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Influence of Zinc Oxide Nanoparticles (ZnONPs), Seaweed Extract and Microbial Inoculation with Rhizobium on Faba Bean Nodulation, Yield, and Quantity

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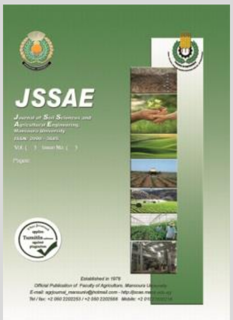

ABSTRACT

Currently, faba beans are farmed all over the world and are a mainstay of many people's diets that are rich in nutrients and health. The world's temperate zones' colder regions are where the crop is primarily farmed. To further enhance the nodulation traits, yield and its components, and nutritional status, the present study was conducted on faba bean plants (*Vicia faba* L.) in the experimental farm at Sids Agricultural Research Station, Beni-Suef Governorate, ARC, Egypt, for two consecutive seasons (2022/2023 and 2023/2024). Various treatments including microbial inoculation, seaweed extract, and Zinc Oxide Nanoparticles (ZnONPs) were applied alone and in combination. Additionally, the faba bean seeds were inoculated with a 250 g microbial inoculum before planting and sprayed with a foliar spray solution containing 1% seaweed extract and 50 ppm Zinc Oxide Nanoparticles twice during the growing period. The results showed that all treatments, either alone or combined, had a significant impact on the plant traits. The combined applications were found to be more effective than individual ones, with the triple application (microbial inoculation + seaweed extract + Zinc Oxide Nanoparticles) showing the most improvement in nodulation, yield, and seed quality of the faba bean plants. Therefore, it is advised to apply, under Middle Egypt conditions, a combination of 50 ppm of Zinc Oxide Nanoparticles, 1% of seaweed extract applied foliar, and 250 g of rhizobium microbiological inoculation.

Keywords: Faba bean, Nano zinc oxide particles, Seaweed extract, and Microbial inoculation.

INTRODUCTION

A greater demand for agricultural production is anticipated because of the projected 9.7 billion people on the planet by 2050 (Bahar *et al*., 2020). It is essential to raise agricultural yield to meet demand. By making the most of the potential of the arable land that is currently available and making efficient use of resources and technology, this can be accomplished (Abd El-Azeim *et al*., 2023). Eastern Mediterranean regions were the first to domesticate faba beans, one of the first Mediterranean food legumes. Grown all over the world, but especially in the colder parts of temperate zones, they were highly prized in ancient Egypt (Lippolis *et al*., 2023).

Nanotechnology is the study of individual molecules and atoms smaller than 100 nanometers. It is a relatively new field. Technology's use in agriculture has evolved and grown in recent years. Smart solutions to agricultural problems have been made possible by nanotechnology (Abd El-Azeim *et al*., 2020). One such example is the use of nanomaterials to increase crop yields, such as nano fertilizers, herbicides, and pesticides. By giving crops direct access to nutrients, nanomaterials effectively raise crop yield (Salehi *et al*., 2022). Because it avoids soil fixation, is simpler to apply, and has a lower potential for toxicity than soil application, foliar spraying nanoform microelements is thought to be an extremely effective method of delivering nutrients (Abdel Wahab *et al*., 2019). Applying small amounts of nano zinc oxide can significantly improve the growth characteristics of many plants and control tryptophan synthesis, which in turn affects plant quality (García-López *et al*., 2019; Abou El-Nasr *et al*., 2021; Mekawy, 2021). There has been a recent push to switch out chemical fertilizers with environmentally friendly alternatives because they are less harmful to the environment and require smaller quantities than traditional fertilizers (Davarpanah *et al*., 2016; Kah *et al*., 2018). Particle size reduction increases the specific surface area of a fertilizer, which accelerates the rate of dissolution of low-water-soluble fertilizers such as zinc oxide (ZnO) (Mortvedt, 1992). By increasing the surface area of contact and the rate at which the zinc is absorbed and moves through the plant's vascular tissues, this improved distribution of zinc improves the efficiency of zinc absorption (Liscano *et al*., 2000).

The use of seaweed extracts in integrated crop management is now regarded as essential because of improvements in crop productivity techniques. Seaweed contains a variety of bioactive substances, such as vitamins, minerals, proteins, carbohydrates, and other vital trace elements. Furthermore, seaweed has balanced amounts of carbon and nitrogen, which can promote crop plant vitality and growth. The main products made from seaweed include chips, flakes, powders, organic fertilizers, and soil conditioners (Ali *et al*., 2021). Increases in growth parameters like shoot length, root length, number of leaves, number of branches, dry weight, and topological parameters like crop spread were observed in plants treated with an aqueous solution containing 10% seaweed extract. It has also been

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found that applying seaweed extract to crops increases their quality and yield, including fruit, vegetables, and flowers (Tejasree *et al*., 2024). Studies have demonstrated that adding seaweed extract to strawberry, radish, cabbage and tomatoes increased the amount of fruit production, quality, and the weight of roots per plant. Additionally, seaweed extracts significantly improved the vegetative growth, yield, and yield attributes of tomatoes (Raja and Vidya, 2023). Kakabra (2024) reports that when onion bulbs were treated with seaweed extract, their depth also increased significantly.

For the sustainable development of horticultural crops, using bio-stimulants (PBs) is a significant substitute for reducing the use of chemical fertilizers (Rouphael and Colla, 2020). By increasing nutrient use efficiency and increasing nutrient accessibility in the soil or rhizosphere, bio-stimulants aid in the activation of plant nutrition processes (Samri *et al*., 2021). Biological nitrogen fixation, particularly the symbiosis between rhizobia and legumes, is another efficient way to increase soil fertility, decrease the need for inorganic N fertilizers, and lower production costs (Peoples *et al*., 1995). According to Herridge *et al.* (2008), nodules of legumes, such as oilseeds and pulses, fix nitrogen (N_2) and provide 21.45 million tons of nitrogen to agricultural systems annually worldwide. When native rhizobia are insufficient or competing with ineffective ones, external seed inoculation with rhizobia is a sustainable and environmentally friendly method of increasing the crop capacity to fix nitrogen (Tolera *et al*., 2009).

Considering the abovementioned data, the main objective of this study was to investigate the vegetative growth characteristics and quality attributes of faba beans by utilizing Zinc Oxide Nanoparticles, seaweed extract, and microbial inoculation either individually or in combination.

MATERIALS AND METHODS

Two consecutive seasons (2022/2023 and 2023/2024) of a field experiment were carried out at Sid's Agricultural Research Station in Beni-Suef Governorate, ARC, Egypt, to evaluate the effects of rhizobium inoculation, seaweed extract, and zinc nanoparticles on faba bean plants (*Vicia faba* L.). A surface soil sample (0.0–30 cm) was taken to ascertain the precise physical (Klute, 1986) and chemical (Page *et al*., 1982) properties, which are displayed in Table 1 to depict the characteristics of the experimental soil.

Table 1. Some chemical and physical characteristics of the experimental soil.

Soil properties	20222/2023	2023/2024
Physical properties:		
Particle size distribution:		
Clay (%)	54.7	56.9
Silt (%)	34.2	32.1
Sand (%)	11.1	11.0
Texture grade	Clay	Clay
Chemical properties:		
pH (1:2.5)	8.0	7.9
EC (ds m^{-1})	1.23	1.31
Organic matter (%)	1.32	1.42
CaCO3 (%)	1.52	1.57
Available N (µgg^{-1})	21.1	22.9
Available P (µgg^{-1})	16.6	15.8
Available K (µgg^{-1})	141	148
Available Zn (µgg^{-1})	2.4	1.9
Available Fe (µgg^{-1})	3.7	3.4
Available Mo (µgg^{-1})	0.6	0.46

Cotton (*Gossypium barbadense* L.) was the previous crop in both growing seasons. In preparation for planting, 31 kg of superphosphate (15.5% P_2O_5) and 24 kg of potassium sulphate (48% K_2O) were added per feddan. Prior to seeding, 10 kg of ammonium nitrate (33.5% N) of nitrogen were added per feddan. The Soil, Water, and Environment Institute, ARC's Department of Microbiology treated the experimental plot (3.0 x 3.5 m) with a particular Rhizobium using Arabic gum and 1% glucose (w/w) for the inoculated treatments. Then, on October 15 and October 20, during both growing seasons under investigation, faba bean seeds (variety Giza 843) were planted at a rate of one seed per hill.

The experiment made use of a modified extract of Ascophyllum nodosum marine plant, which contains alginate and mineral elements. The extract was obtained from the Agricultural Research Centre in Giza, Egypt (see Table 2). At the Nanotechnology Lab, Plant Pathology Research Institute, Agricultural Research Centre, Giza, Egypt, Zinc Oxide Nanoparticles were prepared at a concentration of 50 parts per million (ppm). Seaweed extract and Zinc Oxide Nanoparticles were used in two foliar spraying, the first occurred 30 days after sowing and the second 15 days later. Spraying was done until runoff occurred, with each foliar solution containing 0.1% Triton B as a wetting agent.

Table 2. constituents of seaweed extract.

Composition of seaweed extract	Values
Organic matter (%)	51.0
Nitrogen (%)	1.25
Phosphorus (%)	0.03
Potassium (%)	10.1
Calcium (%)	0.06
Magnesium (%)	0.03
Sulphur (%)	0.30
Zinc (ugg^{-1})	50.0
Iron (ugg^{-1})	115.0
Manganese (ugg^{-1})	7.0

Four replications of a randomized complete block design (RCBD) were employed in the experiment. Among the treatments were:

1. Control (untreated),
2. Microbial inoculation with Rhizobium at 250 g inoculum,
3. Foliar spray with seaweed extract at 1%,
4. Foliar spray with Zinc Oxide Nanoparticles at 50 ppm,
5. Microbial inoculation with Rhizobium + Foliar spray with seaweed extract at 1%,
6. Microbial inoculation with Rhizobium + Foliar spray with Nano-zinc oxide particles at 50 ppm,
7. Foliar spray with seaweed extract at 1% + Foliar spray with Nano-zinc oxide particles at 50 ppm, and
8. Microbial inoculation with Rhizobium + Foliar spray with seaweedextract at 1% + Foliar spray with Zinc Oxide Nanoparticles at 50 ppm.

Each experimental plot received a 75 g N/fed application of ammonium nitrate. Fava beans were produced using customs and traditions from the local community. Ten plants were selected at random from the two middle rows, and after 48 days of planting, soil was carefully removed with a ball of earth. After giving the roots a thorough cleaning, the nodules were extracted and tallied. The nodules were then weighed (in milligrams) and dried in an oven for 72 hours at 70 ^oC.

To quantify the different aspects of yield, including the weight (in grammes) of one hundred seeds, the number of pods per plant, and the number of seeds per pod, a random sample of ten plants was taken at maturity from the middle two ridges of each plot. Furthermore, the yields of seeds (ardab/fed) and straw (ton/fed) were computed. Faba bean seeds were subjected to tests for zinc, iron, molybdenum, phosphorus, potassium, and nitrogen using protocols described by Cottenie *et al.* (1982).

The experiment layout made full use of block design randomization. Snedecor and Cochran (1980) state that this data set's statistical analysis is complete. At the five percent, the averages were contrasted with the new L.S.D. values (Steel and Torrie, 1980).

RESEULTS AND DISCUSSION

Impact on the nodulation

Table 3 displays the effects of two growing seasons of microbial inoculation with rhizobium, seaweed extract, and nano zinc oxide particles, either separately or in combination, on the quantity of nodules per plant and their dry weight (in milligrams). Regardless of whether treatments were applied singly or in combination, the results show that in the seasons 2022/2023 and 2023/2024, there was a significant increase in both the number and dry weight of nodules per plant when compared to the control. Microbial inoculation with rhizobium proved to be the most successful of the individual treatments during both seasons. The rhizobium-based microbial inoculation was the most effective method, followed by seaweed extract and nano zinc oxide particles. When comparing the number and dry weight of nodules per plant between the combined treatments and the individual treatments, a significant increase was observed. The combination of rhizobium + seaweed extract microbial inoculation proved to be the most advantageous in both seasons, according to the combined treatments' results. The efficacy of the two treatments was as follows: rhizobium + seaweed extract microbial inoculation > rhizobium + nano zinc oxide particles microbial inoculation > seaweed extract + nano zinc oxide particles. Additional examination revealed that the number of combined treatments had a significant effect, and that the effect grew with the number of combined treatments. The triple treatment approach (rhizobium + seaweed extract + nano zinc oxide particles) yielded the highest significant values for these traits in both seasons when compared to all other treatments.

Table 3. Rhizobium, seaweed extract, and nano-zinc oxide particle microbial inoculation as affected the quantity and dry weight of faba bean nodules in the 2022/2023 and 2023/2024 seasons.

Treatments	Studied attributes			
	No. of nodules/plant		Dry weight of nodules/plant (mg)	
	2022/2023	2023/2024	2022/2023	2023/2024
Control (untreated)	14.5	15.6	82.4	86.2
Microbial inoculation with rhizobium (MIR)	18.0	18.7	91.2	93.3
Seaweed extract (SE)	17.7	18.5	88.3	92.3
Nano zinc oxide particles (ZnONPs)	16.8	17.8	85.8	91.1
MIR + SE	20.3	21.9	97.7	102.7
MIR + (ZnONPs)	19.7	20.2	95.3	99.7
SE + (ZnONPs)	19.2	19.8	94.7	96.6
MIR + SE + (ZnONPs)	21.5	22.6	101.7	106.7
L.S.D. at 0.05	1.0	1.2	2.99	3.68

Inoculation with rhizobium may be advantageous for these parameters because it generates some enzymes that improve root respiration, enhance element uptake, and produce growth-promoting compounds like cytokinin, which may spur growth through increased cell division (Herridge *et al*., 2008; Abebe and Tolera, 2014). Kutafo and Alemneh (2021), discovered that rhizobium inoculation increased the number of nodules per plant in comparison to the untreated (control) group, is also in line with the results obtained here. The reason for this could be the high nodulation-inducing capacity of the inoculated bacterial strain.

The presence of active organic substances such as laminarin, a 1.3-1.6 D-glucan oligosaccharide, in seaweed extract can lead to an increase in nodule parameters. These compounds function as activators of the synthesis of polyamines (PAs), significant growth regulators that stimulate cell elongation and division, increasing the length of shoots and area of leaves (Colavita *et al*., 2011).

In addition to supporting plant growth and protein synthesis, nano zinc oxide particles are important for the absorption of auxin, which in turn stimulates cell division and elongation. A key ingredient in IAA, tryptophan is necessary for cell elongation as well as division (Castillo-Gonzalez *et al*., 2018).

Impact on the components of yield

Table 4 presents the attributes of the components that make up the yield of faba beans, including the weight of 100 seeds after two growing seasons, the number of pods per plant, and the number of seeds per pod. Additionally displayed are the results of three treatments: rhizobium microbial inoculation, nano zinc particles, and seaweed extract. In comparison to the control, all treatments single or combined significantly improved the yield component characteristics of faba beans in the 2022/2023 and 2023/2024 seasons. Regarding individual treatments, the use of Zinc Oxide Nanoparticles and biofertilizer outperformed the others in both seasons. The order of effectiveness was as follows: seaweed extract > nano-zinc particles > rhizobium-based microbial inoculation. The combination of rhizobium + nano zinc oxide particles for microbial inoculation proved to be the most beneficial during both growing seasons, although combined treatments were even more successful. For microbial inoculation, the effects were found to be as follows in decreasing order: rhizobium + nano zinc oxide particles > rhizobium + seaweed extract > seaweed extract + nano zinc oxide particles. A more thorough investigation showed that the number of combined treatments also had a significant impact. For these traits in both seasons, the triple application method microbial inoculation with rhizobium + seaweed extract + nano zinc oxide particles produced the highest significant values.

Table 4. Shows how the rhizobium, seaweed extract, and nano-zinc oxide particle microbial inoculation affected the number of pods per plant, number of seeds per pod, and weight of 100 seeds of faba bean plants in the 2022/2023 and 2023/2024 seasons.

Treatments	Studied attributes					
	No of pods/plant		No of seeds/pod		100-seed weight	
	2022/2023	2023/2024	2022/2023	2023/2024	2022/2023	2023/2024
Control (untreated)	28.33	31.70	2.44	2.46	14.21	14.45
Microbial inoculation with rhizobium (MIR)	31.72	34.85	2.92	2.84	16.09	16.20
Seaweed extract (SE)	29.76	33.63	2.63	2.75	15.58	15.87
Nano zinc oxide particles (ZnONPs)	32.04	36.08	2.97	3.02	16.30	16.48
MIR + SE	33.83	37.30	3.37	3.47	17.68	17.92
MIR + (ZnONPs)	34.48	38.01	3.65	3.54	18.44	18.72
SE + (ZnONPs)	33.02	36.94	3.29	3.41	17.21	17.57
MIR + SE + (ZnONPs)	35.62	39.93	3.73	3.78	19.28	19.51
L.S.D. at 0.05	0.98	1.58	0.08	0.11	0.50	0.46

As was covered in the preceding sections, improved nodulation may result in improved biological nitrogen fixation. The increase in the number of pods per plant, the number of seeds per pod, and the weight of 100 seeds after inoculation may be due to this improvement. Nitrogen is necessary for the synthesis of several biological molecules required for photosynthesis and the production of chlorophyll, according to Werner and Newton (2005) and Marschner (2011). Robust vegetative growth and increased biomass production are facilitated by these processes.

It has been discovered that using seaweed extract as a bio-stimulant increases the weight of 100 seeds, the number of pods per plant, and the number of seeds per pod. The high concentrations of organic materials and minerals in the extract improve the absorption of macronutrients like potassium (K), phosphorus (P), and nitrogen (N). As a result, as the plant grows and matures, it absorbs more of these nutrients, which causes their concentrations to rise (Ghanaym *et al*., 2022). These results align with the research conducted by Sulieman *et al*. (2023). Furthermore, by encouraging the synthesis of ascorbic acid, seaweed extract can help prevent damage to the photosynthetic apparatus. This, in turn, lowers the degradation of chlorophyll and raises the amount of chlorophyll in plants when compared to untreated plants (Aboualhamed and Loutfy, 2020).

ZnO NPs, or zinc oxide nanoparticles, may improve zinc metabolism and lessen the harmful effects of overfertilization. Additionally, they have the ability to boost antioxidant enzyme activity, shielding plants from harm from reactive oxygen species (Ragab *et al*., 2022; Shareef *et al*., 2023). Prior studies have demonstrated that ZnO NPs applied topically can lower reactive oxygen species (ROS) by elevating antioxidant enzyme levels. According to Elsheery *et al*. (2020b), photoinhibition and additional photodamage must be avoided by carefully controlling the flow of electrons between photosystems.

Impact on the faba bean plant seed and straw yields

The effects of several treatments (seaweed extract, nano zinc oxide particles, and rhizobium microbial inoculation), applied singly or in combination, on the faba bean seed and straw yields (ton/fed) in the 2022–2023 and 2023–2024 seasons are displayed in Table 5. In both growing seasons, all the treatments generally demonstrated a significant improvement over the control. To be more precise, when compared to the control, all treatments single or combined produced statistically significant increases in seed and straw yields (ton/fed).

A greater concentration of phytohormones and photosynthates, which are controlled by microorganisms, may be the cause of the increased seed and straw yield in plants following microbial inoculation with rhizobium (Bona *et al*., 2017).

Table 5. Shows how the rhizobium, seaweed extract, and nano-zinc oxide particle microbial inoculation affected the seed and straw yield of faba bean plants in the 2022/2023 and 2023/2024 seasons.

Treatments	Studied attributes			
	Seed yield (ton/fed)		Straw yield (ton/fed)	
	2022/2023	2023/2024	2022/2023	2023/2024
Control (untreated)	1.01	1.12	1.29	1.42
Microbial inoculation with rhizobium (MIR)	1.14	1.25	1.52	1.63
Seaweed extract (SE)	1.10	1.23	1.46	1.60
Nano zinc oxide particles (ZnONPs)	1.15	1.28	1.56	1.66
MIR + SE	1.25	1.39	1.67	1.81
MIR + (ZnONPs)	1.30	1.45	1.71	1.87
SE + (ZnONPs)	1.22	1.37	1.65	1.81
MIR + SE + (ZnONPs)	1.36	1.51	1.74	1.89
L.S.D. at 0.05	0.03	0.03	0.02	0.01

The outcomes of our study are consistent with field tests showing the beneficial effects of seaweed extract on the yield of straw and faba beans. Auxins, gibberellins, cytokinins, and a variety of microelements, including Cu, Zn, Mo, B, and Co, are all found in seaweed extracts. Seaweed extract strengthens the stem, increases leafy area, and encourages plant growth when applied topically. These actions ultimately increase root and vegetative growth and yield. According to Abd-Elwahid *et al*. (2019), using a spray method to apply marine plant extract increased the size, weight, and yield of the fruit on the plant. Cell division is encouraged by the extract's high cytokine content. According to Beckett *et al*. (1994) and Temple and Bomke (1989), seaweed extract functions as a biostimulant for bean plants as opposed to merely fertilizer. They proposed that seaweed extract could increase yield in two ways: either by improving the fruit's assimilation potential to increase the number of cotyledon cells and final seed mass, or by increasing leaf area and photosynthetic rates to provide more assimilates for bean filling.

Zinc, which is involved in numerous enzyme activities and metabolic processes, is a micronutrient that is vital for both plants and animals. This is why nano zinc oxide particles contain zinc. Lower yields are the result of decreased zinc levels in plants. The outcomes corroborate the findings of Irfan and Bhatti (2023) and Srivastav *et al*. (2021), who found that plant biomass and length were enhanced by nano zinc oxide particles. Because zinc influences numerous enzyme activities, protein synthesis, metabolic processes, gene expression, and membrane integrity, plants need it for healthy growth. Increased zinc levels promoted faster plant growth and were in line with the results of applying nano zinc oxide particles.

Impact on the concentrations of nitrogen, phosphorus, potassium, and zinc in faba bean seed plants

All applications, either separately or in combination, greatly raised the levels of mineral elements like total nitrogen, phosphorus, potassium, and zinc in comparison to the control in both growing seasons, as shown by the data in Table 6. For each season, the following descending order of individual treatments was found to be most effective: rhizobium application combined with microbial inoculation > seaweed extract > nano zinc oxide particles. It was discovered that the simultaneous application of rhizobium and seaweed extract microbial inoculation greatly improved these parameters, making the two applications more beneficial than the one. After more investigation, it was found that the triple application strategy (rhizobium + seaweed extract + nano zinc oxide particles) produced the highest significant values in both growing seasons and was the most successful in increasing the seed content of N, P, K, and Zn when compared to the other treatments. A large amount of assimilates translocated towards the roots of plants inoculated with rhizobium, which is likely to have resulted in an increase in seed concentrations of total N, P, K, and Zn. This increase may also have contributed to an increased photosynthetic rate. These results are in line with those of Kucuk and Kivanc (2008), who noted a noteworthy rise in seed weight, yield, and protein range in three bean (Phaseolus vulgaris L.) varieties that were inoculated with Rhizobium spp. Higher nodulation, higher N2-fixation, and improved root development in field or regulated conditions are likely causes of the co-inoculated plants' greater dry matter and nitrogen content (Dashti *et al*., 1998). Furthermore, by solubilizing insoluble phosphates, PGPR bacteria can enhance biological nitrogen fixation and plant availability of other nutrients, consequently raising the availability of P (Gyaneshwar *et al*., 2002).

To improve agricultural productivity, seaweed extracts are employed as a sustainable and natural source of biostimulants. The higher concentrations of minerals, amino acids, and plant hormones found in them have the potential to boost antioxidant activity and shield the body from stress-related oxidative damage. These extracts may also enhance membrane and DNA repair processes, which would enhance seed physiological performance in extremely cold temperatures (Ali *et al*., 2021).

Table 6. Shows how the rhizobium, seaweed extract, and nano-zinc oxide particle microbial inoculation affected the concentration of N, P, K, and Zn in seeds of faba bean plants in the 2022/2023 and 2023/2024 seasons.

Treatments	Studied attributes							
	N%		P%		K%		Zn ppm	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Control (untreated)	3.90	3.93	0.47	0.44	1.56	1.52	20.75	22.13
Microbial inoculation with rhizobium (MIR)	4.13	4.06	0.70	0.64	1.70	1.64	26.67	31.42
Seaweed extract (SE)	4.05	3.96	0.59	0.59	1.64	1.60	24.78	27.79
Nano zinc oxide particles (ZnONPs)	4.00	3.94	0.51	0.50	1.61	1.58	26.04	29.90
MIR + SE	4.56	4.46	0.92	0.86	1.86	1.79	32.83	37.95
MIR + (ZnONPs)	4.36	4.20	0.84	0.75	1.81	1.74	30.87	35.77
SE + (ZnONPs)	4.23	4.06	0.78	0.69	1.75	1.70	29.19	34.91
MIR + SE + (ZnONPs)	4.77	4.63	0.98	0.98	1.93	1.81	36.61	40.52
L.S.D. at 0.05	0.07	0.10	0.03	0.04	0.06	0.04	3.42	2.49

The study discovered that, in comparison to untreated plants, faba bean plants treated with zinc oxide nanoparticles produced higher amounts of zinc, P, K, and N in their seeds. The results were significantly affected by the spray application of zinc oxide nanoparticles. Deka (2019) talked about how the growth and nutrient content of the plants can be impacted by various elements, including the size and shape of the particles, the application technique, the length of time the plant is exposed to them, and other chemical and physical characteristics. These results align with the findings of Dimkpa *et al*. (2019).

CONCLUSION

In two consecutive seasons (2022/2023 and 2023/2024), there was an improvement in the number and dry weight of nodules and plant traits, nutritional status, yield, and yield component attributes of faba bean plants. This improvement was achieved through the use of applications such as microbial inoculation with rhizobium, seaweed extract, and Zinc Oxide Nanoparticles , either alone or in combination. The research findings indicated that the triple application of microbial inoculation with Rhizobium, seaweed extract, and Zinc Oxide Nanoparticles significantly enhanced the number and dry weight of nodules and other plant traits. It also increased the content of mineral elements in the leaves and improved the yield and yield attributes of faba bean plants. Therefore, it is recommended to apply the combined application of Zinc Oxide Nanoparticles at 50 ppm, foliar spray with seaweed extract at 1%, and microbial inoculation with rhizobium at 250 g under Middle Egypt conditions.

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تأثير جزيئات أكسيد الزنك النانومترية، مستخلص الطحالب، والتلقيح الميكروبي مع الريزوبيوم على تكوين العقد، والمحصول، والكمية في الفول البلدي

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الملخص

تهدف الدراسة إلى تحسين نمو وإنتاجية نباتات الفول البلدي في محطة البحوث الزراعية بسدس بني سويف في مصر على مدى موسمين متتاليين (٢٠٢٣/٢٠٢٢ و٢٠٢٤/٢٠٢٣). تم تطبيق معاملات متنوعة بما في ذلك تلقيح الميكروبات، مستخلص الطحالب، وجزيئات أكسيد الزنك النانوميترية بشكل منفرد ومجتمعة. بالإضافة إلى ذلك، تم تلقيح بذور الفول البلدي بمقدار ٢٥٠ جرام من اللقاح الميكروبي قبل الزراعة ورشها بمحلول رذاذ ورقي يحتوي على ١٪ من مستخلص الطحالب و٥٠ جزء في المليون من جزيئات أكسيد الزنك النانومترية مرتين خلال فترة النمو. أظهرت النتائج أن جميع العلاجات، سواء كانت بمفردها أو مجتمعة، كان لها تأثير كبير على صفات النبات. اظهرت النتائج أن التطبيقات المجمعة كانت أكثر فاعلية من التطبيقات الفردية، حيث أظهر التطبيق الثلاثي (تلقيح ميكروبي + مستخلص الطحالب + جزيئات أكسيد الزنك النانومترية) أكبر تحسين في تكوين العقد، والإنتاج، وجودة البذور لنباتات الفول البلدي .لذا، يُوصى بتطبيق الاستخدام المشترك لجزيئات أكسيد الزنك النانومترية بتركيز ٥٠ جزء في المليون، ورش الأوراق بمستخلص الطحالب بتركيز ١٪، والتلقيح الميكروبي مع الريزوبيا بوزن ٢٥٠ جرام تحت ظروف مصر الوسطي.