil in some pots. Plants growth and agricultural parameters were observed. Data about crop yield, water consumption, leaf area, and chlorophyll were collected. Lab analysis of soil characteristics was also done to assess the impact of the products on soil.

**Results:** The results showed that the yield production was the maximum in the plot of combining the benefits of biological and the chemical fertilizers compared to the control plot by 48%. The same plot showed water saving with 32.4% over the control plot. The bacterial biofertilizers enhanced the seedling growth all the time during the experiment by 14% more than the plants in the control plot. The average leaves area in plot with bio-products was 22.6% bigger than the control plot. In addition, the chlorophyll test indicated that the chlorophyll content was more in plot with biofertilizers. According to the soil analysis, the presence of bacterial biofertilizers enhanced the plant's absorption of nutrients, and accordingly the EC decreased in the soil.

**Discussion:** The results of the experiment showed superiority of plot using the bacterial biofertilizers along with the chemical fertilizer, over the plots either using the chemical fertilizers alone or the bacterial biofertilizers alone. This can be attributed to the addition of bacterial biofertilizers with the chemical fertilizers in appropriate conditions. Our findings highlight the potential for bacterial biofertilizers to significantly improve crop yields and resource efficiency, contributing to food system transformation. This aligns with the UN Sustainable Development Goals, particularly SDG 2 (Zero Hunger) and SDG 15 (Life on Land), by offering sustainable agricultural solutions.

KEYWORDS

bacterial biofertilizers, plant–microbe interactions, sustainable agriculture, plant growth, cucumber, Jordan

## Introduction

Achieving food security poses a significant challenge in Jordan and many countries worldwide, especially in light of increasing climate change and environmental disruptions, decreasing soil fertility, environmental degradation, urbanization, and the increase in food demand for the increasing world population (Al-Bakri et al., 2013; Rabboh et al., 2023). To address such global challenges, there is a pressing need to seek sustainable solutions to increase crop production efficiently while utilizing limited resources (Jordan et al., 2007). Biofertilizer products, "specifically those containing beneficial bacteria, are able to promote plant growth by producing hormones and other compounds that help the plant absorb nutrients, increase root growth, and improve water and nutrient uptake from the soil" (Naik et al., 2020; Priya et al., 2023). Biofertilizers stand as an innovative approach aimed at improving crop production and enhancing agricultural sustainability (Zambrano-Mendoza et al., 2021).

This study represents a fundamental contribution, specifically within the context of Jordan, to exploring the role of bacterial biofertilizers in promoting plant growth and crop yield and improving the typical agricultural practices, such as the use of fertilizers, pesticides, and herbicides, which pose serious threats to the environment and cause soil degradation (Prashar and Shah, 2016; Tripathi et al., 2020). The experiment and intensive research conducted over a period exceeding 84 days have yielded tangible results demonstrating the benefits of using those products in elevating crop productivity per cubic meter of irrigation water (water productivity) for agricultural crops (Hussain et al., 2018; Danish et al., 2020).

This experiment delves into the concept of utilizing bacterial biofertilizers to enhance soil health and boost its capacity to provide nutrients to plants. It sheds light on the impact of these products on various aspects of plant growth and crop production, including the improvement of leaf color and the control of agricultural pests (Adesemoye and Kloepper, 2009).

Building upon the mentioned findings, this study aspires to provide practical recommendations that contribute to enhancing food security in Jordan and improving sustainability in agriculture (Hayat et al., 2010). As a scientific study offering an in-depth exploration of the practical aspects and expected outcomes of using bacterial biofertilizers, this study represents a significant step toward achieving food security and sustainable agriculture in Jordan and similar regions facing similar challenges.

This study will show the significant results and conclusions obtained from this study, reaffirming the added value of using bacterial biofertilizers in agriculture to enhance crop productivity sustainably.

By addressing the critical challenges of food security and agricultural productivity in arid regions, this study supports global efforts to transform food systems. Our experiment directly contributes to the UN Sustainable Development Goals, especially SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land).

## Materials and methods

### Bacterial biofertilizers

Three types of local bacterial biofertilizers (STIMULANT A, STIMULANT B, and PHYTO-EM) were obtained from the local market. The products are composed of a natural preparation containing a compatible group of beneficial microorganisms. STIMULANT A and B are mainly Rizobacteria (Lugtenberg and Kamilova, 2009), which is one of the most important products that play a role in plant growth, the liberation of the potassium element in the soil even in the absence of iron, and secretion of natural disinfectants of the soil and natural growth hormones, in addition to secrete compounds that increase the natural resistance of the Induced Systematic Resistance (ISR) plant (van Loon et al., 1998). These bacteria act as insect inhibitors by reducing the hatching of insects' eggs in the soil (Disi et al., 2019). This bacterium can work properly in cold weather, and it works efficiently in breaking down toxic organic compounds in soil in hours rather than years. PHYTO-EM is also a natural preparation containing a compatible group of beneficial microorganisms (photosynthesis bacteria, nitrogen fixation, and lactobacillus plantarum beneficial bacteria). These species have an active and effective role in improving agricultural soil fertility, stimulating growth hormones, vitamins, antibiotics, and mineral elements, and lowering the soil pH and electrical conductivity "EC" (Лiманська et al., 2018). It is a safe and healthy product, is not genetically modified, and does not contain any pesticides or harmful chemicals.

### Experimental design

A greenhouse of dimension 10*3 m was constructed at the Water & Environment Centre building rooftop. The greenhouse was covered with agricultural plastic sheets, equipped with a fly insect's net mesh (60%), and movable plastic sides for ventilation to control the indoor environment (manual ventilation system). The soil was sourced from the Middle Jordan Valley (Mu'addi) on Tuesday, 29th March 2022. The soil was mixed well with the manure, where 18 bags of soil and 5 bags of naturally treated manure were used (The net weight of the soil bag is 25 kg and the weight of the manure bag is 10 kg). The soil was distributed equally into the 18 pots (30 kg of soil in each pot). Eighteen pots of 50 L size and 40 cm diameter were provided and filled with 30 kg media soil each. The pots were categorized into three plots: (A) Using chemical fertilizers "CF," soil, and manure (organic fertilizer) as control plot for the experiment, according to the normal farmers' practices, (B) Using chemical fertilizers, manure (organic fertilizer), soil, and a mixture of the three bacterial biofertilizers products together, and (C) Using a mix of manure (organic fertilizer), soil, and the three products only, without chemical fertilizers.

## Cucumber seedlings and dosing of bacterial biofertilizers

Two cucumber seedlings were used to cultivate in each pot. Each seedling was coded as the following: Plot A (A1, A1', A2, A2'… A6, A6'), Plot B (B1, B1', B2, B1'…B6, B6'), and Plot C (C1, C1', C2, C2'… C6, C6'). The bio-products were prepared at the time of application by adding two tablespoons of date syrup to the water, then adding 10 mL of the PHYTO-EM product, followed by equal amounts of products STIMULANT B and STIMULANT A. The mixture was stirred well and fermented for 1 h using date molasses.

At day (0) of the experiment, when planting the seedling, 30 mL of the mixture (bio-products) was applied to each pot of the bio-products bacteria to each seedling in Plots B and C only. A second dose was applied 25 days later with the same amount of the mixture.

## Fertigation, irrigation, and drainage systems

An integrated fertilization program was customized throughout the period of plant growth and fruition in Plot A and Plot B only, started on day (Prashar and Shah, 2016) through a traditional fertilization program: (Iron + Balanced Compound Fertilizer (NPK 20–20-20) + Microelements). Chlorine-free water was used for irrigation in this experiment and placed in two equalization tanks of 2 m3 each. Then, the water is pumped to three secondary small feeding tanks (irrigation tanks 125 L). The drippers were installed at a rate of PC = 4/h, while the automatic irrigation program was scheduled at (9:00–9:15 AM) and (4:00–4:15 PM) daily at the growth stage (day 0–day 35). Separate drainage networks were provided to the three plots so as to avoid any potential interference/contamination. The draining system was working with high efficiency.

## Challenges and solutions

When soil is saturated with water, all the pores are filled with water, and there is no room for air in the soil. However, if the soil is drained well, water soon drains out of the macro-pores, and air takes its place. That is how plant roots can breathe. Most plants and crops die after a few days if their soil is saturated. For this reason, plant thirsting is necessary. The plant thirst started from day 2 to day 4.

Plant disease causes a reduction in yield, crop quality deterioration, leaf loss, and increased tissue size. The diseases were controlled and mitigated by closing the greenhouse, using fly mesh, using proper pesticides, proper watering, mulching, pruning, and proper fertilizing. In addition, Plants may respond to the change of season by losing their leaves or flowering. High temperatures also may affect the plant growth. The temperature inside the greenhouse was maintained appropriately through proper daily ventilation (day opening and night closing), spraying shaded materials over plastic, and using greenhouse fans and a cooling system.

## Crop harvesting

Cucumber harvesting began on day 32 of the experiment, and the crop yield collection was approximately every 3 to 4 days. The collection was done by separating the seedlings into right and left categories, taking each plant in a plastic bag separately, and then weighing each bag.

## Statistical analysis

The data for crop yield, highest plant growth, and leaf area were expressed at mean ± standard deviation. A one-way ANOVA test was used to compare different values in all groups using OpenEpi software (Emory University, United States). Parameter differences were considered statistically significant at $p < 0.05$.

# Results

## Crop yield

Cucumber harvesting began on day 32 of the experiment, and the crop collection was approximately every (Jordan et al., 2007; Priya et al., 2023) days. Table 1 shows the crop yield weights for Plots A, B, and C for each harvesting day, where data are plotted in Figure 1. The results showed that the highest crop yield, on any specific date, was in Plot B, followed by Plot A, while the lowest yield crop was in Plot C.

TABLE 1 Crop yield weight for each harvesting (in kg).

| Serial no. | Harvesting date | Day of experiment | Plot A | Plot B | Plot C |
|---|---|---|---|---|---|
| 1 | 5-May | 32 | 1.445 | 1.59 | 0.555 |
| 2 | 9-May | 36 | 1.165 | 2.52 | 0.815 |
| 3 | 12-May | 39 | 0.825 | 2.205 | 0.745 |
| 4 | 16-May | 43 | 2.17 | 3.11 | 1.29 |
| 5 | 19-May | 46 | 0.91 | 2.05 | 0.375 |
| 6 | 23-May | 50 | 2.66 | 4.675 | 1.18 |
| 7 | 25-May | 52 | 0.795 | 1.47 | 0.305 |
| 8 | 29-May | 56 | 3.92 | 6.015 | 1.235 |
| 9 | 2-June | 60 | 2.575 | 2.902 | 1.92 |
| 10 | 5-June | 63 | 2.35 | 3.3 | 0.54 |
| 11 | 9-June | 67 | 3.14 | 3.405 | 1.095 |
| 12 | 13-June | 71 | 3.625 | 4.47 | 1.22 |
| 13 | 16-June | 74 | 1.54 | 3.915 | 0.71 |
| 14 | 20-June | 78 | 2.87 | 3.58 | 1.375 |
| 15 | 26-June | 84 | 3.030 | 3.655 | 1.630 |
| Total Weight (kg) | | | 33.02 | 48.862 | 14.99 |

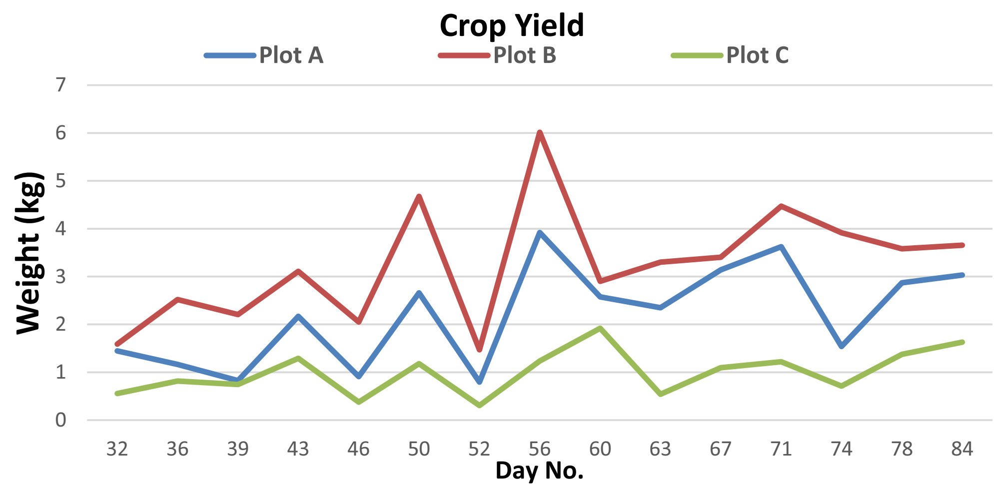


FIGURE 1
Crop yield in the three plots for the total period of crop harvesting.

TABLE 2 Gross crop yield for each plot (in kg).

| Gross crop yield | Plot A (Control Plot) | Plot B | Plot C | Gross weight (kg) |
|---|---|---|---|---|
| | Soil, manure, and chemical fertilizers only | Soil, manure, chemical fertilizers, and bacterial biofertilizers | Soil, manure, and bacterial biofertilizers only without chemical fertilizers | |
| Total weight (kg) | 33.02 | 48.862 | 14.99 | 96.872 |
| % Yield Increment compared to the control plot | – | +48.0% | −54.6% | |

Plot A yield production matches the normal farmers' practices (control plot) by adding sufficient quantities of fertilizers to the plant. The total crop weight for Plot A production was 33.02 kg during the monitored period (due to the crop calendar). Plot B's yield production was always significantly the maximum yield compared to Plots A and C ($p < 0.05$) since it combines the benefits of normal fertigation using chemical fertilizers, in addition to adding the bacterial biofertilizers. The total crop weight for Plot B production was 48.862 kg during the monitored period (due to the crop calendar). Plot C has the least yield production due to the lack of fertilizers. Even the bacterial biofertilizers were added to this plot, but they were unable to replace the fertilizers completely. The total crop weight for Plot C production was 14.99 kg during the monitored period (due to the crop calendar).

Table 2 shows the gross crop yield for each plot, where Plot B was more productive than the control plot by 48% ($p < 0.05$), while Plot C was less productive than the control plot by 54.6%.

## Water productivity and preserving

Water productivity depends on several factors, such as farm geographic location, quality of water irrigation, characteristics of the crop (type), soil characteristics, climatic conditions, and crop management. Therefore, the discussed results are representative of the experiment only since each plot was irrigated with equal amounts of irrigation water (1.2 m3 of water during the experiment lifespan). The same above "crop yield" percentages apply for "Water Productivity," i.e., each cubic meter of irrigation water produced 27.5, 40.7, and 12.5 kg in Plots A, B, and C, respectively. Alternatively, the crop water requirements in the experiment for producing 1 kg of cucumber were 36.3, 24.6, and 80.1 L in Plots A, B, and C, respectively. Accordingly, the percentage of water saving in Plot B compared to the control plot A was 32.4%, as shown in Table 3.

## Plant growth

Plant height is a central part of plant ecological strategy. It is strongly correlated with life span, seed mass, and time to maturity and is a major determinant of a species' ability to compete for light. Higher light levels at our altitude will generally increase photosynthesis, resulting in strong plant growth. The seedling heights differ widely between plots, as shown in Figure 2. All seedlings in Plot B were taller than the seedlings in Plots A and C, and the differences were not significant for the average plant height for each group ($p > 0.05$). Seedlings in Plot B were 14% taller than seedlings in control plot

A. Meanwhile, seedlings in Plot C were 25% shorter than those in control plot A during the monitored period. This means that the addition of the bacterial biofertilizers enhanced seedling growth throughout the experiment, resulting in a 14% increase compared to the plants in the control plot.

## Leaf Area

The leaf is a plant organ with crucial functions. The main function of leaves is to produce food. It produces food through photosynthesis. They are designed to minimize the loss of water from a plant and make sugars through photosynthesis. Their primary function is to serve as the site of photosynthesis. However, plants adapt leaves to serve different purposes. The leaf area (A) of cucumber could be estimated using the following equation (Blanco and Folegatti, 2005):

$$A = 0.88^{*} L^{*} W - 4.27$$

Where (L) is the length of the leaf, while (W) is the width.

In the experiment, the average leaf area in Plot B, where the bacterial biofertilizers were added, was 22.6% bigger than the control plot (significantly not different at the average leaf area across the whole study period for each group, $p > 0.05$), while Plot C was 12.1% smaller than the control plot (significantly not different at the average leaf area across the whole study period for each group, $p > 0.05$). The leaves area of cucumber for all plots across the experiment is shown in Figure 3. Increasing the leaf area increases the surface area, which means absorption of more sunlight and carbon dioxide in comparison to Plots A and C, and more photosynthesis. This process increases the production of plant food and thus reflects positively on the number of produced flowers and ripening fruits. This result confirms and justifies the large crop yield in Plot B compared to control groups.

## Chlorophyll

Chlorophyll is an essential pigment for photosynthesis as it can convert light energy into chemical energy (ATP). Other pigments act as accessory pigments because they collect and transfer light energy to chlorophyll-a for photosynthesis. During photosynthesis, chlorophyll captures the sun's rays and creates sugary carbohydrates or energy, which allows the plant to grow in the correct way (Rabinowitch and Govindjee., 1965). As a result of the increase in the leaf surface area, the number of stomata openings will increase, thus increasing their ability to absorb an additional amount of sunlight and carbon dioxide, thus increasing the concentration of chlorophyll in the plant leaves, which is also reflected in the color of plant leaves and fruits (dark green color-blue leaves).

Two groups of leaves were collected on day 44 and day 72 from the three plots. The largest amount of chlorophyll content was in Plot

TABLE 3 Water saving.

| | Plot A (Control Plot) | Plot B | Plot C |
|---|---|---|---|
| | Soil, manure, and chemical fertilizers only | Soil, manure, chemical fertilizers, and bacterial biofertilizers | Soil, manure, and bacterial biofertilizers only without chemical fertilizers |
| Irrigation water used (L) | 1,200 | 1,200 | 1,200 |
| Total weight (kg) | 33.02 | 48.86 | 14.99 |
| Water requirements (L/kg) | 36.3 | 24.6 | 80.1 |
| % Water saving increment compared to the control plot | | 32.4% | |

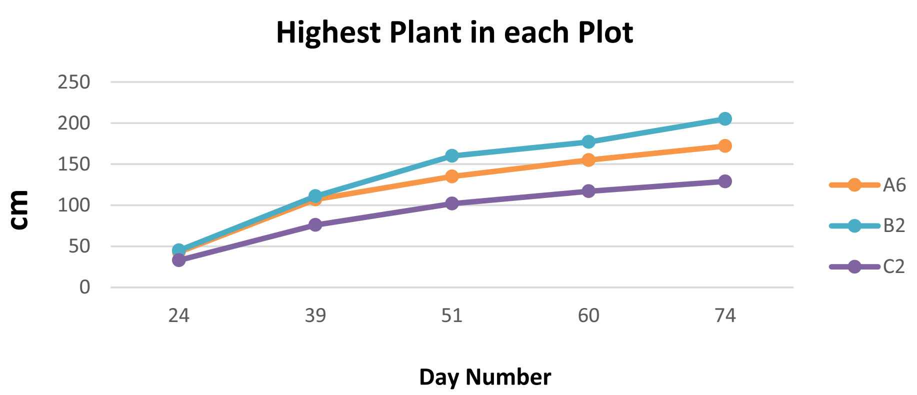


FIGURE 2
Highest plant growth in each plot.

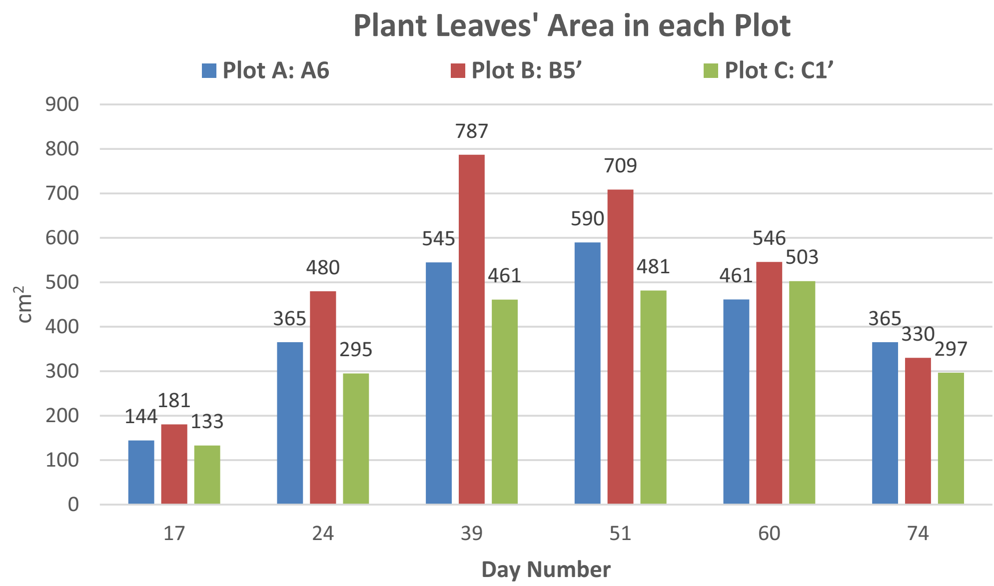


FIGURE 3
Cucumber leaf area.

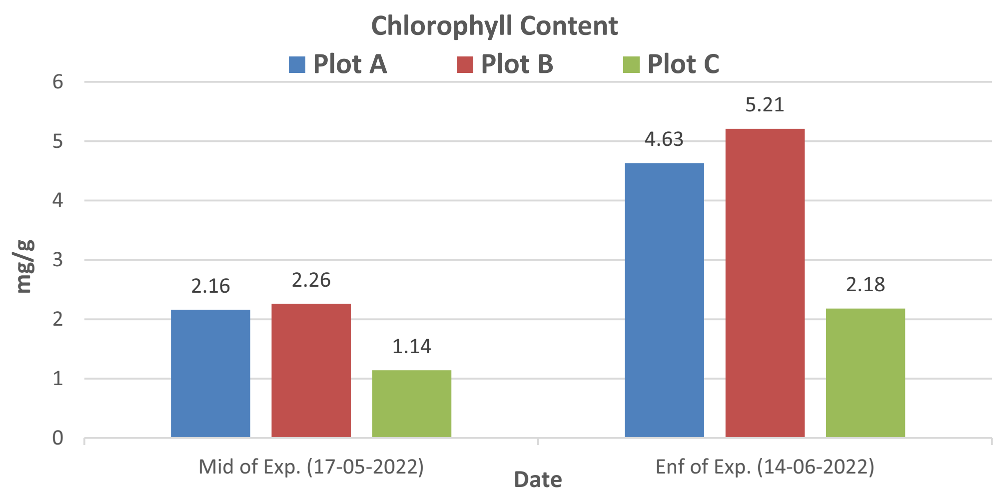


FIGURE 4
Chlorophyll content.

B, then in Plot A, while the least amount was in Plot C on both test days, as shown in Figure 4.

## Soil analysis

Three soil samples were collected from the three plots on days 0, 44, and 72 of the experiment. The first sample was taken after mixing the soil with the natural manure and before adding any other additives (NPK/BioTech). The analysis of soil samples was conducted at the laboratories of the Royal Scientific Society of Jordan for the following parameters: pH, electrical conductivity “EC,” NO3, NH4, PO4, and K.

The results of the analysis, as shown in Table 4, revealed that the characteristics of the first batch of soil samples from the three plots were very close, which indicates the homogenies of soil composition for all pots prior to launching the experiment. By the end of the experiment, Plots B and C (with bacterial biofertilizers) had fewer EC values than Plot A (No bio-products). Due to the addition of the chemical fertilizer a day before collecting soil samples, the EC value was decreased in Plots B and C. This means that there is an acceleration in plant absorption (fertilizers–salts) with the presence of bacterial biofertilizers so that nutrients become available to the plant. Hence, the presence of bacterial biofertilizers enhanced the plant’s absorption of nutrients, and accordingly, the EC decreased in the soil. For Plot A, the process of absorption of nutrients (fertilizers–salts) was delayed

TABLE 4 Soil analysis results.

| | Unit | A | B | C | A | B | C | A | B | C | Test method no. and date |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Day 0 | | | Day 44 | | | Day 72 | | | |
| EC (1:1) | μS/cm | 7,500 | 8,530 | 8,720 | **9,900** | **9,050** | **6,150** | 4,260 | 3,960 | 2,250 | ICARDA, 2013, Third Edition |
| pH (1:1) | SU | 7.85 | 7.98 | 7.98 | **7.75** | **7.93** | **8.14** | 7.19 | 7.91 | 8.00 | |
| $NO_3$-N | mg/kg (Dry) Weight | 1.64 | 1.11 | 0.916 | **203** | **82.2** | **1.08** | 18.7 | 9.63 | 0.493 | SM.4110-B:2020 |
| K-extractable | mg/kg (Dry) Weight | 2,649 | 3,160 | 3,238 | **2,219** | **2,310** | **2070** | 1,473 | 1,470 | 877 | SOP. No.: 71 / 02 / 01 /02/8, Issue 1 |
| $NH_4$-N | mg/kg (Dry) Weight | 218 | 206 | 238 | **105** | **86.8** | **90.6** | 84.4 | 95.5 | 20.8 | ICARDA, 2013, Third Edition, 9.5.1 |
| $PO_4$-P | mg/kg (Dry) Weight | 290 | 310 | 340 | **360** | **285** | **243** | 295 | 449 | 170 | Practical Environmental Analysis, 2006, second edition, 5.10.4 |
| Moisture content | % | -- | -- | -- | **4.84** | **4.43** | **5.45** | 3.87 | 7.46 | 4.42 | SOP NO:71/02/03/03/04 Issue 1 |

because it took longer time to become available to the plant. The chemical fertilizers were added to Plots A and B only. Due to the presence of the bacterial biofertilizers in Plot B, the EC value was decreased by 7% compared to Plot A (bacteria-free) at the end of the experiment.

In this experiment, it is not considered to have a significant change in pH value. On the other hand, there is no significant effect on acidic values (pH value) as a result of adding microorganisms to the soil media. On the other hand, the potassium (K)-extractable decreased gradually from all plots until the end of the experiment, while the EC, K-extractable, NH4-N, and PO4-P decreased gradually in Plot C until the end of the experiment by 74, 73, 91, and 50%, respectively, due to the nutrient's abstraction from the soil in the presence of the bacterial biofertilizers, in addition to the absence of any chemical fertilizers in Plot C.

## Discussion

The design of the experiment is crucial in this study, starting with choosing the appropriate variety (summer season; cucumber crop), preparing the agricultural media, irrigation scheduling, fertilization, drainage system, and monitoring until the end of crop harvesting. The experiment was designed to simulate and compare traditional Jordanian farmer practices, especially those in the Jordan Valley region for cucumber cultivation.

The results of the experiment, which extended for over 84 days, have provided valuable insights into the effectiveness of bacterial biofertilizers in enhancing cucumber crop yield during the summer season. Plot B demonstrated clear superiority over Plots A and C in terms of increased crop yield, plant adaptability to environmental conditions, and pH stability throughout the crop cultivation period. This enhancement can be attributed to the presence of bacteria that stimulated the nutrient absorption by the roots from the chemical fertilizers and the naturally treated manure in the soil (Osorio Vega, 2007; Wong et al., 2015; Meena et al., 2017; Bargaz et al., 2018; Itelima et al., 2018). Several studies have been conducted in other countries that revealed the reasonability of using bacterial biofertilizers in enhancing production in cucumber crop planting (Parmar et al., 2011; Isfahani and Besharati, 2012; Kumar et al., 2018).

The key findings from this study showed that Plot B consistently outperformed other plots in terms of crop yield. The ascending order of the crop yield across plots on any given date was consistently Plot C, Plot A, and then Plot B. Plot A's yield production is aligned with the conventional farming practices, relying on sufficient chemical fertilization, while Plot B achieved the highest yield, benefiting from both chemical and bio-based bacteria products. The bacteria used in this experiment contains *Pseudomonas putida*, which enhanced germination rate and several growth parameters, including plant height, fresh weight, and dry weight of cotton under conditions of alkaline and high salt via increasing the rate of uptake of K+, Mg2+, and Ca2+ and by decreasing the absorption of $Na^+$ (Itelima et al., 2018).

Conversely, Plot C displayed the lowest yield due to inadequate fertilization, even with the presence of bio-products. Relative to the control plot (A), Plot B demonstrated a 48% increase in productivity, while Plot C showed a 54.6% decrease. This decrease coincides with other studies showing that the most important limitation of biofertilizers is their nutrient content when compared to inorganic fertilizers. This might result in deficiency symptoms in plants grown with the biofertilizer (Itelima et al., 2018).

Key findings from this study showed that Plot B consistently outperformed other plots in terms of crop yield. The ascending order of the crop yield across plots on any given date was consistently Plot

C, Plot A, and then Plot B. Plot A's yield production is aligned with the conventional farming practices, relying on sufficient chemical fertilization, while Plot B achieved the highest yield, benefiting from both chemical and bio-based bacteria. Conversely, Plot C displayed the lowest yield due to inadequate fertilization, even with the presence of bio-products. Relative to the control plot (A), Plot B demonstrated a 48% increase in productivity, while Plot C showed a 54.6% decrease. Additionally, water productivity figures (kg/m3 of water) for Plots A, B, and C were 27.5, 40.7, and 12.5, respectively, reinforcing the yield productivity percentages. The use of biofertilizers has previously been recognized as a practical solution to address water scarcity and reduce water consumption in agriculture. It has been proved that the application of biofertilizers will improve water productivity under certain conditions (Monem et al., 2001; Singh et al., 2011; Al-Amri, 2021).

Furthermore, an early appearance of buds and flowers was noticed in Plot B, likely attributable to the bio-products acting as a growth stimulant when added to the agricultural medium. Additionally, leaves in Plots A and B exhibited a healthier green color than the yellow-green leaves in Plot C, thus improving plant growth and nutrition (Orozco-Mosqueda et al., 2021). Notably, *Thrips* [1]and *Powdery mildew*[2] were absent in Plots B and C.

The study also noted that all seedlings in Plot B exhibited greater height than those in Plots A and C, with Plot B seedlings being 14% taller than control plot A. In addition, the average leaf area in Plot B was 22.6% larger than in the control plot, indicating that the bio-products contributed to enhanced photosynthesis and subsequently increased food production, flower production, and fruit ripening. This justified the overall increase in crop yield in Plot B. Using biofertilizers stabilized the plant cell membrane and increased the rate of photosynthesis, which led to the improvement of plant growth (Zhang et al., 2023).

The characteristics of the first soil sampling are very close for the three samples, which reflects the homogenies of soil composition for all pots prior to starting the experiment. The EC, K-extractable, $NH_4$-N, and $PO_4$-P decreased gradually in the soil in Plot C until the end of the experiment due to the nutrient's abstraction from the soil in the presence of the bacterial biofertilizers (Singh et al., 2016; Karapetyan, 2022). Plots B and C (with bacterial biofertilizers) had fewer EC values than Plot A (bacteria-free). In this experiment, it is not considered to have a significant change in pH value. On the other hand, there is no significant effect on acidity values (pH value) as a result of adding microorganisms to the soil media (Pierre, 1928). The K-extractable decreased gradually from all plots until the end of the experiment. In other studies, they assessed the impact of the application of biofertilizers along with chemical fertilizers on the soil characteristics. Dan et al. (2010) found that the activities of soil urease, acid phosphatase, and catalase were higher when applying this approach (Dan et al., 2010).

The higher chlorophyll content in Plot B and the consistent soil characteristics across all plots before the experiment's commencement suggest that the addition of bio-products primarily affected nutrient absorption rather than soil composition. The experiment's findings highlight the potential of using bio-products to improve nutrient uptake, increase plant size, enhance chlorophyll content, and ultimately boost crop yield, water productivity, and disease resistance (Chaudhari, 2017; Shivakumar and Bhaktavatchalu, 2017; Backer et al., 2018; Bargaz et al., 2018; Mącik et al., 2020). Consequently, these results have significant implications for improving agricultural practices, especially in regions such as the Jordan Valley, with potential enhancement of food security and sustainable agriculture (Arora, 2018; Daniel et al., 2022; Demir et al., 2023).

1 (Rabboh et al., 2023): A minute black-winged insect that sucks plant sap can be a serious pest of food plants when present in large numbers.

2 (): Mildew on a plant which is marked by a white floury covering consisting of fungi spore.

## Conclusion

In summary, the presence of bacterial biofertilizers enhanced the plant's absorption of nutrients, and accordingly, buds and flowers started earlier, chlorophyll content was enhanced, leaves grew bigger by 22.6%, the plant was taller by 14%, yield, and water productivity increased by 48% extra, with an absence of thrips and powdery mildew, and soil EC decreased.

This study provides valuable insights into sustainable agricultural practices with broad applicability in arid regions. The demonstrated improvement in crop yields through bacterial biofertilizers suggests significant potential for large-scale adoption, contributing to food system transformation and the achievement of the UN Sustainable Development Goals, particularly SDG 2 (Zero Hunger) and SDG 15 (Life on Land), at regional, national, and global levels.

## Recommendations

1) Based on the above results and good crop management practices, it is recommended to use the bacterial biofertilizers as a bio-soil improver, along with the organic manure and the chemical fertilizer to increase plant productivity and sufficient use of irrigation water, where both results will positively reflect on food security in Jordan.
2) Further study is needed to determine the exact water consumption of each plot since this needs a specific setup before starting the experiment.
3) Further study is needed to optimize the needed quantities of chemical fertilizers versus bacterial biofertilizers.
4) Further study is needed to determine the yield/water productivity versus crop type when using bacterial biofertilizers.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

MM: Methodology, Writing – original draft, Data curation, Formal analysis, Investigation. AA: Conceptualization, Supervision, Writing – review & editing. NA-H: Conceptualization, Supervision, Writing – review & editing, Funding acquisition, Project administration. HA: Project administration, Supervision, Methodology, Writing – original draft, Data curation, Investigation, Validation. RA: Data curation, Writing – original draft, Formal Analysis. MA: Project administration, Writing – original draft, Conceptualization, Methodology.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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