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Research Article

Efficacy of nanomaterials for sustainable crop productivity of Capsicum (*Capsicum annuum* L.) var. Rani under naturally ventilated polyhouse

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Abstract
Nanomaterials, as a source of plant nutrients, play a significant role in cellular metabolism and nutrients uptake by plants, so they have the potential to improve the growth and productivity of Capsicum. A replicated field trial was carried out in 3 x 3 factors Randomized Block Design (RBD) with two factors *viz.*, micronutrients (Cu, B and Mn) and nanomaterials (nano-Fe, nano-Zn and nano-Mg) applied at the rate of 1000 ppm to explore efficacy of nanomaterials and micronutrient for enhancing productivity of Capsicum (*Capsicum annuum* L.) var. Rani. The layout of experimental area was designed to accommodate 9 treatments (3 x 3) and a control (without treating with micronutrients and nanomaterials). Inside the naturally ventilated polyhouse, the raised beds (height-30 cm, length-50 m, width-90 cm and bed spacing-60 cm) were prepared for the transplanting capsicum seedlings. Application of nano-Zn and/or nano-Fe @ 1000 ppm in combination with borax and/or $CuSO_4$ @ 1000 ppm was significant ($p<0.05$) for improving various plant growth and productivity parameters of Capsicum. The combined application of nano-Zn with borax or $CuSO_4$ and nano-Fe with borax or $CuSO_4$ (@ 1000 ppm each) was the effective approach for improvement in plant height, number of leaves, number of flowers, number of fruits, yield plant^{-1} and estimated yield hectare^{-1}. The experimental findings of the present study confirm the necessities of nanomaterials as a nutrient source for enhancing capsicum's productivity to achieve food and nutritional security and promote sustainable agriculture, inclusive and sustainable economic growth of the farming community.

Keywords: Boron, Capsicum, Copper, Nano-Fe, Nano-Zn, Sustainable crop productivity

INTRODUCTION

The *Capsicum* is a solanaceous vegetable crop which includes nearly 30 species, five of which have been domesticated for human consumption, namely *Capsicum annuum, Capsicum pubescens, Capsicum chinense, Capsicum baccatum* and *Capsicum frutescens*. Although it is currently cultivated worldwide, Capsicum originates originally from Central and South America. *C. annuum* is known as bell pepper or chilli pepper and is consumed fresh as a salad, cooked, or processed (Padmanabhan *et al*., 2016). Capsicum is also well suited for cultivation under protected conditions where it is grown under a temperature range of 25 -30˚C (day temperature) to 18-20˚C (night temperature) and 50 -70 % of RH (relative humidity) with increased yield (80 -100 tons/ hectare), extended crop duration (7 -10 months) and quality of fruit (Pramanik *et al*., 2020). Nutritional imbalance results in poor crop growth and yield and is a major challenge for the quality production of Capsicum. Further, the application of primary macronutrient has a limited effect on achieving higher productivity. Application of micronutrients and nanomaterials has greater potential for improvement in the growth and productivity of Capsicum.

Copper is a micronutrient which plants require in very minute quantities; however, it is very foremost to sustain normal growth and development in plants because of its vital role in plant metabolism, including photosynthesis and oxidative phosphorylation, which remarkably increase the yield of crops especially vegetables (Kumar *et al*., 2021; Mir *et al*., 2021). Copper plays a critical role in photosynthesis, particularly as a component or activator of several enzymes involved in the electron transport system (ETS) (Mir *et al*., 2021). Boron is also an essential micronutrient for plants and contributes towards a number of functions, including absorption and translocation of minerals (nitrogen and phosphorus) and water by plants (Abou Seeda *et al.*, 2021; Shireen *et al.*, 2018); translocation of photosynthates (sugar and starch) (Abou Seeda *et al.*, 2021; Kumar *et al.*, 2019); synthesis of amino acids and proteins (Kumar *et al.*, 2019); nitrogen and carbohydrate assimilation; and cell division (Shireen *et al.*, 2018).

Application of nanomaterials as nano-fertilizers or nano-encapsulated nutrients releases the nutrient as per the demand that synchronizes the growth of a plant and increases target activity. In many studies, a fact came across that zinc oxide nanoparticles (ZnO NPs) enhanced seed germination, seedling vigour, plant growth and development (García-López *et al*., 2019). According to investigations by various authors, the NPs have antifungal efficacy against several plant pathogenic fungi. Magnesium oxide nano particles (MgO NPs) are an anti-bacterial agent with the advantage of being non-toxic and relatively easy to obtain. MgO NPs enhanced light uptake and promote the plant's photosynthetic activities to boost plant growth (Adhikari, 2019). In addition to nano size, the iron nanoparticles (Fe NPs) bear the additional attribute of being magnetic which induces an accelerated nutrient absorption response and photosynthetic properties (Batool *et al.*, 2021; Yuan *et al*., 2018).

Based on the previous studies, it can be inferred that the nanomaterials have greater potential to be used as a nutrient source to improve plant growth, flowering, fruiting, and yield (Fatima *et al*., 2021). Thus, the experiment was conducted in naturally ventilated polyhouse to find the efficacy of micronutrients (Cu, B, Mn) in combination with nanomaterials (Zn, Fe, Mg) on the productivity of Capsicum grown in a polyhouse.

MATERIALS AND METHODS

Preliminary information

The field trial was carried out at the Naturally Ventilated Polyhouse (NVP) of the Agriculture Department, ITM University, Gwalior, during the year 2021-22 under soil conditions of Northern Madhya Pradesh. The experimental area is located in the Gwalior district of the Gird region of northern Madhya Pradesh in India. The region is characterized by a semi-arid and subtropical climate with extreme weather attributed to hot and dry summer (up to 47˚C); cold winter (up to 2.8˚C); annual rainfall of 700 to 800 mm (confined during July to mid-September); and occasional light rain and frost during winter. The naturally ventilated polyhouse (NVP) used for experiment work has a structure made up of galvanized iron pipes, 40 mesh insect-proof nylon net and 200-micron thick-transparent polythene film. This polyhouse was basically ventilated by natural environment and a climate-controlled polyhouse. For irrigation purpose, low pressure drip irrigation system was used. A replicated field trial with treatment randomization was carried out in 3 x 3 factor Randomized Block Design (RBD) with two factors *viz.*, micronutrients (Cu, B and Mn) at the rate of 1000 ppm and nanomaterials (nano-Fe, nano-Zn and nano-Mg) which were applied in capsicum (*Capsicum annuum* L.) var. Rani. The layout of the experimental area was designed to accommodate 9 treatments, two factors, each with three levels (3 x 3) and a control (without treating with micronutrients and nanomaterials), with three replications and each replication had 15 plants. From each replication (15 plants), five plants were randomly selected and were used for taking observations. Inside the polyhouse the raised bed (30 cm) was prepared for the transplanting of capsicum seedlings. The dimensions of the bed were bed length (50 m), the width of the bed (90 cm) and pathways between beds (60 cm). The seedlings were raised in portrays of 135 cavities filled with the growing media containing 20 % soil, 30 % vermicompost and 50% cocopeat and transplanting was done after 30 days of seeds sowing. Before transplanting the seedling, beds were irrigated lightly to maintain moisture in the soil. During the bed preparation, neem cake was applied @ 1kg/ sq m, which prevented the Capsicum from nematodes.

Application of nanomaterials and micronutrients

The nanomaterials used in treatments were purchased from Geolife Agritech India Pvt. Ltd., Mumbai, Maharashtra. Geolife Nano-Zn and Nano-Fe are water-soluble white powder formulations, chelated with EDTA & Amnios, and are available in 12 % composition, while Nano-Mg is a water-soluble white powder formulation, chelated with EDTA (Ethylenediaminetetraacetic acid) and is available in 9.5 % composition. Boron was applied as AR/ACS (American Chemical Society Committee on Analytical Reagents) grade (99.5 % purity) hydrated sodium salt of borax [Di-sodium tetrahydroxy tetraborate octahydrate; $Na_2B_4O_5(OH)_4.8H_2O$ or sodium tetraborate decahydrate; $Na_2B_4O_7.10H_2O$], called as borax, containing 11.34 % of boron; copper was applied as AR/ACS grade $CuSO_4$ salt [Copper (II) Sulphate pentahydrate; $CuSO_4.5H_2O$] (99.0 % purity), containing 25.45 % of Cu; manganese was applied as AR/ACS grade $MnSO_4$ salt [Manganese (II) Sulphate monohydrate; $MnSO_4.H_2O$] (98.0 % purity), containing 32 % of Mn. These materials were used at 1000 ppm concentration. In order to make 1000 ppm solution of said materials, 1 g of salt was dissolved in 1 litre of water. The amount of water per plot was determined by using the standard value of 500 litres required for 1 hectare of the cropped area. The treatments were applied through foliar spray at 30 days, 45 days and 60 days after transplanting.

Growth parameters

The plant growth parameters like average plant height (cm), and average number of leaves, flowers and fruits per plant were measured or counted on each randomly selected plant of a plot at 45, 60 and 75 days after transplanting. The average value was estimated by adding each plant's plant height or leaf count in a plot and by dividing it by the number of plants.

Yield parameters

The fruits were harvested through manual picking at 5 days until the plants reached complete senescence. The frequency of harvesting where at least one fruit was harvested from a plant was taken as the number of pickings. Total weight of harvested fruits from all plants of a plot was taken to obtain the average yield of fruits in gram per plant. Further, the yield per hectare was estimated using the number of plants per hectare of polyhouse area and yield per plant and expressed in quintals per hectare.

Statistical analysis

All the data related to different parameters taken or estimated by various means were subjected to statistical analysis by using OPSTAT software (http://14.139.232.166/opstat/). The raw data taken through fieldwork were tabulated and average values were represented as replication. The replicated data were statistically analysed for two-way analysis of variances (ANOVA) to understand the efficacy of various factors and their interaction, to validate the null hypothesis, and to estimate the contribution of various independent variables towards the dependent variable. The combination of micronutrients and nanomaterials was further compared with the control to understand the efficacy of these treatments over standard practice as control.

RESULTS AND DISCUSSION

Plant growth parameters

The nanomaterials and micronutrient application significantly influenced the average plant height of Capsicum measured at 45 days, 60 days, and 75 days after transplanting, where the highest plant height was recorded after application of nano-Zn @ 1000 ppm (28.25, 33.50 and 36.31 cm, respectively) followed by nano-Fe @ 1000 ppm (25.67, 31.19 and 34.00 cm, respectively) (Table 1). The impact of $CuSO_4$ application @ 1000 ppm on plant height (28.22, 33.75 and 36.44 cm, respectively) was at par with borax @ 1000 ppm (27.94, 33.31 and 35.97 cm, respectively). The interaction effect of nanomaterials and micronutrients on average plant height was significant at 60 and 75 days after transplanting and the highest average plant height was measured after combined application of N_1M_2 (nano-Zn and borax @ 1000 ppm each) (36.50 and 39.25 cm, respectively), which was at par with N_1M_1 (nano-Zn and $CuSO_4$ @ 1000 ppm each) application (35.58 and 38.42 cm, respectively). However, the lowest plant height was recorded in control (23.55 and 25.43 cm, respectively) at 60 and 75 days after transplanting, where micronutrients and nanomaterials were not applied. Thus, the present study confirms a significant improvement in the plant height of Capsicum due to the application of nanomaterials or/and micronutrients over control. The positive influence of nano-Zn might be associated with the synthesis of plant growth promoters, auxin, which stimulated better growth in capsicum plants (Al Jabri *et al*., 2022). Further, Zn can enhance the photosynthetic activities of plants due to its contribution to the synthesis of tryptophan and IAA, which could be attributed to better plant growth when applied as nano-Zn (Amiri *et al*., 2016). It is also associated with improvement in antioxidant enzymatic activities in almond seedlings enabling the plants to grow well against stress (Amiri *et al*., 2016). In the present study, nano-Fe has significantly followed the nano-Zn to regulate the plant height of Capsicum, which could be due to the contribution of iron towards amino acids metabolism, synthesis of enzymes essential for cellular divisions, and activation of enzymes against cellular oxidation in citrus (El-Gioushy *et al*., 2021). Application of copper as well as boron had also significantly influenced plant growth when applied alone or in combination with nanomaterials which could be due to the catalytic role of copper in photosynthesis and respiration and the positive balance of these two metabolic processes (Pietrini *et al*., 2019). Similarly, boron is also involved in cell wall synthesis and structural integration, improving growth and yield (Shireen *et al*., 2018; Salim *et al*., 2019).

The nanomaterials, micronutrients and their interaction has significantly influenced the average number of leaves of Capsicum counted at 45 days, 60 days, and 75 days after transplanting, where the maximum leaf count was recorded after application of nano-Zn @ 1000 ppm (19.64, 30.47 and 35.56, respectively) followed by nano-Fe @ 1000 ppm (17.75, 27.03 and 32.22, respectively); however, the effect of borax @ 1000 ppm (18.92, 29.08 and 34.39, respectively) was at par with $CuSO_4$ @ 1000 ppm (18.83, 28.64 and

Table 1. Plants height of Capsicum after nanomaterials and micronutrients application

Factors/ Treatments	Average plants height (cm) of Capsicum		
	At 45 days after transplanting	At 60 days after transplanting	At 75 days after transplanting
N_1	28.25[a]	33.50[a]	36.31[a]
N_2	25.67[b]	31.19[b]	34.00[b]
N_3	24.00[c]	29.06[c]	31.72[c]
CD	1.070	0.69	0.753
SE(d)	0.501	0.323	0.352
SE(m)±	0.354	0.228	0.249
P value	< 0.01**	< 0.01**	< 0.01**
M_1	28.22[a]	33.75[a]	36.44[a]
M_2	27.94[a]	33.31[a]	35.97[a]
M_3	21.75[b]	26.70[b]	29.61[b]
CD	1.070	0.69	0.753
SE(d)	0.501	0.323	0.352
SE(m)±	0.354	0.228	0.249
P value	< 0.01**	< 0.01**	< 0.01**
N_1M_1	30.25[a]	35.58[a]	38.42[a]
N_1M_2	31.00[a]	36.50[a]	39.25[a]
N_1M_3	23.50[a]	28.42[d]	31.25[c]
N_2M_1	27.25[a]	33.17[b]	35.83[b]
N_2M_2	28.00[a]	33.58[b]	36.17[b]
N_2M_3	21.75[a]	26.83[e]	30.00[d]
N_3M_1	27.17[a]	32.50[b]	35.08[b]
N_3M_2	24.83[a]	29.83[c]	32.50[c]
N_3M_3	20.00[a]	24.84[f]	27.58[e]
Control	19.86[a]	23.55[g]	25.43[f]
CD	NS	1.195	1.304
SE(d)	0.867	0.559	0.610
SE(m)±	0.613	0.395	0.431
P value	0.08143	0.00178**	0.00408**

N: Nanomaterial, N_1: nano-Zn, N_2: nano-Fe, N_3: Nano-Mg; M: Micronutrients, M_1: $CuSO_4$, M_2: Borax, M_3: $MnSO_4$ each at 1000 ppm; Control (treatments without supplementing with micronutrients and nanomaterials), NS: Non-significant effect; * and ** indicate significance at the 0.05 and 0.01 probability levels, respectively.

34.11, respectively) (Table 2). The influence of nano-Zn in the expansion of leaves might be associated with the auxin-mediated response of zinc metals through tryptophan formation (Wang *et al.*, 2021). Application of iron has significantly improved the number of leaves that might be associated with its ability to increase photosynthetic pigments and indole acetic acid (IAA) in the plants, which could be the result of increased peroxidase, polyphenol oxidase and nitrate reductase activities in the plants (Tawfik *et al.*, 2021). Further, iron is associated with regulating CO_2 uptake in plants and enhanced photosynthesis resulting in the accumulation of carbohydrates and better plant growth (Yoon *et al.*, 2019). Boron is an important nutrient for cell wall formation and inducing cell differentiation leading to shoot growth and development of leaf primordia which could be associated with the enhancement of nutrient uptake, photosynthesis, and higher metabolic activity (Poudel *et al.*, 2022). The combined application nano-Zn and B in N_1M_2 (nano-Zn and borax @ 1000 ppm each) increased the leaf number per plant (21.75, 33.17 and 38.17, respectively) at 45, 60 and 75 days after transplanting and was at par with N_1M_1 (nano-Zn and $CuSO_4$ @ 1000 ppm each) (21.08, 31.33 and 36.67, respectively) which could be due to synergistic impact of boron in combination with nano-Zn. However, the lowest leaf count per plant was recorded in control (12.75, 20.05 and 24.25, respectively) at 45, 60 and 75 days after transplanting,

Table 2. Average number of leaves of Capsicum after nanomaterials and micronutrients application

Factors/ Treatments	Average number of leaves per plant		
	At 45 days after transplanting	**At 60 days after transplanting**	**At 75 days after transplanting**
N_1	19.64[a]	30.47[a]	35.56[a]
N_2	17.75[b]	27.03[b]	32.22[b]
N_3	14.53[c]	23.19[c]	28.83[c]
CD	0.993	0.597	0.716
SE(d)	0.465	0.279	0.335
SE(m)±	0.329	0.197	0.237
P value	< 0.01**	< 0.01**	< 0.01**
M_1	18.83[a]	28.64[a]	34.11[a]
M_2	18.92[a]	29.08[a]	34.39[a]
M_3	14.17[b]	22.97[b]	28.11[b]
CD	0.993	0.597	0.716
SE(d)	0.465	0.279	0.335
SE(m)±	0.329	0.197	0.237
P value	< 0.01**	< 0.01**	< 0.01**
N_1M_1	21.08[a]	31.33[b]	36.67[b]
N_1M_2	21.75[a]	33.17[a]	38.17[a]
N_1M_3	16.08[c]	26.92[e]	31.83[d]
N_2M_1	19.17[b]	29.00[d]	34.17[c]
N_2M_2	20.25[ab]	30.25[c]	35.50[b]
N_2M_3	13.83[d]	21.83[h]	27.00[f]
N_3M_1	16.25[c]	25.58[f]	31.50[d]
N_3M_2	14.75[cd]	23.83[g]	29.50[e]
N_3M_3	12.58[d]	20.17[i]	25.50[g]
Control	12.75[d]	20.05[i]	24.25[h]
CD	1.721	1.034	1.240
SE(d)	0.805	0.484	0.580
SE(m)±	0.569	0.342	0.410
P value	0.01885*	0.00002**	0.00026**

N: Nanomaterial, N_1: nano-Zn, N_2: nano-Fe, N_3: Nano-Mg; M: Micronutrients, M_1: $CuSO_4$, M_2: Borax, M_3: $MnSO_4$ each at 1000 ppm; Control (treatments without supplementing with micronutrients and nanomaterials), NS: Non-significant effect; * and ** indicate significance at the 0.05 and 0.01 probability levels, respectively.

where micronutrients and nanomaterials were not applied. Thus, the present study confirms a significant improvement in the leaf count of Capsicum due to the application of nanomaterials or/and micronutrients over control. Further, copper (Cu) regulates protein synthesis, cellular metabolism like electron transport, redox processes and cell wall alteration as it is co-factor of many enzymes (Migocka *et al*., 2018). Various authors reported similar findings for nano-micronutrients in Capsicum (Ahmed and Abdelkader, 2020), nano-Zn in Capsicum (Sánchez-Pérez *et al*., 2023), nano-Fe or nano-Zn in Capsicum (El-Gioushy *et al*., 2021) and Fe application in Capsicum (Yuan *et al*., 2018).

Flowering and fruiting parameters

The nanomaterials and micronutrients application significantly influenced the flowers and fruits formation in Capsicum taken at 45 days, 60 days, and 75 days after transplanting and among all the nanomaterials, the maximum flower (Table 3) count was recorded after application of nano-Zn @ 1000 ppm (5.97, 4.58 and 1.50, respectively) followed nano-Fe @ 1000 ppm (5.64, 4.11 and 1.03, respectively); however, among micronutrients, application of borax @ 1000 ppm (6.08, 4.47 and 1.47, respectively) and $CuSO_4$ @ 1000 ppm (5.94, 4.42 and 1.44, respectively) reflected at par response for flowers count per plant. Similarly, the maximum fruit (Table 4) count was recorded after applica-

Table 3. Average number of flowers per plant after nanomaterials and micronutrients application

Factors/ Treatments	Average number of flowers per plant		
	At 45 days after transplanting	**At 60 days after transplanting**	**At 75 days after transplanting**
N_1	5.97[a]	4.58[a]	1.50[a]
N_2	5.64[b]	4.11[b]	1.03[b]
N_3	4.97[c]	3.69[c]	1.28[ab]
CD	0.185	0.159	0.343
SE(d)	0.087	0.074	0.161
SE(m)±	0.061	0.053	0.114
P value	< 0.01**	< 0.01**	0.03142*
M_1	5.94[a]	4.42[a]	1.44[a]
M_2	6.08[a]	4.47[a]	1.47[a]
M_3	4.56[b]	3.50[b]	0.89[b]
CD	0.185	0.159	0.343
SE(d)	0.087	0.074	0.161
SE(m)±	0.061	0.053	0.114
P value	< 0.01**	< 0.01**	0.00321**
N_1M_1	6.50[b]	4.75[b]	1.58[a]
N_1M_2	6.83[a]	5.08[a]	1.75[a]
N_1M_3	4.58[f]	3.92[d]	1.17[a]
N_2M_1	5.83[c]	4.33[c]	1.17[a]
N_2M_2	6.25[b]	4.58[bc]	1.25[a]
N_2M_3	4.83[f]	3.42[e]	0.67[a]
N_3M_1	5.50[d]	4.17[cd]	1.58[a]
N_3M_2	5.17[e]	3.75[d]	1.42[a]
N_3M_3	4.25[g]	3.17[ef]	0.83[a]
Control	4.14[g]	3.11[f]	0.72[a]
CD	0.321	0.275	NS
SE(d)	0.15	0.129	0.278
SE(m)±	0.106	0.091	0.197
P value	0.00008**	0.00437**	0.89966

N: Nanomaterial, N_1: nano-Zn, N_2: nano-Fe, N_3: Nano-Mg; M: Micronutrients, M_1: $CuSO_4$, M_2: Borax, M_3: $MnSO_4$ each at 1000 ppm; Control (treatments without supplementing with micronutrients and nanomaterials), NS: Non-significant effect; * and ** indicate significance at the 0.05 and 0.01 probability levels, respectively

tion of nano-Zn @ 1000 ppm (3.28, 2.44 and 5.67, respectively) followed nano-Fe @ 1000 ppm (3.00, 2.31 and 5.17, respectively); however, among micronutrients, application of borax @ 1000 ppm (3.25, 2.50 and 5.67, respectively) and $CuSO_4$ @ 1000 ppm (3.17, 2.42 and 5.58, respectively) reflected at par response for fruit count per plant at 45, 60 and 75 days after transplanting.

Application of nano-Zn positively influenced the various flowering and fruiting attributes which could be due to increased levels of growth promoters like IAA (Mondal *et al*., 2023), improvement in nutritional status within the plants and its translocation to apical meristems of shoots to induce early flowering (Ali *et al*., 2021). Further, zinc could also be involved in the accumulation of amino acids and reducing sugar in plants which are needed for the increase in flowering branches and photosynthates translocation to the flowers and developing fruits to reduce the abscission of flowers and fruits (Ghani *et al*., 2022). Boron (B) is essential for carbohydrate metabolism, synthesis of nucleic acids, IAA metabolism, synthesis of proteins and hormonal regulation for cellular differentiation, which promotes flowering (Abou Seeda *et al*., 2021; Du *et al*., 2020). Further, it regulates the nitrogen and phosphorus metabolism and is accountable for enhancing the receptivity of stigma, pollen germination and pollen tube growth which is essential for effective fertilization and fruit set (Shireen *et al*., 2018; Khan *et al*., 2022a; Haleema *et al*., 2018). Thus, the application of boron might be responsible for

Table 4. Average number of fruits per plant after nanomaterials and micronutrients application

Factors/ Treatments	Average number of fruits per plant		
	At 45 days after transplanting	**At 60 days after transplanting**	**At 75 days after transplanting**
N_1	3.28[a]	2.44[a]	5.67[a]
N_2	3.00[b]	2.31[b]	5.17[b]
N_3	2.75[c]	2.00[c]	4.69[c]
CD	0.135	0.084	0.159
SE(d)	0.063	0.039	0.074
SE(m)±	0.045	0.028	0.053
P value	< 0.01**	< 0.01**	< 0.01**
M_1	3.17[a]	2.42[a]	5.58[a]
M_2	3.25[a]	2.50[a]	5.67[a]
M_3	2.61[b]	1.83[b]	4.28[b]
CD	0.135	0.084	0.159
SE(d)	0.063	0.039	0.074
SE(m)±	0.045	0.028	0.053
P value	< 0.01**	< 0.01**	< 0.01**
N_1M_1	3.50[a]	2.67[b]	6.33[a]
N_1M_2	3.67[a]	2.83[a]	6.00[b]
N_1M_3	2.67[d]	1.83[e]	4.67[d]
N_2M_1	3.08[bc]	2.33[c]	5.50[c]
N_2M_2	3.25[b]	2.58[b]	5.75[bc]
N_2M_3	2.67[d]	2.00[d]	4.25[e]
N_3M_1	2.92[c]	2.25[c]	4.92[d]
N_3M_2	2.83[cd]	2.08[d]	5.25[c]
N_3M_3	2.50[d]	1.67[f]	3.92[f]
Control	2.23[e]	1.61[f]	3.61[g]
CD	0.234	0.145	0.275
SE(d)	0.109	0.068	0.129
SE(m)±	0.077	0.048	0.091
P value	0.00623**	0.00003**	0.0075**

N: Nanomaterial, N_1: nano-Zn, N_2: nano-Fe, N_3: Nano-Mg; M: Micronutrients, M_1: $CuSO_4$, M_2: Borax, M_3: $MnSO_4$ each at 1000 ppm; Control (treatments without supplementing with micronutrients and nanomaterials), NS: Non-significant effect; * and ** indicate significance at the 0.05 and 0.01 probability levels, respectively

higher flowering, fruiting and yield in Capsicum. The interaction effect of nanomaterials and micronutrients was also significant for flower count per plant at 45 days and 60 days after transplanting and the highest flower count was recorded after combined application of N_1M_2 (nano-Zn and borax @ 1000 ppm each) (6.83 and 5.08, respectively) followed by N_1M_1 (nano-Zn and $CuSO_4$ @ 1000 ppm each) (6.50 and 4.75, respectively) and N_2M_2 (nano-Fe and borax @ 1000 ppm each) (6.25 and 4.58, respectively) while the lowest was reported in control (4.14 and 3.11, respectively) where nanomaterials and micronutrients were not applied; however, this variation was non-significant at 75 days after transplanting. About fruit count per plant, the interaction effect was significant at 45, 60 and 75 days after transplanting and the highest count was recorded in after combined application of N_1M_2 (nano-Zn and borax @ 1000 ppm each) (3.67, 2.83 and 6.00, respectively) followed by N_1M_1 (nano-Zn and $CuSO_4$ @ 1000 ppm each) (3.50, 2.67 and 6.33, respectively) and N_2M_2 (nano-Fe and borax @ 1000 ppm each) (3.25, 2.58 and 5.75, respectively) while the lowest was reported in control (2.23, 1.61 and 3.61, respectively) where nanomaterials and micronutrients were not applied. The combination of Zn and B promotes the carbohydrate translocation from apical meristems to ensure uniform floral bud differentiation, flower initiation and fruit development (Haleema *et al*., 2018; Khan *et al*., 2022b). Various authors have reported similar findings after applying nano-Fe or nano-Zn (El-Gioushy *et al*., 2021) and

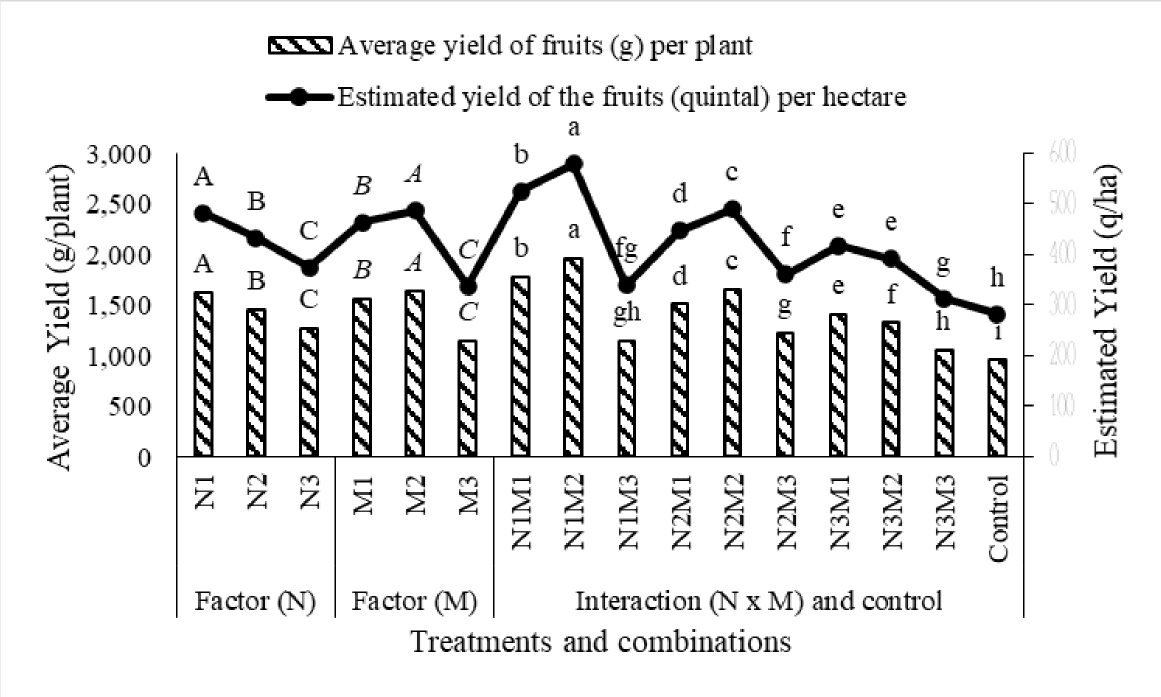

Fig. 1. *Average yield of fruits (g per plant, quintal per hectare) in Capsicum after nanomaterials and micronutrients application [N: Nanomaterial, N_1: nano-Zn, N_2: nano-Fe, N_3: Nano-Mg; M: Micronutrients, M_1: $CuSO_4$, M_2: Borax, M_3: $MnSO_4$ each at 1000 ppm; Control (treatments without supplementing with micronutrients and nanomaterials); p value < 0.01**]*

for the combined application of B and Zn in Capsicum (Khan *et al*., 2022b).

Yield and related attributes

The average yield of Capsicum was significantly influenced by application of nanomaterials with the highest (1626 g per plant and 481.33 q per hectare) after application of nano-Zn followed by nano-Fe (1460 g per plant and 432.11 q per hectare); this was attributed with highest number of pickings in these treatments (Fig. 1). The yield was also significantly influenced by application of micronutrients with the highest yield (1644 g per plant and 486.78 q per hectare) after application of borax @ 1000 ppm followed by $CuSO_4$ @ 1000 ppm (1564 g per plant and 463.00 q per hectare). Further, the significantly highest yield (1957 g per plant and 579.33 q per hectare) was estimated after application of N_1M_2 (nano-Zn and borax @ 1000 ppm each) followed by N_1M_1 (nano-Zn and $CuSO_4$ @ 1000 ppm each) (1774 g per plant and 525.33 q per hectare) while the lowest was recorded in control (1057 g per plant and 313 q per hectare) where no any micronutrients and/or nanomaterials were applied. The nanomaterials play an important role in the synthesis and activation of several enzymes involved in biological processes in plants and regulate the hormonal balance in plants, which is essential for accumulating photosynthates in fruits, resulting in greater fruit size and weight (Kumar *et al*., 2021). Zinc is accountable for the metabolism of nucleic acids and proteins, carbohydrates translocation and increased synthesis of auxins which is involved in the enlargement of fruit size and fruit weight (Haleema *et al*., 2018). The plants treated by nano-Zn demonstrated a better quantity of fruits and higher yield, which could be associated with increased photosynthetic rate, accelerated activities of antioxidant enzymes and improved accumulation of proline and proteins (Faizan *et al*., 2020). The improvement in yield and related attributes in Capsicum due to combined application of copper with Zn or Fe might be associated with the better absorptions, translocation, and assimilation of these bivalent ions in the presence of copper at balanced concentration (1000 ppm) (Yuan *et al.,* 2018; Pietrini *et al*., 2019; Yoon *et al*., 2019; Migocka and Malas, 2018). The results also confirm the beneficial effect boron on yield and related attributes of Capsicum, which might be associated with the essentiality of micronutrients in the translocation and metabolism of macronutrients and carbohydrates (Agarwal, 2018).

Conclusion

Based on the present investigation consisting of the application of micronutrients (Cu, B, Mn) and nanomaterials (Zn, Fe, Mg) to evaluate the effect of these treatments and their interactions over various growth, flowering, fruiting and yield-related parameters, it can be interpreted that the application of nano-Zn and/or nano-Fe @ 1000 ppm is significant for improving various plant growth and productivity of Capsicum (cv. Rani) under naturally ventilated polyhouse. Further, the application of borax and/or $CuSO_4$ @ 1000 ppm is significant for improving various plant growth and productivity of Capsicum under naturally ventilated polyhouse. The combined application of nano-Zn and borax @ 1000 ppm each (1957 g per plant and 579.33 q per hectare) or nano-Zn and $CuSO_4$ @ 1000 ppm each (1774 g per plant and 525.33 q per hectare) has resulted in greater yield and is the effective approach for improvement in plant growth and productivity in Capsicum grown under naturally ventilated polyhouse.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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