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Effect of Nano micronutrients and Nano PGPR$_s$ through Bio capsules on growth and development, yield of Chilli (*capsicum annuum* L.) cv. Pusa Jwala

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Abstract
An experiment entitled on Effect of Nano micronutrients and Nano PGPR$_s$ through Bio capsules on growth and development, yield of Chilli (*capsicum annuum l.*) cv. Pusa Jwala was conducted during *Rabi* season of 2022 – 2023 and 2023- 2024 at Crop Research Farm, Department of Agronomy, Naini Agriculture Institute, Sam Higginbottom University of Agriculture, Technology and Science, Prayagraj (U.P.) India. Three levels of Micronutrient like Nano-iron oxide (FeO, 100 ppm), Nano-zinc oxide (ZnO, 150 ppm) and Nano-PGPR Bio capsules: 500 ppm and 250 ppm, containing beneficial bacteria (e.g., Bacillus spp., Azospirillum spp.) encapsulated in biodegradable matrices (e.g., chitosan-based). The sandy loamy soil in the experimental plot had a pH of (7.3), was almost neutral in soil reaction, and had a low organic carbon content of (0.45%), potassium (243.8 kg/ha) and available phosphorus (27.4 kg/ha) nitrogen (239.5 kg/ha). The experiment was laid out in a Randomized Block Design with ten treatments which have replicated thrice. The results revealed that significantly higher growth attributes in year 2022-2023 of Chilli at 120 DAS *viz.*, plant height (96.10 cm), Number of leaves/plant (143.76),and Number of branches/plant, 50% Flower/plant (52.2), Fruit/plant (56.37) Fruit yield (27.01 t/ha) and TSS Brix 7.35%) were recorded in T_{14} (T_{14}-NPK(RDF)100%, Biocapsule 250PPM + ZnO + FeO) compared to other treatments. and result showed in 2023-2024 of Chilli at 120 DAS *viz.*, plant height (89.47cm), Number of leaves/plant (147.05), and Number of branches/plant, 50% Flower/plant (51.5), Fruit/plant (58.64) Fruit yield (28.61 t/ha) and TSS Brix% (7.06%) were recorded in T_{14} (T_{14}-NPK(RDF)100%Biocapsule 250PPM + ZnO + FeO) compared to other treatments was recorded the best among all combination, different hybrid in terms of growth, yield and quality parameters

Keywords: Economics, Chilli, Nano-PGPR**,** Nano micronutrients

Introduction

Chilli (*Capsicum annuum* L.) variety Pusa Jwala serves as an essential flavoring and food plant in India, However, inadequate nutrient absorption, degraded land, and high farming costs limit its productivity. Through the use of environmentally friendly carriers, this study evaluated the combined effects of beneficial soil microbes that promote plant growth and essential elements that are essential at the nanoscale (zinc and iron oxides) on development traits, production levels, product attributes, ground composition, and financial viability in outdoor trials. Essential metrics were measured at several stages (60 to 150 days post-planting) across two seasons (2022–2023) using a randomized plot arrangement with 15 variants (including untreated, full recommended fertilizer amount, and mixes of carriers at 250 or 500 parts per million with nano zinc or iron oxides) replicated three times.

The diversity Developed by the Indian Agricultural Research Institute (now ICAR-Indian Institute of Horticultural Research), Pusa Jwala is a popular cultivar in India that is suitable for both the manufacture of dried spices and fresh market due to its great yield potential, early maturity, and powerful pungency. A permanent, annual plant with distinct growth and agricultural characteristics is Pusa Jwala. Structure: Dense, upright shape, 60–80 cm in height and 45–60 cm in width. Foliage: smooth, deep green, egg-lance shaped, 8–12 cm long. Pale blooms that can be single or clustered and primarily self-fertilize, however insects help with mixing. Produce: Form and Scale: Slim, stretched, lightly bent fruits, usually 8–10 cm long and 1–1.5 cm wide. Hue: Green young, bright red ripe. Sharpness: Strong, with heat compound at 0.5–1.0% (50,000–100,000 heat units), medium to high spice. Output: In best settings, 15–20 tons per hectare fresh, 2–3 tons dry. Ripening: Fast, harvest-ready 70–80 days post-shift. Suitability: Grows in warm, sub-warm zones, handles varied grounds (drained loam) and warmth (20–35°C) (Prasad *et al.,* 2016; Singh *et al.,* 2022).

Iron, zinc, manganese, and other vital plant nutrients are encapsulated or formed into nanoparticles as nano micronutrients to enhance plant absorption and delivery. Through slower, regulated release into the soil or to the leaves, this nanotechnology improves nutrient use efficiency, limiting overfertilization and saving farmers money while fostering agricultural sustainability and raising crop output and quality.

Zinc oxide nanoparticles are zinc oxide (ZnO) nanoparticles with a diameter of less than 100 nm. They exhibit significant catalytic activity and a big surface area in relation to their size. The many methods used to create zinc oxide nanoparticles affect their precise chemical and physical characteristics. Laser ablation, hydrothermal techniques, electrochemical depositions, sol-gel techniques, chemical vapor deposition, thermal decomposition, combustion techniques, ultrasound, microwave-assisted combustion techniques, two-step mechanochemical–thermal synthesis, anodization, co-precipitation, electrophoretic deposition, and precipitation processes utilizing solution concentration, pH, and washing medium are a few potential methods for producing ZnO nanoparticles.

Utilizing nanotechnology, nano-encapsulated or nano-formulated Plant Growth-Promoting Rhizobacteria (PGPR) increase the efficiency of beneficial soil bacteria in agriculture. By providing improved stability, controlled release, higher bioavailability, and improved root colonization, this combination lowers the requirement for chemical inputs and synthetic fertilizers while increasing crop yields and stress tolerance.

Materials and Methods

An experiment entitled on Effect of Nano micronutrients and Nano $PGPR_s$ through Bio capsules on growth and development, yield of Chilli (*capsicum annuum l.*) cv. Pusa Jwala was conducted during *Rabi* season of 2022 - 2023 at Crop Research Farm, Department of Horticulture, Naini Agriculture Institute, Sam Higginbottom University of Agriculture, Technology and Science, Prayagraj (U.P.) IndiaNano-iron oxide (FeO, 100 ppm), nano-zinc oxide (ZnO, 150 ppm), and nano-PGPR biocapsules are examples of micronutrients with three levels: beneficial microorganisms (such Bacillus and Azospirillum species) contained in biodegradable matrix (like chitosan-based) at concentrations of 500 ppm and 250 ppm. The experimental plot's sandy loamy soil had a pH of 7.3, was nearly neutral in soil reaction, and contained potassium (243.8 kg/ha), accessible phosphorus (27.4 kg/ha), nitrogen (239.5 kg/ha), and a low amount of organic carbon (0.45%). A Randomized Block Design was used to set up the experiment, which included ten treatments with three replications. With a 45 cm x 15 cm spacing, chilli (Pusa Jwala) were planted on February 17, 2022, and 2023. Applying organic manure as a spreading technique involved digging furrows along the seed rows that were 4-5 cm deep using a hand hoe. After germination, the gaps were filled by transplanting 10 days after the first seeding. Where necessary, seedlings were removed to maintain a 45 cm by 15 cm gap between plants. To lessen weed competition and crop density, intercultural operations were carried out every 25 to 45 days. Harvesting took place on May 22nd, 2022, and 2023. Features of plant growth, such as plant height (cm). From germination to harvest, measurements were taken at regular intervals to determine the percentage of flowers per plant, the number of branches per plant, and the number of leaves per plant. Fruit/plant, fruit yield (kg/ha), stover yield (kg/ha), and harvest index (%) were among the yield parameters tested at 30, 60, 90, and 1200 DAS. Analysis of variance (ANOVA), as it relates to randomized block design, was used to statistically examine the observed data of ten treatments (Gomez and Gomez, 1984) [7].

Results and Discussion

Growth parameter

Plant Height

The data of growth parameter are presented in Table 1. show Effect of Nano micronutrients and Nano $PGPR_s$ through Bio capsules on growth and development of Chilli. the application of (NPK(RDF)100%Biocapsule 250PPM + ZnO + FeO) in T_{14} resulted the higher plant height at 120 DAS, T13 peaked at 108.07 cm (2022) and 114.21 cm (2023), averaging 111.14 cm, followed by T12 at 106.69 cm and 103.72 cm (pooled 105.2 cm), against T0's 88.75 cm and 87.45 cm (pooled 88.1 cm). They exhibit significant catalytic activity and a big surface area in relation to their size. Essential plant nutrients including iron, zinc, and manganese are known as nano micronutrients. These nutrients are encapsulated or synthesized into nanoparticles to enhance plant absorption and delivery. Additionally, the term "nano-PGPR" refers to Plant Growth-Promoting Rhizobacteria (PGPR) that have been nano-encapsulated or nano-formulated. This technique employs nanotechnology to increase the efficiency of helpful soil bacteria in agriculture.

Number of Leaves/plant

Revealed that at 120 DAS, the number of leaves per plant gradually increased as treatments improved foliar development. T0 had 114.17 and 115.15 (pooled 114.66) at 120 DAS, while T12 had 144.8 and 141.39 (pooled 143.09) and T14 had 143.76 and 142.68 (pooled 143.22). Zinc oxide nanoparticles are nanoparticles of zinc oxide (ZnO) that have diameters less than 100 nanometers. They have a large surface area relative to their size and high catalytic activity. Nano micronutrients are essential plant nutrients, such as iron, zinc, and manganese, encapsulated or formulated into nanoparticles to improve their delivery and absorption by plants. This nanotechnology enhances nutrient use efficiency by enabling slower, controlled release into the soil or to the leaves, preventing over-fertilization and reducing costs for farmers while promoting agricultural sustainability and increased crop productivity and quality.

Number of branches/plant

The result showed that increases in number of branching increased, and lateral development was encouraged by combined treatments at 120 DAS, T0 had 15.18 and 15.59 (pooled 15.38), while T14 had 19.58 and 19.92 (pooled 19.75) and T13 had 19.23 and 19.05 (pooled 19.14). T0 reported 19.48 and 20.82 (pooled 20.15). Nano-PGPR refers to nano-encapsulated or nano-formulated Plant Growth-Promoting Rhizobacteria (PGPR), which uses nanotechnology to improve the effectiveness of beneficial soil bacteria in agriculture. This combination offers enhanced bioavailability, controlled release, improved stability, and better root colonization, leading to increased crop yields and stress tolerance while reducing the need for synthetic fertilizers and chemical inputs.

50% Flowering/plant and TSS (Brix%)

The study of Nano micronutrients and nano-PGPR Bio capsules affected the time required to reach 50% flowering, which differed among treatments (Rai *et al.*, 2021) [12]. With a pooled mean of 51.85 days, the control (T0) had the longest time, averaging 52.2 days in 2022 and 51.5 days in 2023, suggesting a later initiation of reproduction in the absence of supplementation. Flowering was accelerated by treatments that included Bio capsules and Nano micronutrients. Interestingly, T13 saw 38.92 days in 2022 and 41.67 days in 2023, with an average of 40.3 days, and T_{14} saw 39.51 days in 2022 and 41.22 days in 2023, with an average of 40.36 days. On average, T_{14} displayed 40.36 days, with 39.51 days in 2022 and 41.22 days in 2023. The average duration of T_{11} was 42.92 days (pooled), whereas the entire RDF treatment (T_1) was roughly 48 to 50 days, underscoring the effectiveness of biocapsule-enhanced treatments in encouraging earlier flowering (Sharma *et al.*, 2020; Choudhary *et al*., 2020; Rai *et al*., 2021; Kumar *et al*., 2021) [14, 6, 12, 10]. Total soluble solids (TSS) were highest in T14 at 7.35% (2022) and 7.06% (2023), averaging 7.21%, and T10 at 7.06% and 6.87% (pooled 6.96%), compared to T0's 6.08% and 6.12% (pooled 6.1%). To enhance their delivery and absorption by plants, critical plant nutrients like iron, zinc, and manganese are encapsulated or formed into nanoparticles, which are known as nano micronutrients. The term "nano-encapsulated" or "nano-formulated" Plant Growth-Promoting Rhizobacteria (PGPR) is used to describe a technique that use nanotechnology to increase the efficiency of helpful soil bacteria in agriculture.

Fruit per plant

According to the statistical data in Table 2, The application of ((NPK(RDF)100%Biocapsule 250PPM + ZnO + FeO) had the significantly highest Fruit counts per plant were highest in integrated treatments. T14 recorded 56.37 (2022) and 58.64 (2023), averaging 57.5, while T13 had 55.35 and 55.06 (pooled 55.2), compared to T0's 40.19 and 40.6 (pooled 40.39). To enhance their delivery and absorption by plants, critical plant nutrients like iron, zinc, and manganese are encapsulated or formed into nanoparticles, which are known as nano micronutrients. The delayed, controlled release of nutrients into the soil or leaves made possible by this nanotechnology improves nutrient use efficiency, prevents overfertilization, lowers farmer expenses, and promotes agricultural sustainability as well as higher crop output and quality.

Fruit yield/ hectare (t/ha)

Hectare yield was greatest in T14 at t/ha (2022) and 28.61 t/ha (2023), averaging 27.81 t/ha, and T13 at 27.94 t/ha and 26.46 t/ha (pooled 27.2 t/ha), while T0 was lowest at 20.39 t/ha and 19.93 t/ha (pooled 20.16 t/ha). The F-test was significant, with SEm± of 0.48 (years) and 0.34 (pooled), CD at 5% of 1.44 (years) and 1.03 (pooled), and CV% of 2.63 (years) and 1.88 (pooled) (Sharma *et al.*, 2020; Choudhary *et al.*, 2020; Rai *et al.*, 2021; Kumar *et al.*, 2021) [14, 6, 12, 11]. Essential plant nutrients including iron, zinc, and manganese are known as nano micronutrients. These nutrients are encapsulated or synthesized into nanoparticles to enhance plant absorption and delivery. By permitting a slower, regulated flow of nutrients into the soil or to the leaves, this nanotechnology improves the efficiency of nutrient utilization, limiting overfertilization and saving farmers money while fostering agricultural sustainability and raising crop output and quality.

Table 1: Effect of Nano micronutrients and Nano $PGPR_s$ through Bio capsules on growth and development of Chilli

S. No.	Treatments	Plant height (cm)	Plant height (cm)	No of Leaves/ plant	No of Leaves/plant	No of branches/plant	No of branches/ plant)	50% Flowering /plant	50% Flowering /plant
		2022-23 120 DAS	2023-24 120 DAS	2022-23 120 DAS	2023-24 120 DAS	2022-23 120 DAS	2023-24 120 DAS	2022-23 120 DAS	2023-24 120 DAS
0	Control (Without treatment)	73.87	70.37	114.17	115.15	15.18	15.59	52.2	51.5
1.	N P K (RDF) 100%	81.27	77.37	117.21	120.11	15.02	15.84	48.21	49.92
2.	Biocapsule 500ppm (Soil drenching)	79.83	76.03	122.21	125.6	15.31	15.33	48.45	47.1
3	Biocapsule 250ppm (Soil drenching)	78.27	74.57	122.38	122.4	15.71	15.72	47.87	47.78
4	NPK(RDF) 100% + ZnO	85.70	81.57	124.52	124.09	16.52	16.14	46.31	48.11
5	NPK(RDF) 100% + FeO	84.23	80.23	127.0	127.3	16.39	16.52	45.18	45.8
6	N P K (RDF) 100%+ ZnO+ FeO	90.80	86.53	128.34	128.67	17.05	16.66	44.43	46.0
7	N P K (RDF) 100%+ Biocapsule 500ppm	88.63	84.43	131.08	132.6	16.85	17.42	44.54	42.96
8	N P K (RDF) 100%+ Biocapsule 250ppm	86.73	82.63	134.23	134.97	17.16	17.51	44.55	43.81
9	NPK(RDF)100% + Biocapsule 500PPM + ZnO	94.17	88.67	136.09	132.55	17.74	18.2	43.85	43.76
10	NPK(RDF)100%Biocapsule 500PPM+ FeO	92.63	87.57	137.74	135.12	18.31	18.02	43.17	43.16
11	NPK(RDF)100%Biocapsule500PPM + ZnO + FeO	99.67	86.93	139.57	138.29	18.1	18.77	42.92	42.91
12	NPK(RDF)100% + Biocapsule 250PPM + ZnO	90.80	86.53	144.8	141.39	18.94	18.8	40.21	41.12
13	NPK(RDF)100%Biocapsule 250PPM+ FeO	89.30	85.07	139.97	147.05	19.23	19.05	38.92	41.67
14	NPK(RDF)100%Biocapsule 250PPM + ZnO + FeO	96.10	89.47	143.76	142.68	19.58	19.92	39.51	41.22
	S.Em(+)	3.15	2.75	3.43	3.43	0.41	0.41	0.9	0.9
	CD (P= 0.05)	6.04	8.25	10.29	10.29	1.23	1.23	2.7	2.7

Table 2: Effect of Nano micronutrients and Nano PGPRs through Bio capsules on fruit yield and TSS (Brix%) of Chill

S. No.	Treatments	TSS (Brix%)	TSS (Brix%)	Fruit per plant	Fruit per plant	Fruit/ Hectare (t/ha)	Fruit/ Hectare (t/ha)
		2022-23 120 DAS	2023-24 120 DAS	2022-23 120 DAS	2023-24 120 DAS	2022-23 120 DAS	2023-24 120 DAS
0	Control (Without treatment)	6.08	6.12	40.19	40.6	4.86	5.00
1.	N P K (RDF) 100%	6.05	6.15	42.11	42.31	5.34	5.50
2.	Biocapsule 500ppm (Soil drenching)	6.25	6.31	41.61	40.66	5.49	5.70
3	Biocapsule 250ppm (Soil drenching)	6.29	6.08	42.0	42.89	5.30	5.40
4	NPK(RDF) 100% + ZnO	6.41	6.37	43.77	45.0	5.83	6.00
5	NPK(RDF) 100% + FeO	6.55	6.43	44.23	45.79	5.73	5.90
6	N P K (RDF) 100%+ ZnO+ FeO	6.36	6.52	46.62	46.25	6.32	6.50
7	N P K (RDF) 100%+ Biocapsule 500ppm	6.6	6.77	49.37	48.02	6.12	6.30
8	N P K (RDF) 100%+ Biocapsule 250ppm	6.56	6.51	50.22	50.22	5.93	6.10
9	NPK(RDF)100% + Biocapsule 500PPM + ZnO	6.99	6.7	49.6	51.18	6.61	6.80
10	NPK(RDF)100%Biocapsule 500PPM+ FeO	7.06	6.87	51.67	48.43	6.46	6.70
11	NPK(RDF)100%Biocapsule500PPM + ZnO + FeO	6.87	6.77	52.6	52.16	6.59	7.30
12	NPK(RDF)100% + Biocapsule 250PPM + ZnO	6.8	6.9	51.32	53.77	6.32	6.50
13	NPK(RDF)100%Biocapsule 250PPM+ FeO	6.97	6.9	55.35	55.06	6.73	6.30
14	NPK(RDF)100%Biocapsule 250PPM + ZnO + FeO	7.35	7.06	56.37	58.64	7.47	7.00
	S.Em(±)	0.33	0.13	0.96	0.96	0.35	0.41
	CD (P= 0.05)	1.09	1.39	2.88	2.88	1.23	1.23

Conclusion

On the basis of two year experimentation, it concludes that with the application of application of ((NPK(RDF) 100% Biocapsule 250PPM + ZnO + FeO) performed better in growth and yield of Greengram has recorded highest test weight, grain yield, stover yield, net return and benefit cost ratio and as well as economically profitable.

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Competing Interests

Authors have declared that no competing interests exits.

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