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# Efficacy of mineral nutrients and nanomaterials on the productivity of capsicum (*Capsicum annuum* L. cv. Rani) under polyhouse

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**ABSTRACT**

The application of minerals as nanomaterials has greater scope to bring improvement in the growth and yield of capsicum. The nanomaterials play a significant role in cellular metabolism and uptake of nutrients so have the potential to improve the productivity of capsicum. The experiment was conducted in a naturally ventilated polyhouse at a horticulture farm of the ITM University, Gwalior, Madhya Pradesh, during 2021–2022 with the view to find the efficacy of mineral nutrients, namely calcium (Ca), Sulfur (S), and molybdenum (Mo) in combination with nanomaterials, namely nano-Zinc (nano-Zn), nano-Iron (nano-Fe), and nano-magnesium (nano-Mg) on the productivity of capsicum (cv. Rani). The combined application of calcium and nano-Zn or nano-Mg as $N_1M_1$ (nano-Zn and $CaCl_2$ at 1000 ppm each) and $N_3M_1$ (nano-Mg and $CaCl_2$ at 1000 ppm each) is the effective approach for improvement in productivity of capsicum. The combined application of these nanomaterials in the presence of calcium is mainly attributed to effective nutrient uptake and utilization due to the positive Ca-Zn or Ca-Mg interaction.

## 1. INTRODUCTION

The genus *Capsicum*, consisting of various types of peppers, is a solanaceous vegetable crop and is native to tropical America. Naturally, it is a cool-season and perennial crop and is successfully grown under conditions having 25–30°C of day temperature, 18–20°C of night temperature, and 50–60% of RH for quality fruit production. The capsicum can yield an average of 20–40 tonnes of fruits per hectare during a life span of 4–5 months; however, under protected conditions or a naturally ventilated polyhouse (NVP), the crop can grow for 7–10 months with a potential yield of 80–100 tonnes of green or colored fruits in 1 ha.

Capsicum is a heavy feeder of nutrients which are essential for high productivity. Calcium is required for the integrity of tissues and cell walls, so it is essential during the rapid growth of fruits (log phase) in pepper plants. If the availability of calcium is not enough to meet the requirement of growing fruits of solanaceous crops, the fruits start to show rotting at the distal end due to the collapse of cell walls or tissues [1]. Sulfur has a significant role in the synthesis of proteins and enzymatic activation, so it is a necessary element for the defense of plants against biotic and abiotic stresses [2]. The application of nanomaterials as nano-fertilizers or nano-coated nutrients provides the nutrient as per the demand of the crop that synchronizes the growth of a plant and increases target activity. In many studies, a fact came that zinc oxide nanoparticles (ZnO-NPs) improved seed germination, seedling vigor, plant growth, flowering, and fruiting [3]. According to investigations carried out, the NPs (Zn, Cu, Ag, Fe, Mg, and $TiO_2$) have also shown antifungal efficacy against several pathogens including many species of *Penicillium*, *Botrytis*, *Aspergillus*, and *Fusarium* [4-7]. Magnesium oxide nanoparticles (MgO-NPs) are an anti-bacterial agent with the advantage of being non-toxic and relatively easy to obtain [8]. MgO-NPs enhanced light uptake and promoted the plant's photosynthetic activities to boost plant growth in *Ananas comosus* var. *bracteatus* at the concentration of 1 g/mL while higher concentration has a negative impact [9]. Iron nanoparticles (Fe-NPs) bear magnetic properties, so it is effective to boost the rate of nutrient absorption, translocation, and utilization to improve the photosynthetic process [10]. According to research reports, the Fe-NPs have a two-fold impact on plants as it has been reported to have a highly positive impact on growth and development when applied in low concentrations while it seems to have a detrimental effect when applied in higher concentration [11].

It can be inferred from studies of available literature that nanomaterials have greater potential to improve plant growth, flowering, fruiting,

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and yield in capsicum; however, there is a need to understand the effectiveness of interaction between nanomaterials and mineral nutrients. Thus, the experiment was conducted to evaluate the efficacy of mineral nutrients (Ca, S, and Mo) in combination with nanomaterials (Zn, Fe, and Mg) on the productivity of capsicum grown under NVP.

## 2. MATERIALS AND METHODS

### 2.1. Experimental Area and Materials

The study was conducted during 2021–2022 under NVP at the agriculture farm of ITM University, Gwalior. The experimental area was located latitudinally around 26˚13' N and longitudinally around 76°14' E at an altitude of 211.52 m from the mean sea level in the Gwalior district of the gird region of northern Madhya Pradesh. The polyhouse, which was used for experimentation, is comprised of galvanized iron pipes, a 40-mesh insect-proof nylon net, and a 200-micron-thick translucent polythene sheet. Since the polyhouse was naturally ventilated, an insect-proof nylon net was employed to allow for natural air movement and insect-free ventilation. The cultivar Rani was selected for study as it is a high-yielding hybrid variety of capsicum that alone has a cultivated area of 3000 ha in India.

### 2.2. Experimental Design and Details

*2.2.1. Treatments details and application*

The experiment was set as factorial randomized block design (RBD) with two factors: Mineral nutrients (Ca, S, and Mo) and nanomaterials (nano-Fe, nano-Zn, and nano-Mg) applied at the rate of 1000 ppm as a foliar application. Each mineral nutrient and nanomaterial were replicated thrice and randomized separately.

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 and amnios, and are available in 12% composition while nano-Mg is a water-soluble white powder formulation, chelated with EDTA and amnios, and is available in 9.5% composition. These materials were used at 1000 ppm concentration. Calcium was applied as laboratory-grade anhydrous salt of $CaCl_2$, containing 36% of calcium; sulfur was applied as wettable sulfur (80%); and molybdenum was applied as ammonium molybdate tetrahydrate $[(NH_4)_6Mo_7O_{24}.4H_2O]$, containing 53% of Mo. These materials were also used at 1000 ppm concentration.

*2.2.2. Climatic and soil conditions in the polyhouse*

The temperature inside the polyhouse was optimized up to 25°C with a relative humidity of around 65% by running the foggers for 5 min as and when the leaves become dry (at an interval of 2–5 h) during day time. The soil condition was suitable for the cultivation of capsicum with pH of 7.6 and electrical conductivity of 0.32 ds/m; however, the organic carbon (45%) and available nitrogen (197 Kg/ha) were low with moderately available phosphorus (19 Kg/ha) and potassium (241 Kg/ha).

*2.2.3. Agronomical operations*

Capsicum plants were grown in raised beds of dimensions including the bed's height (30 cm), breadth (90 cm), and distance between beds (60 cm) [Figure 1]. Before transplanting the seedlings, the beds are lightly irrigated to keep the soil moist. The neem cake was mixed at the rate of 1 kg/sq m during the bed preparation to protect the capsicum from worms. Regular training and pruning were carried out to maintain 3–4 stems in each plant. Irrigation was provided with a low-pressure drip irrigation system (discharge rate of 2 L/h) to keep optimum soil moisture level (more than 70 %) in the beds. Vermicompost was applied at the rate of 5 g/Kg of soil and was thoroughly mixed up to a depth of 30 cm in bed. The fertilizers were applied through fertigation of NPK (19:19:19) at the rate of 2 kg per acre on weekly basis. At the initial 60 days, two weedings were carried out; however, in the later phase, weeds were not grown due to the dense canopy of capsicum plants. Imidacloprid, a systemic insecticide was applied (2 mL/L of water) three times after flowering at an interval of 15 days to control aphids and thrips.

**Figure 1:** Raised bed with two lines of capsicum grown at a spacing of 45 cm × 45 cm.

### 2.3. Observations Recorded

*2.3.1. Plant growth parameters*

The plant height (cm) and number of leaves per plant were taken on each plant of a plot at 45, 60, and 75 days after transplanting. The average value was estimated after dividing the sum of plant heights or leaf counts by the number of plants taken under observation.

*2.3.2. Flowering and fruiting*

The number of flowers and fruits was counted on each plant of a replicated plot at 45, 60, and 75 days after transplanting and the average was estimated after dividing the counted value by the number of plants taken under observation.

*2.3.3. Yield and related parameters*

Harvesting of fruits was done through manual picking at the frequency of 5–6 days till the plants reached senescence. The frequency of harvesting where at least one fruit was harvested from the plant was taken as the number of pickings. The total fruit weight of harvested fruits from all plants of a plot was divided by the number of plants in each plot to obtain the average yield of fruits in grams per plant. Further, the yield (in quintals) per hectare was estimated using the number of plants per hectare of polyhouse area and yield per plant.

### 2.4. Statistical Analysis

All the data related to different parameters taken, or estimated by various means, were tabulated and average values were represented as replication. The replicated data were subjected to statistical analysis for two-way analysis of variance using OPSTAT software to understand the efficacy of various factors and their interaction, to validate the null hypothesis, and to estimate the contribution of various independent variables toward the dependent variable.

## 3. RESULTS AND DISCUSSION

### 3.1. Plant Growth Parameters

#### *3.1.1. Average plant height*

The application of nano-Zn at 1000 ppm has significantly improved the height of capsicum plants followed by nano-Mg at 1000 ppm [Table 1] which might be associated with the role of Zn in the synthesis of plant growth promoters such as auxins, its participation as a co-factor in the synthesis of various enzymes, and the formation of amino acids such as tryptophan accounting for the better growth of capsicum plant [12]. Further, the application of nano-Mg might have played a significant role in the synthesis of chlorophyll which could be responsible for enhanced photosynthesis and accumulation of photosynthates to improve biomass production [13]. In addition, the nano-Mg had also been reported for increased synthesis of secondary metabolites which could be accountable for systemic stimulation against plant pathogenic microbes ensuring better plant growth [14].

The application of S at 1000 ppm resulted in the highest plant height which was at par with the application of $CaCl_2$ at 1000 ppm [Table 1]. Further, the significant interaction of these mineral nutrients with nanomaterials at 60 and 75 days after transplanting could be associated with the tolerance of plants against toxicity of heavy metals attributed to the enhanced biosynthesis of glutathione and phytochelatins in roots [15]. Although calcium does not have a direct role in the synthesis of biomolecules, it is essential for the integrity of cell walls so has given a significant response when combined with nano-Zn [16]. The present findings can be validated by the recommendations of [17], [18], Fazelian and Yousefzadi [19], [20].

#### *3.1.2. Average number of leaves per plant*

In contrast, the application of nano-Mg at 1000 ppm followed by nano-Fe at 1000 ppm resulted in the highest number of leaves [Table 2] in capsicum plants while the response of nano-Zn in the number of leaves was reported to be the least which could be due to its utilization for axial growth (plant height). The application of nano-Mg might have significantly improved the synthesis of chlorophyll which could be associated with the proliferation of leaves primordia [21]. This could be further justified based on the necessity of Mg for the synthesis of major enzymes which present in the chloroplast including

**Table 1:** Plants height (cm) of capsicum after application of minerals and nanomaterials.

| Average plant height at 45 days after transplanting | | | | |
|---|---|---|---|---|
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | $30.72^b$ | $33.13^a$ | $28.61^b$ | $30.82^A$ |
| $N_2$ | $30.62^b$ | $29.90^b$ | $25.16^c$ | $28.56^B$ |
| $N_3$ | $28.19^c$ | $31.63^a$ | $28.90^b$ | $29.57^A$ |
| Mean M | $29.84^B$ | $31.56^A$ | $27.56^C$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | 1.355 | 0.634 | 0.448 | 0.0092** |
| Factor (M) | 1.355 | 0.634 | 0.448 | 0.00012** |
| Factor (N×M) | 2.348 | 1.098 | 0.776 | 0.01526* |
| **Average plant height at 60 days after transplanting** | | | | |
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | $40.02^a$ | $41.85^a$ | $37.63^b$ | $39.83^A$ |
| $N_2$ | $39.46^b$ | $38.63^b$ | $35.33^c$ | $37.81^B$ |
| $N_3$ | $37.20^b$ | $40.69^a$ | $38.27^b$ | $38.72^A$ |
| Mean M | $38.89^B$ | $40.39^A$ | $37.08^C$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | 1.358 | 0.635 | 0.449 | 0.01929* |
| Factor (M) | 1.358 | 0.635 | 0.449 | 0.00035** |
| Factor (N×M) | 2.352 | 1.1 | 0.778 | 0.03248* |
| **Plant height at 75 days after transplanting** | | | | |
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | $43.39^a$ | $44.53^a$ | $41.31^b$ | $43.08^A$ |
| $N_2$ | $42.33^b$ | $41.97^b$ | $36.93^c$ | $40.41^C$ |
| $N_3$ | $40.71^b$ | $43.90^a$ | $41.59^b$ | $42.07^B$ |
| Mean M | $42.14^B$ | $43.46^A$ | $39.94^C$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | 0.981 | 0.459 | 0.324 | 0.00011** |
| Factor (M) | 0.981 | 0.459 | 0.324 | 0.00001** |
| Factor (N×M) | 1.699 | 0.795 | 0.562 | 0.001** |

N: Nanomaterial, $N_1$: Nano-Zn, $N_2$: Nano-Fe, $N_3$: Nano-Mg; M: Mineral nutrients, $M_1$: $CaCl_2$, $M_2$: Sulfur, $M_3$: Molybdenum each at 1000 ppm, *level of significance is 0.05, **level of significance is 0.01

**Table 2:** Average number of leaves of capsicum after application of minerals and nanomaterials.

| Average number of leaves at 45 days after transplanting | | | | |
|---|---|---|---|---|
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | $23.33^d$ | $26.17^d$ | $25.08^d$ | $24.86^C$ |
| $N_2$ | $30.08^c$ | $36.92^b$ | $28.83^c$ | $31.94^B$ |
| $N_3$ | $34.08^b$ | $40.83^a$ | $27.42^c$ | $34.11^A$ |
| Mean M | $29.17^B$ | $34.64^A$ | $27.11^C$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | 1.955 | 0.914 | 0.647 | 0.000001** |
| Factor (M) | 1.955 | 0.914 | 0.647 | 0.000002** |
| Factor (N×M) | 3.386 | 1.584 | 1.12 | 0.00085** |
| **Average number of leaves at 60 days after transplanting** | | | | |
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | $25.33^e$ | $28.58^d$ | $27.42^d$ | $27.11^C$ |
| $N_2$ | $33.33^c$ | $37.67^b$ | $31.25^c$ | $34.08^B$ |
| $N_3$ | $36.08^b$ | $41.83^a$ | $30.17^d$ | $36.03^A$ |
| Mean M | $31.58^B$ | $36.03^A$ | $29.61^B$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | 1.8 | 0.842 | 0.595 | 0.000015** |
| Factor (M) | 1.8 | 0.842 | 0.595 | 0.000001** |
| Factor (N×M) | 3.118 | 1.458 | 1.031 | 0.00177** |
| **Average number of leaves at 75 days after transplanting** | | | | |
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | $24.42^d$ | $27.00^d$ | $25.75^d$ | $25.72^B$ |
| $N_2$ | $30.33^c$ | $34.25^b$ | $29.00^c$ | $31.19^A$ |
| $N_3$ | $33.33^b$ | $37.67^a$ | $27.58^c$ | $32.86^A$ |
| Mean M | $29.36^B$ | $32.97^A$ | $27.44^C$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | 1.901 | 0.889 | 0.629 | 0.000003** |
| Factor (M) | 1.901 | 0.889 | 0.629 | 0.00005** |
| Factor (N×M) | 3.293 | 1.54 | 1.089 | 0.01095* |

N: Nanomaterial, $N_1$: Nano-Zn, $N_2$: Nano-Fe, $N_3$: Nano-Mg; M: Mineral nutrients, $M_1$: $CaCl_2$, $M_2$: Sulfur, $M_3$: Molybdenum each at 1000 ppm, *level of significance is 0.05, **level of significance is 0.01

RUBISCO (ribulose-1,5-bisphosphate carboxylase, or oxygenase), ATP synthetase, or enzymes of photosystems [22]. Equally, iron has the ability to increase photosynthetic pigments and indole acetic acid (IAA) in plants resulting in increased peroxidase, polyphenol oxidase, and nitrate reductase activities [23]. Further, uptake and utilization of iron are improved when it is applied in form of nano-Fe which could have promoted uptake and utilization of $CO_2$ and other photosynthetic inputs in plants resulting in enhanced photosynthetic activities and accumulation of carbohydrates necessary for plant growth [24].

Further, the application of S at 1000 ppm has resulted in the highest number of leaves when applied in combination with nanomaterials as $N_3M_2$ (nano-Mg and S at 1000 ppm each) followed by $N_2M_2$ (nano-Fe and S at 1000 ppm each) [Table 2]. The interaction of nanomaterials with sulfur might have enhanced the synthesis of sulfur-containing aminoacids, resulting synthesis of protein which is essential for increasing the number of leaves [15]. The present experimental outcomes can be confirmed by the research outcomes of Haleema *et al.* [17], Schmidt *et al.* [25], and Shah *et al.* [26].

### 3.2. Flowering and Fruiting

The response of nanomaterials application on the average number of flowers and fruits per plant was not significant while a significant influence of mineral nutrients was reported on the flowering and fruiting of capsicum with the highest after application of $CaCl_2$ at 1000 ppm followed by S at 1000 ppm [Tables 3 and 4]. The interaction of sulfur and calcium with nanomaterials was substantial where $N_1M_1$ (nano-Zn and $CaCl_2$ at 1000 ppm each), $N_3M_1$ (nano-Mg and $CaCl_2$ at 1000 ppm each), and $N_2M_1$ (nano-Fe and $CaCl_2$ at 1000 ppm each) were at par with each other. The influence of nanomaterials (zinc, magnesium, and iron) might be associated with the improvement in the uptake of nutrients by the plants resulting in the improvement of plant metabolism including regulation of genes [27,28] as these are essential elements for many enzymatic reactions and optimization of amino acid-mediated cellular metabolism in plants. However, the effect of zinc on flowering attributes was more prominent when it was applied in combination with the macronutrient like calcium where zinc might have maintained the hormonal and nutritional balance within the plants to induce early growth and flowering [29,30]. Further, the

**Table 3:** Average flower count of capsicum after application of minerals and nanomaterials.

| Average number of flowers at 45 days after transplanting | | | | |
|---|---|---|---|---|
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | 7.083$^a$ | 5.833$^d$ | 4.333$^h$ | 5.750 |
| $N_2$ | 6.500$^c$ | 5.247$^e$ | 5.000$^f$ | 5.582 |
| $N_3$ | 6.833$^b$ | 5.500$^e$ | 4.667$^g$ | 5.667 |
| Mean M | 6.806$^A$ | 5.527$^B$ | 4.667$^C$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | NS | 0.064 | 0.045 | 0.05624 |
| Factor (M) | 0.136 | 0.064 | 0.045 | 0.000015** |
| Factor (N×M) | 0.236 | 0.11 | 0.078 | 0.000001** |
| **Average number of flowers at 60 days after transplanting** | | | | |
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | 5.500$^a$ | 4.667$^b$ | 3.250$^e$ | 4.472 |
| $N_2$ | 5.000$^b$ | 4.250$^c$ | 4.000$^d$ | 4.417 |
| $N_3$ | 5.500$^a$ | 4.500$^c$ | 3.583$^e$ | 4.528 |
| Mean M | 5.333$^A$ | 4.472$^A$ | 3.611$^B$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | NS | 0.09 | 0.064 | 0.48298 |
| Factor (M) | 0.192 | 0.09 | 0.064 | 0.000001** |
| Factor (N×M) | 0.333 | 0.156 | 0.11 | 0.00021** |
| **Average number of flowers at 75 days after transplanting** | | | | |
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | 2.78$^a$ | 1.92$^c$ | 1.00$^g$ | 1.90$^A$ |
| $N_2$ | 2.00$^b$ | 1.60$^d$ | 1.33$^e$ | 1.64$^B$ |
| $N_3$ | 2.23$^b$ | 1.68$^c$ | 1.25$^f$ | 1.72$^C$ |
| Mean M | 2.34$^A$ | 1.73$^B$ | 1.19$^C$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | 0.159 | 0.074 | 0.053 | 0.01022** |
| Factor (M) | 0.159 | 0.074 | 0.053 | 0.000011** |
| Factor (N×M) | 0.276 | 0.129 | 0.091 | 0.00029** |

N: Nanomaterial, $N_1$: Nano-Zn, $N_2$: Nano-Fe, $N_3$: Nano-Mg; M: Mineral nutrients, $M_1$: $CaCl_2$, $M_2$: Sulfur, $M_3$: Molybdenum each at 1000 ppm, *level of significance is 0.05, **level of significance is 0.01

**Table 4:** Average fruits count of capsicum after application of minerals and nanomaterials.

| Average number of fruits at 45 days after transplanting | | | | |
|---|---|---|---|---|
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | 4.28 | 3.77 | 2.87 | 3.64 |
| $N_2$ | 4.12 | 3.42 | 3.27 | 3.60 |
| $N_3$ | 4.12 | 3.58 | 3.03 | 3.58 |
| Mean M | 4.17$^A$ | 3.59$^B$ | 3.06$^C$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | NS | 0.106 | 0.075 | 0.84481 |
| Factor (M) | 0.226 | 0.106 | 0.075 | 0.000021** |
| Factor (N×M) | NS | 0.183 | 0.129 | 0.10251 |
| **Average number of fruits at 60 days after transplanting** | | | | |
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | 3.58$^a$ | 3.17$^b$ | 2.33$^e$ | 3.03 |
| $N_2$ | 3.33$^b$ | 2.83$^c$ | 2.75$^d$ | 2.97 |
| $N_3$ | 3.50$^a$ | 3.00c | 2.67$^d$ | 3.06 |
| Mean M | 3.472$^A$ | 3.0$^B$ | 2.583$^C$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | NS | 0.057 | 0.04 | 0.35056 |
| Factor (M) | 0.121 | 0.057 | 0.04 | 0.00004** |
| Factor (N×M) | 0.21 | 0.098 | 0.069 | 0.00051** |
| **Average number of fruits at 75 days after transplanting** | | | | |
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | 3.917$^a$ | 3.333$^c$ | 2.5$^e$ | 3.25 |
| $N_2$ | 3.417$^b$ | 3.083$^c$ | 2.917$^d$ | 3.139 |
| $N_3$ | 3.75$^a$ | 3.083$^c$ | 2.667$^d$ | 3.167 |
| Mean M | 3.694$^A$ | 3.167$^B$ | 2.694$^C$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | NS | 0.084 | 0.059 | 0.40917 |
| Factor (M) | 0.18 | 0.084 | 0.059 | 0.00001** |
| Factor (N×M) | 0.311 | 0.146 | 0.103 | 0.00501** |

N: Nanomaterial, $N_1$: Nano-Zn, $N_2$: Nano-Fe, $N_3$: Nano-Mg; M: Mineral nutrients, $M_1$: $CaCl_2$, $M_2$: Sulfur, $M_3$: Molybdenum each at 1000 ppm, *level of significance is 0.05, **level of significance is 0.01

sulfur application could be associated with the protein-mediated transformation of vegetative primordia into the reproductive primordia as sulfur and sulfur-containing molecules act as signaling material during various metabolic and physiological processes [31]. The present experimental outcomes can be confirmed by the findings of [32], [33], and [34].

### 3.3. Yield and Related Attributes

The average yield was significantly influenced by the application of mineral nutrients with the highest yield (2403.93 g/plant and 671.81 q/ha) after the application of $CaCl_2$ at 1000 ppm followed by S at 1000 ppm (1765.61 g/plant and 522.62 q/ha) [Table 5]. The interaction of calcium and sulfur with nanomaterials was also significant and the highest yield (2403.93 g/plant and 711.56 q/ha) was estimated after the application of $N_1M_1$ (nano-Zn and $CaCl_2$ at 1000 ppm each) followed by $N_3M_1$ (nano-Mg and $CaCl_2$ at 1000 ppm each) (2305.94 g/plant and 682.55 q/ha. The improvement in yield after the combined application of these nanomaterials in the presence of calcium is mainly attributed to the positive Ca-Zn or Ca-Fe or Ca-Mg interaction. Calcium is well known for its physiological roles as an intracellular messenger and for maintaining the ionic balance which counteracts the toxic effects of other nutrients ensuring the improvement in productivity [35,36]. Calcium is also attributed to enhancing the uptake of phosphorus which corresponds to a decrease in nitrate accumulation resulting in improvement in fruiting, yield, and quality in solanaceous crops [37]. Moreover, Buczkowska *et al*. [38] found an increment of 2.8–8.6% in total fruit yield while 12.1–21.8% in the marketable yield of pepper plants under foliar application of $Ca^{+2}$. In addition to Ca, sulfur had also a wide array of functions including as a structural component of biomolecules that can regulate a few physiological processes and induce tolerance against abiotic stress which might be involved in the augmentation of crop productivity [39], [40] also reported the maximum fruit size, fruit count, fruit weight, and fruit yield in greenhouse-grown tomatoes after treatment with nano-Fe at a dosage of 100 mg/kg. Thus, the use of nanomaterials as a source of nutrients has greater scope for improvement in nutrient use efficiency, prevention of nutrient leaching, and restoration of the fertility of the soil which is essential for enhancing crop yield [41].

**Table 5:** Average yield of capsicum after application of minerals and nanomaterials.

| Average yield of fruits (g per plant) | | | | |
|---|---|---|---|---|
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | $2,403.93^a$ | $1,986.35^b$ | $1,236.03^d$ | 1,875.44 |
| $N_2$ | $2,098.72^b$ | $1,645.04^c$ | $1,531.65^c$ | 1,758.47 |
| $N_3$ | $2,305.94^a$ | $1,665.44^c$ | $1,352.78^c$ | 1,774.72 |
| Mean M | $2,269.53^A$ | $1,765.61^B$ | $1,373.49^C$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | NS | 77.243 | 54.619 | 0.28834 |
| Factor (M) | 165.158 | 77.243 | 54.619 | 0.000021** |
| Factor (N×M) | 286.063 | 133.789 | 94.603 | 0.02007* |
| **Average yield of the fruits (quintal per hectare) in capsicum** | | | | |
| **Treatments** | **$M_1$** | **$M_2$** | **$M_3$** | **Mean N** |
| $N_1$ | $711.56^a$ | $587.96^b$ | $365.86^d$ | 555.13 |
| $N_2$ | $621.22^b$ | $486.93^c$ | $453.37^c$ | 520.507 |
| $N_3$ | $682.55^a$ | $492.97^c$ | $400.42^d$ | 525.316 |
| Mean M | $671.781^A$ | $522.62^B$ | $406.551^C$ | |
| **Factors** | **C.D.** | **SE (d)** | **SE (m)** | ***P* value** |
| Factor (N) | NS | 22.864 | 16.167 | 0.28825 |
| Factor (M) | 48.886 | 22.864 | 16.167 | 0.00001** |
| Factor (N×M) | 84.674 | 39.601 | 28.002 | 0.02007* |

N: Nanomaterial, $N_1$: Nano-Zn, $N_2$: Nano-Fe, $N_3$: Nano-Mg; M: Mineral nutrients, $M_1$: $CaCl_2$, $M_2$: Sulfur, $M_3$: Molybdenum each at 1000 ppm, *level of significance is 0.05, **level of significance is 0.01

## 4. CONCLUSIONS

Based on the present investigation, it can be interpreted that the application of nano-Mg and/or nano-Zn at 1000 ppm is significant for improving the productivity of capsicum under polyhouse. Further, the application of $CaCl_2$ at 1000 ppm in combination with nano-Zn (2403.93 g/plant and 711.56 q/ha) and nano-Mg (2305.94 g/plant and 682.55 q/ha) is the effective approach for improvement in productivity of capsicum grown under NVP.

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## 6. AUTHORS' CONTRIBUTION

All authors made significant contributions to the design of the research work, data collection, data analysis, and interpretation. They have also contributed to the draft of the present manuscript and have revised it critically to improve the concept. All are in agreement for submission of this manuscript to the current journal, have approved this for publication, and bear accountability for all aspects of this work. All the authors are eligible to be an author as per the international committee of medical journal editors (ICMJE) requirements/guidelines.

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The authors report no financial or any other conflicts of interest in this work.

## 9. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

## 10. DATA AVAILABILITY

The data are available with the first and corresponding author as it is from the dissertation work of the first author. This has been incorporated in the dissertation report submitted to the university where work was done and has been presented in the current manuscript.

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