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Response of tomato (*Solanum lycopersicum* L.) to foliar application of eggshell powder and micronutrients under subtropical conditions of Uttarakhand

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ABSTRACT

Nutrient imbalances and suboptimal growing conditions limit the productivity and fruit quality of tomato (Solanum lycopersicum L.) in the hilly regions of Uttarakhand. To overcome this problem, a field experiment was conducted to assess the impact of eggshell powder in conjunction with selected micronutrients (boron, zinc, and iron) on the growth yield and quality attributes of tomato cv. Pant T-3 during the spring-summer season of 2023. The results revealed the maximum plant height at 60 and 90 days after transplanting (DAT) (82.50 cm and 93.23 cm, respectively), number of primary branches per plant (10.33), number of flower clusters per plant at 60 DAT (27.50), number of flowers per cluster at 60 DAT (6.23), number of fruits per cluster (5.60), number of fruits per plant (57.36), average fruit weight (49.76 g), fruit length (3.68 cm), fruit yield per plant (2.32 kg), fruit yield per plot (25.71 kg), fruit yield per hectare (476.21 q), titratable acidity (0.46%) and vitamin C content (26.59 mg/100 g), and minimum incidence of fruit borer (20.58%) with the application of the treatment T_9 (Eggshell powder @1% + B @100 ppm + Zn @100 ppm + Fe @100 ppm). Therefore, this integrated nutrient management strategy may be recommended as a sustainable, low-cost and environmentally friendly solution for enhancing tomato production under the subtropical conditions of Uttarakhand.

Keywords: *Tomato, eggshell powder, micronutrients, growth, yield, quality.*

Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most important vegetable crops in the world, ranking second only to potato in terms of consumption [1,2]. Its cultivation is constantly expanding due to its rising global demand and the large number of food industries that rely on it [3]. Like most horticultural crops, tomato has high requirements for external inputs in order to maximize its yield to the optimum, and, therefore, it significantly depletes soil nutrients during its life cycle. In this sense, application of organic manures and fertilizers, including micronutrients, is one of the principal strategies to improve the growth and yield potential of tomato crop [4].

Micronutrients, in particular, play key roles in maintaining the overall health of the plants as they are involved in a variety of physiological and biochemical processes, each of which contributes uniquely to plant growth and yield [5,6]. Micronutrient deficiency can lead to metabolic disturbances and physiological disorders, ultimately affecting both the yield and quality of vegetable crops [7].

Among the essential micronutrients, boron (B), zinc (Zn), and iron (Fe) are especially important for the healthy growth and development of tomato plants.

Zinc contributes to carbohydrate metabolism, synthesis of RNA, DNA, and proteins, production of chlorophyll and auxins as well as reproductive processes such as fertilization [8], and tomato is particularly vulnerable to Zn deficiency [9,10]. Boron is involved in cell division, cell wall formation, flowering, fruit set, nucleic acid synthesis, absorption of nitrogen, phosphorus and calcium, and the movement of carbohydrates and proteins within the plant [11]. Deficiency of boron leads to poor fruit development, unfruitfulness, and induced oxidative damage, thereby retarding plant growth [12]. Iron is critical for physiological processes like respiration, photosynthesis, chlorophyll formation and energy transfer [13], and its deficiency is marked by interveinal chlorosis and yellowing of young leaves due to impaired photosynthetic efficiency [14]. Therefore, appropriate management of these micronutrients is essential for sustaining tomato productivity and ensuring optimal crop performance.

As a readily available low-cost agricultural byproduct, eggshells can be processed into fine powder and serve as a valuable organic source of calcium (Ca) and other trace mineral elements required for plant growth. Foliar or soil application of eggshell powder has been shown to improve plant vigour, enhance flowering, and increase fruit yield by strengthening cell walls and minimizing physiological disorders such as blossom end rot (BER).

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This not only improves fruit quality but also enhances market value [15].

Keeping in view the importance of Ca, B, Zn and Fe in improving tomato productivity and quality, the current investigation was conducted with the following objectives: to study the effect of foliar application of Ca, B, Zn and Fe on plant growth, fruit yield and fruit quality of tomato; and to elucidate the effect of these nutrients on tomato fruit borer incidence. Foliar application of the nutrients was selected as a suitable strategy as it reduces nutrient losses through fixation and leaching, and provides ample scope for easy and efficient penetration of plant nutrients as well as rapid correction of nutrient deficiencies.

Materials and Methods

The experiment was conducted during the spring-summer season of 2023 at the Horticultural Research Centre, Chauras Campus, H. N. B. G. U., Srinagar (Garhwal), Uttarakhand, using the tomato cv. Pant-T3, developed by the G. B. Pant University of Agriculture & Technology, Pantnagar, Uttarakhand. The experimental location lies in the Alaknanda valley (30°13'9"N, 78°47'30"E) at an altitude of 540 m above mean sea level.

The experimental soil was sandy loam in texture with neutral reaction (pH = 7.13). The bulk density, organic carbon, available N, P and K were 0.60 Mg/m^3, 0.80%, 96.6 kg/ha, 23.21 kg/ha and 166.90 kg/ha, respectively. The experiment was laid out in three replications, in a randomized block design (RBD), comprising ten treatments, viz. T_0 (Control), T_1 (Eggshell powder @0.5%), T_2 (Eggshell powder @1%), T_3 (B @50 ppm), T_4 (B @100 ppm), T_5 (Zn@50 ppm), T_6 (Zn@100 ppm), T_7 (Fe @50 ppm), T_8 (Fe @100 ppm) and T_9 (Eggshell powder @1% + B @100 ppm + Zn @100 ppm + Fe @100 ppm). The sources of B, Zn and Fe used were boric acid, zinc sulphate and ferrous sulphate, respectively. The foliar treatments were applied twice, at 20 and 40 days after transplanting (DAT). All the foliar applications were carried out early in the morning for better absorption of the nutrients. Each replication comprised ten individual plots, each measuring 2.4 m × 1.8 m. One month -month-old tomato seedlings were transplanted at a spacing of 60 cm × 45 cm. The recommended doses of NPK @120:75:60 kg/ha were applied in the form of urea, single super phosphate and muriate of potash in all the treatment plots. Half a dose of N and full doses of P and K were applied before transplanting as the basal dose. The remaining half dose of N was applied in two split doses at 30 and 45 DAT as top dressing. Standard intercultural practices and plant protection strategies recommended for optimal tomato cultivation were thoroughly implemented.

The observations for growth, yield, and quality parameters were taken from five randomly selected plants from each plot. These included plant height at 30, 60 and 90 DAT, number of primary branches per plant, days to first flowering and fruiting, number of flower clusters per plant at 30 and 60 DAT, number of flowers per cluster at 30 and 60 DAT, number of fruits per cluster, number of fruits per plant (kg), average fruit weight (g), fruit length and diameter (cm), fruit yield per plant and per plot (kg), fruit yield per hectare (q), total soluble solids (°Brix), titratable acidity (%), vitamin C content (mg/100 g) and percentage of fruit borer infestation. To assess the statistical significance of treatment effects, analysis of variance (ANOVA) was performed and the critical difference (CD) at 5% level of significance was calculated to compare the treatment means for all the recorded attributes.

Results and Discussion

Growth Attributes

The perusal of data depicted in Table 1 and Table 2 revealed that the growth characters were significantly influenced by the treatments. Among the various treatments, T_2 (Eggshell powder @1%) recorded the maximum plant height at 30 DAT (47.56 cm), while the minimum (43.16 cm) was observed under the treatment T_3 (B@50 ppm). Plant heights at 60 and 90 DAT (82.50 cm and 93.23 cm, respectively) were recorded maximum in T_9 (Eggshell powder @1% + B @100 ppm + Zn @100 ppm + Fe @100 ppm), whereas the minimum (68.33 cm and 72.53 cm, respectively) were noted under T_0 (Control). The observed increase in plant height could be attributed to the role of Zn in promoting auxin biosynthesis, B in cell division and elongation, and Fe in increasing the chlorophyll content, which may have enhanced photosynthesis and metabolic processes, and Ca present in eggshells in strengthening the plant cells [16]. Similar findings were reported in brinjal [17], where the combined application of B, Zn, and Fe significantly enhanced plant vigour and shoot length.

The treatment T_9 (Eggshell powder @1% + Zn @100ppm + B @100ppm + Fe @100ppm) recorded the highest number of primary branches per plant (10.33). In contrast, the lowest number of branches (7.00) was observed in the control treatment (T_0). The significant result of this treatment might be attributed to the synergistic effect of micronutrients such as Zn, which plays an important role in tryptophan formation; Fe, which regulates chlorophyll synthesis; and B, which plays a substantial role in the translocation of photosynthates. The combined foliar application of B, Zn, Fe, and eggshell powder enhanced the plant height, which in turn promoted the development of nodes and internodes, ultimately contributing to an increased number of primary branches per plant [18]. Supporting evidence from a Solanaceae context was reported in chilli, where foliar application of Zn, Fe, and B at 1% concentration resulted in the highest number of primary branches per plant [19].

The earliest onset of flowering (28.66 days) was recorded under treatment T_6 (Zn@100 ppm), while T_4 (B@100 ppm) registered the maximum days to flowering (31.53). The early flowering observed in plants treated with Zn may be attributed to the efficient influx of essential ions into the plant system. Moreover, Zn is known to enhance photosynthetic activity, regulate hormonal metabolism and promote cell expansion, which might have ultimately led to flower initiation and development [20]. A similar observation was reported with zinc oxide nanoparticles (ZnO-NPs) in tomato [21]. The treatment T_6 also exhibited the shortest duration to first fruiting, with fruits appearing as early as 33.33 days after transplanting, compared to the maximum (36.73 days) recorded in T_0 (Control). The foliar application of Zn enhanced the metabolic activities of the plants responsible for the production of sugars and carbohydrates, which are essential for fruit development [20]. These conform with the findings of Kalroo *et al.* [22] in chilli.

Table 1: Effect of eggshell powder and micronutrients on growth and reproductive parameters of tomato

Treatment	Plant height (cm)			NPBP	DFF	DFFr	NFCP	
	30 DAT	60 DAT	90 DAT				30 DAT	60 DAT
T_0	43.90	68.33	72.53	7.00	30.40	36.73	4.93	19.16
T_1	43.26	70.43	76.36	7.73	30.00	35.93	5.06	20.80
T_2	47.56	72.46	79.16	8.00	29.40	34.66	6.40	22.00
T_3	43.16	79.23	86.83	8.80	29.53	35.40	5.80	23.23
T_4	44.20	81.16	88.10	9.06	31.53	35.60	6.20	25.76
T_5	43.56	78.50	90.50	8.20	30.66	35.66	6.66	25.40
T_6	45.60	79.70	91.96	9.53	28.66	33.33	7.33	26.50
T_7	45.33	75.30	82.83	7.80	30.33	35.33	7.46	20.63
T_8	44.30	75.40	83.96	8.06	30.73	36.53	6.86	24.60
T_9	46.80	82.50	93.23	10.33	28.73	34.20	6.00	27.50
CD @5%	**1.81**	**2.09**	**1.07**	**0.52**	**1.52**	**1.27**	**1.12**	**2.26**

***DAT:** Days after transplanting, **NPBP:** Number of primary branches per plant, **DFF:** Days to first flowering, **DFFr:** Days to first fruiting, **NFCP:** Number of flower clusters per plant*

The maximum number of flower clusters per plant at 30 DAT (7.46) was recorded in T_7 (Fe @50 ppm), while the minimum (4.93) was noted in T_0 (Control). However, the maximum number of flower clusters per plant at 60 DAT (27.50) was recorded in T_9 (Eggshell powder @1% + B@100 ppm + Zn@100 ppm + Fe @100 ppm), whereas the minimum (19.16) was observed in T_0 (Control). The combined effect of eggshell powder and micronutrients on promoting increased flowering and flower cluster formation may have resulted from a potential enhancement in photosynthetic efficiency, along with improved translocation of sugars to axillary buds. These processes might likely have reduced the carbon-nitrogen ratio (C:N) and promoted auxin synthesis, which in turn helped minimize flower and fruit drop [23]. These observations are in agreement with the findings of Haleema *et al.* [24], who noted a significant increase in flower clusters and fruit retention in tomato with foliar application of Ca, B and Zn.

The maximum number of flowers per cluster at 30 DAT (6.18) was recorded in plants treated with T_8 (Fe@100 ppm), while the minimum (4.44) was observed with T_3 (B @50 ppm). This effect may be attributed to the role of Fe in promoting the formation of healthy green foliage, thereby improving photosynthesis, promoting carbohydrate assimilation and enabling a more effective distribution of assimilates to the reproductive organs. However, the maximum number of flowers per cluster at 60 DAT (6.23) was recorded in T_9 (Eggshell powder @1% + B@100 ppm + Zn@100 ppm Fe@100 ppm, whereas the minimum (3.63) was recorded in T_0 (Control). This result can be attributed to the functions of B, Zn, and Fe in regulating metabolic activities and supporting the effective translocation of carbohydrates from the source (leaves) to the sink (fruits). Meanwhile, both Ca and B contribute to accelerated cell division, facilitating the transition from vegetative to reproductive growth. Ca also plays a key role in floral induction and inhibition of flower abscission, and enhances P absorption through the root system, an effect that may directly stimulate flowering and increase the number of flowers per cluster [25,26]. Tomato plants treated with Ca and B resulted in an increased number of flowers per cluster [24], which aligns with the present results.

Yield Attributes

The data presented in Table 2 indicate that the treatments influenced all the yield attributes, with foliar application showing a statistically significant improvement over the control. Among all the treatments, the treatment T_9 (Eggshell powder @1% + B @100 ppm + Zn @100 ppm + Fe @100 ppm) registered the maximum number of fruits per cluster (5.60), with the minimum number of fruits per cluster (2.81) observed in T_0 (Control). The increase in the number of fruits per cluster may be attributed to the exogenous application of eggshell powder and micronutrients during critical stages of flowering and fruit development. These treatments likely improved the source-sink dynamics, facilitated the accumulation of photosynthates and promoted more efficient use of stored nutrients for fruit formation. Additionally, B plays a vital role in elevating RNA and DNA synthesis in floral tissues, and enhancing sugar levels of the stigma, thereby promoting pollen germination, growth of pollen tube and successful fruit set [26-28]. Similar results were reported by the Osman *et al.* [29] and Ullah *et al.* [30] in tomato.

The maximum number of fruits per plant (57.36) was recorded in treatment T_9 (Eggshell powder @1% + B @100 ppm + Zn @100 ppm + Fe @100 ppm), while the minimum (46.16) was observed in the control treatment (T_0). This increase may be attributed to the enhanced availability of B, Zn and Fe, which are known to elevate sugar concentrations in the stigma. This, in turn, improved pollen germination and pollen tube elongation, thereby increasing the fruit set percentage in tomato [26,28]. The treatment T_9 also recorded the highest average fruit weight (49.76 g), while the lowest (39.28 g) was noted under the control treatment (T_0). This outcome may be attributed to the roles of Ca and Fe in enhancing photosynthetic efficiency and facilitating improved mineral uptake, metabolic functions, and translocation of assimilates to the fruit. These actions collectively promote cell elongation and division. B contributes by aiding in carbohydrate metabolism, which is closely associated with increased fruit set and fruit mass [26], whereas Zn supports fruit development through its involvement in tryptophan and IAA biosynthesis [26,31] as well as carbohydrate translocation [26,32]. Similar findings were reported in broccoli [33] and tomato [16].

Table 2: Effect of eggshell powder and micronutrients on reproductive and yield attributing parameters of tomato

Treatment	NFC		NFrC	NFrP	AFW (g)	FL (cm)	FD (cm)	FYP (kg)	FYPt (kg)	FYH (q)
	30 DAT	60 DAT								
T_0	5.74	3.63	2.81	46.16	39.28	2.76	3.51	1.19	18.49	342.53
T_1	6.10	5.36	4.76	51.70	47.06	3.49	4.62	2.02	23.08	427.40
T_2	5.49	5.63	5.00	53.70	48.37	3.52	4.89	2.09	24.67	456.97
T_3	4.44	5.23	5.18	52.93	47.21	3.49	4.72	2.01	24.24	449.01
T_4	5.74	5.60	5.32	54.06	48.52	3.65	4.76	2.15	24.75	458.33
T_5	5.50	5.06	4.85	50.03	45.08	3.28	4.56	1.81	22.53	417.21
T_6	5.89	5.10	4.43	53.10	45.35	3.41	4.36	1.87	23.52	435.67
T_7	6.14	4.63	3.80	49.16	45.89	3.19	4.17	1.73	21.87	404.99
T_8	6.18	4.73	4.16	49.96	46.52	3.21	4.24	1.78	22.85	423.26
T_9	5.80	6.23	5.60	57.36	49.76	3.68	4.80	2.32	25.71	476.21
CD @5%	**0.65**	**0.23**	**0.66**	**1.59**	**1.00**	**0.18**	**0.41**	**0.21**	**1.31**	**24.30**

DAT: Days after transplanting, NFC: Number of flowers per cluster, NFrC: Number of fruits per cluster, NFrP: Number of fruits per plant, AFW: Average fruit weight, FL: Fruit length, FD: Fruit diameter, FYP: Fruit yield per plant, FYPt: Fruit yield per plot, FYH: Fruit yield per hectare

The maximum fruit length (3.68 cm) and fruit diameter (4.89 cm) were recorded in plants treated with T_9 (Eggshell powder @1% + B @100 ppm + Zn @100 ppm + Fe @100 ppm) and T_2 (Eggshell powder @1%), respectively, whereas the minimum fruit length and diameter (2.76 cm and 3.51 cm, respectively) were recorded in T_0 (Control). The increase in fruit length may be attributed to the enhanced vegetative growth, which resulted in higher production of photosynthates and ultimately enhanced fruit development [34]. The synergistic role of Ca in stimulating meristematic tissue development, promoting metabolite synthesis, enhancing cell division and activating enzymes associated with cell expansion might have contributed to the production of larger, higher-quality fruits in the long run [35]. These findings are further corroborated by the works of Ali *et al.* [36] and Salam *et al.* [37] in tomato.

The highest fruit yield per plant (2.32 kg), per plot (25.71 kg) and per hectare (476.21 q) were recorded under T_9 (Eggshell powder @1% + B @100 ppm + Zn @100 ppm + Fe @100 ppm), whereas the lowest values (1.19 kg, 18.49 kg and 343.53 q, respectively) were observed in T_0 (Control). Eggshell powder and micronutrients contributed to improved yield by positively impacting vegetative growth and regulating physiological and biochemical processes within the plants. Each micronutrient serves a distinct purpose in influencing overall crop growth. For example, Zn facilitates the production of carbohydrates and their movement towards the fruiting sites, and enhancing enhances fruit set percentage. B is vital for cell wall expansion, pollen germination and pollen tube growth. Fe boosts chlorophyll levels in plants, while Ca prevents disorders like blossom end rot (BER), leading to improved fruit retention and higher yields [18,38]. The foliar application of eggshell powder combined with micronutrients improved all the yield yield-attributing parameters, ultimately enhancing the total fruit yield. The present results are in line with the findings of Kumar *et al.* [17] and Rab and Ihsanul [39] in tomato, and Kumar *et al.* [40] in other solanaceous vegetable crops.

Quality Attributes

Figure 1 clearly shows that all fruit quality parameters of tomato were significantly affected by the foliar treatments of eggshell powder and micronutrients. The maximum TSS (5.1 °Brix) was recorded in fruits of plants treated with T_4 (B@100 ppm), while T_0 (Control) registered the minimum TSS (3.63 °Brix). Generally, the higher value of TSS might be due to the role of B and Zn in the translocation of sugars and carbohydrate metabolism [26,27].

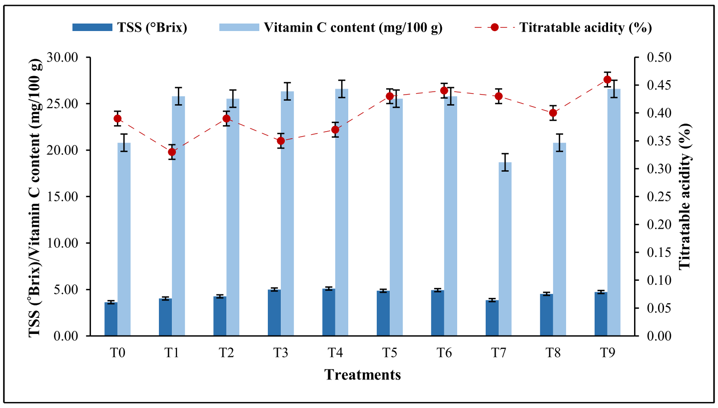

Figure 1: Effect of eggshell powder and micronutrients on quality parameters of tomato

The maximum titratable acidity (0.46%) was observed under T_9 (Eggshell powder @1% + B @100 ppm + Zn @100 ppm + Fe @100 ppm), whereas the minimum titratable acidity (0.33%) was recorded in T_1 (Eggshell powder @0.5%). The elevated titratable acidity in the fruits could be attributed to the synergistic influence of eggshell powder and micronutrients, which may have improved N assimilation and supported the production and movement of carbohydrates and vitamins towards the developing fruits [41]. Harris and Lavanya [42] noted similar findings in tomato in terms of acidity.

The maximum vitamin C content (26.59 mg/100 g) was recorded in both T_9 (Eggshell powder @1% + B @100 ppm + Zn @100 ppm + Fe @100 ppm) and T_4 (B @100 ppm). In contrast, the minimum (18.69 mg/100g) was noted under T_7 (Fe @50 ppm). This effect may be ascribed to the role of B in enhancing Ca uptake and boosting vitamin C levels in tomato fruits by stabilizing cell membranes, moderating biosynthetic processes, and reducing respiration [2]. Additionally, Zn might have contributed to the elevated ascorbic acid levels by stimulating the activity of ascorbic acid oxidase, an enzyme critical to its synthesis [43]. Similar observations were also recorded by Mallick *et al.* [10] in tomato, who reported the synergistic effect of micronutrients in enhancing fruit quality traits.

Screening for Tomato Fruit Borer (*Helicoverpa armigera*) Incidence

As evident from Figure 2, the minimum fruit borer incidence (20.58%) was observed in plants treated with T_9 (Eggshell powder @1% + B @100 ppm + Zn @100 ppm + Fe @100 ppm), indicating moderate susceptibility, whereas the maximum fruit borer incidence (39.10%) was recorded in treatment T_0 (Control), indicating high susceptibility.

This may be attributed to the role of Ca in the formation of thicker cell walls, and the influence of micronutrients in stimulating the biosynthesis of natural defense compounds, such as phytoalexins, antioxidants and flavonoids, thereby enhancing the resistance of plants to pest attack [44].

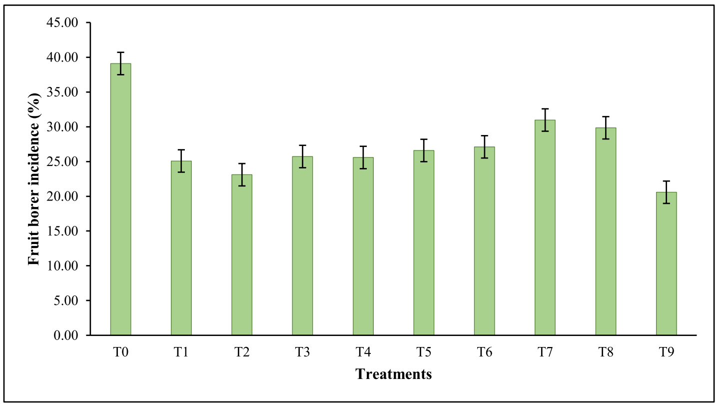

Figure 2: Effect of eggshell powder and micronutrients on tomato fruit borer incidence

Conclusion

The present investigation demonstrated that the foliar application of T_9 (Eggshell powder @1% + B @100 ppm + Zn @100 ppm + Fe @100 ppm) significantly enhanced plant growth, yield and quality of tomato cv. Pant T-3. The combined effect of eggshell powder and essential micronutrients improved the physiological and reproductive functions of plants. Applying nutrients in the right concentration is critical; B, Zn, and Fe at 100 ppm improved enzymatic activity, hormone regulation, and pollen fertility, while 1% eggshell powder ensured adequate Ca availability. Deviations from these levels could lead to nutrient imbalances and reduced crop performance. This cost-effective, eco-friendly approach holds great promise for hilly regions, where soil fertility and input access are challenges. By enhancing fruit yield and quality using locally available resources, this treatment combination can play a transformative role in improving the income and livelihood of small-scale farmers, reducing dependency on costly fertilizers and promoting sustainable agriculture in the subtropical conditions of Uttarakhand.

Authors' Contributions

UP executed the field/laboratory experiment and collected the data; DKR supervised the experiment and validated the data; PP assisted in data analysis, interpretation, and visualization; AS and SRB prepared and edited the manuscript. All the authors read and approved the final manuscript.

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Not applicable.

Conflict of Interest

The authors declare no conflict of interest.

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