International Journal of Advanced Biochemistry Research 2024; 8(11): 1009-1015

International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
IJABR 2024; 8(11): 1009-1015
www.biochemjournal.com
Received: 22-08-2024
Accepted: 26-09-2024

DK Harish
Ph.D. Scholar, Department of Horticulture, College of Agriculture, UAS, Dharwad, Karnataka, India

SG Angadi
Department of Horticulture, College of Agriculture, UAS, Dharwad, Karnataka, India

SM Hiremath
Department of Horticulture, College of Agriculture, UAS, Dharwad, Karnataka, India

Gurudatt Hegde
Department of Plant pathology, College of Agriculture, UAS, Dharwad, Karnataka, India

BH Kumar
Department of Soil Science, College of Agriculture, UAS, Dharwad, Karnataka, India

Corresponding Author:
DK Harish
Ph.D. Scholar, Department of Horticulture, College of Agriculture, UAS, Dharwad, Karnataka, India

Impact of integrated crop management and fertilizer types on post-harvest soil properties in onion cultivation

DK Harish, SG Angadi, SM Hiremath, Gurudatt Hegde and BH Kumar

DOI: https://doi.org/10.33545/26174693.2024.v8.i11m.3007

Abstract
The significant role of integrated crop management (ICM) and targeted fertilizer types in enhancing soil fertility, nutrient availability and overall soil health in onion cultivation. The treatments consisted of first six treatments were with Nano fertilizers (conventional fertilizers viz., T_1: Recommended Package of Practice (RPP); T_2: RPP + Bentonite-S (Sulphur, 50 kg S/ha); T_3: RPP + Bentonite-S (Sulphur, 50 kg S/ha) + Boron @ 2. 5 kg/ha + $ZnSO_4$ @ 25 kg/ha, T_4: RPP + Bentonite-S (Sulphur, 50 kg S/ha) + Boron @ 2. 5 kg/ha+ $FeSO_4$ @ 25 kg/ha; T_5: RPP + Bentonite-S (Sulphur, 50 kg S/ha) + Boron @ 2. 5 kg/ha + $ZnSO_4$ + $FeSO_4$ each at 25 kg/ha; and T_6 = RPP + Bentonite-S (Sulphur, 50 kg S/ha) +Vegetable Special at 5 g per litter (Twice at 45 and 60 DAS) and further six more treatments were modified version of RDF i.e. T_7: 50% Recommended N P + 100% Recommended K and spray of Nano-Urea & DAP @ 4 ml/L, twice at 45 and 60 DAS); T_8: 50% Recommended N P + 100% Recommended K and spray of Nano-Urea & DAP @ 4 ml/L, twice at 45 and 60 DAS + Bentonite-S (Sulphur, 50 kg S/ha); T_9: 50% Recommended N P + 100% Recommended K and spray of Nano-Urea & DAP @ 4 ml/L, twice at 45 and 60 DAS + Boron @ 2.5 kg/ha + Spray with Nano Zn at 2 ml per liter (Twice at 45 and 60 DAS); T_{10}: 50% Recommended N P + 100% Recommended K and spray of Nano-Urea & DAP @ 4 ml/L, twice at 45 and 60 DAS + Boron @ 2.5 kg/ha + Spray with Nano Fe at 2 ml per liter (Twice at 45 and 60 DAS); T_{11}: RPP (50% Recommended N P + 100% Recommended K and spray of Nano-Urea & DAP @ 4 ml/L, twice at 45 and 60 DAS + Boron @ 2.5 kg/ha + Spray with Nano Zn & Fe each at 2 ml per liter (Twice at 45 and 60 DAS); T_{12}: 50% Recommended N P + 100% Recommended K and spray of Nano-Urea & DAP @ 4 ml/L, twice at 45 and 60 DAS +vegetable special at 5 g per litter (Twice at 45 & 60 DAS) and absolute control. The absolute control (T_{13}) exhibited the highest soil pH (8.21 and EC (0.46 dS m^{-1}), T_2 and T_{11} treatments were recorded the lowest pH (7.86) and EC (0.36 dS m^{-1}), respectively. The highest OC, available N, P and K content were recorded with treatment T_5 (5.25 mg kg^{-1}, 232.78 kg/ha, 19.92 kg/ha and 404.75 kg/ha, respectively. The highest micronutrients including zinc (0.68 mg kg^{-1}), iron (4.02 mg kg^{-1}), manganese (0.91 mg kg^{-1}) and copper (2.25 mg kg^{-1}) was recored with treatment T_6. The study highlights the importance of integrated nutrient management, where treatments like T_6 and T_5, significantly improve soil fertility and micronutrient availability, leading to better plant growth and productivity.

Keywords: ICM, post-harvest soil, fertilizer types, onion crop, nano fertilizer

Introduction
Onion (*Allium cepa* L.) is a critical horticultural crop and an essential component of Indian cuisine, contributing significantly to the country's agricultural economy. India ranks among the world's leading producers of onions, producing approximately 26.7 million metric tons in 2022, with Maharashtra, Karnataka and Madhya Pradesh leading in cultivation area and output (FAO, 2022) [10]. Onion cultivation covers about 1.6 million hectares of India agricultural land, accounting for roughly 16% of the global production area and meeting both domestic demand and export needs. However, sustainable production practices are essential to maintain the soil quality of these heavily cultivated areas, as soil health directly impacts both yield quality and crop sustainability.
The conventional cultivation of onions often involves high levels of chemical fertilizers, especially nitrogen (N), phosphorus (P) and potassium (K). Excessive reliance on these conventional fertilizers, however, can lead to soil degradation, reducing the fertility and microbial health of the soil (Ayamba *et al.*, 2023) [4] Studies showed that around 60% of

Indian soils are deficient in nitrogen, 49% in phosphorus and 9% in potassium. With the agricultural sector being a major consumer of chemical fertilizers, there is growing concern over the negative impacts of intensive fertilizer use on soil health, water quality and long-term crop productivity.

Integrated Crop Management (ICM) offers a sustainable alternative, integrating advanced practices that balance nutrient requirements, reduce chemical inputs and improve soil health. ICM includes optimizing nutrient management, crop rotation, efficient water use and adopting new technologies, such as nano fertilizers, which are engineered to increase nutrient efficiency and minimize environmental impacts (Bhati *et al*., 2018) [9]. Nano fertilizers, with particle sizes below 100 nanometers, can provide higher nutrient use efficiency and gradual nutrient release, potentially enhancing crop yields while reducing the risks of leaching and nutrient runoff.

This study aims to explore the effects of various ICM practices, including the application of nano fertilizers, on the physico-chemical properties of soil after the harvest of onion crops. Soil quality indicators such as pH, electrical conductivity (EC), organic carbon, available N, P, K and micronutrients like zinc and iron are analyzed to evaluate the impact of these practices. Given India goal of doubling farmer incomes and increasing sustainable agricultural practices, it is essential to investigate the potential of nano fertilizers in onion cultivation to maintain soil health while optimizing yield.

Materials and Methods

A field experiment on the "impact of integrated crop management and fertilizer types on post-harvest soil properties in onion cultivation" was conducted over two *kharif* seasons (2022-23 and 2023-24) at the All-India Network Research Project on Onion and Garlic, MARS, UAS, located in the Dharwad district of Karnataka, within the Northern Dry Zone (Zone-3). The study was carried out in *Vertosol* soil, and composite surface soil samples were collected from a depth of 0-20 cm prior to the start of the experiment. These samples were analyzed for various physico-chemical properties to establish baseline soil characteristics before applying the treatments.

Experimental details

The experimental details *viz*., design and layout, plot size, treatments, crop and cultural practices adapted during experimentation *etc*., are given below.

Design and layout

Crop	Onion
Variety	Bhima Super
Location	All India Network Research Project on Onion and Garlic, MARS, UAS, Dharwad
Year	2022-2023
Season	Two season (*Kharif*- 2022-23 and 2023-24)
Situation	Rainfed
Method of planting	Drill Sowing
Soil type	Black
Spacing	15 cm x 7.5 cm
Plot size	3 m x 1.2 m
Design	RCBD
Treatments	13
Replication	03

Package of Practice

FYM: 30 t ha^{-1}

$N:P_2O_5:K_2O$- 125:50:125: kg ha^{-1}

Seed treatment - Carbendazim 1.0 gm/litter

Need based blanket application of Profenophos @2.0 ml/lit or Spinosad @ 0.25 ml/lit or – Spinotoram @ 0.50 ml/lit + Propiconazole 1.0 ml/lit followed by Hexaconazole 1.0 ml/lit.

Treatment Details

T_1 = Recommended Package of Practice (RPP)

T_2 = T_1 + bentonite-S (Sulphur @ 50 kg ha^{-1})

T_3 = T_2 + boron @ 2. 5 kg ha^{-1}+ $ZnSO_4$ @ 25 kg ha^{-1}

T_4 = T_2 + boron @ 2. 5 kg ha^{-1}+ $FeSO_4$ @ 25 kg ha^{-1}

T_5 = T_2 + boron @ 2. 5 kg ha^{-1}+ $ZnSO_4$ + $FeSO_4$ each at 25 kg ha^{-1}

T_6 = T_2 + Vegetable Special @ 5g L^{-1} (Twice at 45 and 60 DAS)

T_7 = *RPP (50% Recommended dose of N P and foliar spray of Nano Urea & Nano DAP @ 4 ml L^{-1}, twice at 45 and 60 DAS + 100% Recommended K)

T_8 = T_7 + bentonite-S (Sulphur @ 50 kg ha^{-1})

T_9 = T_8 + boron @ 2. 5 kg ha^{-1}+ spray with Nano Zn @ 2 ml L^{-1} (Twice at 45 and 60 DAS)

T_{10} = T_8 + boron @ 2. 5 kg ha^{-1} + spray with Nano-Fe@ 2 ml L^{-1} (Twice at 45 and 60 DAS)

T_{11} = T_8 + boron @ 2. 5 kg ha^{-1} + spray with Nano-Zn & Nano-Fe each at 2 ml L^{-1} (Twice at 45 and 60 DAS)

T_{12} = T_8 +Vegetable Special @ 5g L^{-1} (Twice at 45 & 60 DAS)

T_{13}= Absolute control

Soil analysis was conducted using various standardized methods to assess different parameters. pH was determined using the potentiometric method with a 1:2 soil-water suspension (Jackson, 1973) [20], while Electrical Conductivity (EC) was measured using the conductometric method with a 1:2 soil-water suspension (Jackson, 1973) [20]. Organic carbon content was assessed through the wet oxidation method (Walkey and Black, 1934) [21], and available nitrogen was measured using the alkaline potassium permanganate method. Available phosphorus (P_2O_5) was determined using Bray's and Olsen's extraction followed by colorimetry (Jackson, 1973) [20], and available potassium (K_2O) was extracted with ammonium acetate (NH_4OAC) and measured by flame photometry (Jackson, 1973) [20]. For micronutrients, DTPA-extractable iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) were analyzed using atomic absorption spectrophotometry.

Statistical analysis

The experiment results were analysed statistically following the procedure as described by Gomez and Gomez (1984) [22]. The level of significance used in F and t test was P= 0.05 critical difference was calculated wherever F test was significance.

Results and Discussion

The study recorded the effects of various treatments on soil pH, Electrical Conductivity (EC), and Organic Carbon (OC) content after the harvest of onions in 2022 and 2023, along with pooled averages for each metric. Soil pH was highest in the absolute control (T_{13}), with values of 8.21 in both years and a pooled average of 8.22, indicating alkaline conditions likely due to the absence of amendments. High soil pH, as observed, can negatively impact nutrient availability, particularly for micronutrients like iron and manganese, which become less accessible in alkaline soils (Abbey and Kanton, 2003) [1]. Treatments T_1 (Recommended Package of Practice, RPP) and T_7 (50% Recommended N and P + 100% Recommended K with Nano-Urea & DAP spray) also recorded high pH values, albeit slightly lower than the control, suggesting that recommended nutrient applications may mitigate soil alkalinity, enhancing nutrient availability (Tekalign and Pant, 2011) [17]. T_2, which included bentonite sulfur (50 kg S/ha), showed the lowest pH with a pooled average of 7.86, highlighting sulfur effectiveness in lowering pH through the formation of sulfuric acid as it undergoes microbial oxidation (Abbey *et al*., 2000) [2]. In terms of EC, the absolute control (T_{13}) again recorded the highest values with a pooled average of 0.46 dS m^{-1}, reflecting a higher salt concentration likely due to the lack of soil amendments, which typically help to balance soil salinity levels (Babajide *et al.*, 2008) [5]. T_{10} and T_{11}, which involved nutrient combinations including sulfur and nano micronutrients, showed comparable and lower EC values, with T_{11} achieving the lowest EC (0.36 dS m^{-1}), suggesting that sulfur and micronutrients may reduce salt concentration by promoting nutrient balance in soil. OC content, T_5 (RPP + bentonite-S, boron, $ZnSO_4$, and $FeSO_4$) had the highest levels with a pooled average of 5.25 mg kg^{-1}, likely due to the beneficial effects of organic amendments in enhancing microbial activity and improving soil structure (Thakur and Kumar, 2021) [18]. T_{13} (absolute control) had the lowest OC content (pooled average of 4.28 mg kg^{-1}), underscoring the importance of organic inputs for maintaining soil organic matter, which supports nutrient retention and overall soil health (Bairagi *et al*., 2015) [6]. Despite differences, most treatments did not show significant variations in OC, although T_5 outperformed others, suggesting that combining organic amendments with micronutrient management can promote soil organic carbon retention.

The data presented in Table 2 showed that treatments had distinct effects on available nitrogen, phosphorus, and potassium in the soil across the years 2022 and 2023. For nitrogen, T_5 (RPP + bentonite-S with sulfur, boron, $ZnSO_4$, and $FeSO_4$) recorded the highest levels, with an average of 232.78 kg/ha, followed closely by T_4 and T_6, which also incorporated sulfur and micronutrient amendments. This elevated nitrogen content in T_5 is attributed to the synergistic effect of sulfur and micronutrients, which enhance nitrogen retention and stimulate microbial processes that convert organic matter into plant-available nitrogen forms (Barakade *et al*., 2011) [7]. Treatments like T_4, which also incorporated sulfur and boron, were similarly effective in boosting nitrogen, highlights the role of comprehensive nutrient strategies in enhancing soil fertility. The absolute control, with an average nitrogen content of 185.80 kg/ha, demonstrated the lowest values, highlighting the importance of management practices in maintaining nitrogen availability in soils (Sharma *et al*., 2022) [15]. Phosphorus, T_6 (RPP + bentonite-S with Vegetable Special application) had the highest content, averaging 20.05 kg/ha, while T_5 was close behind at 19.92 kg/ha. The increase in phosphorus in T_6 is likely due to the combination of bentonite-S and Vegetable Special, which may aid phosphorus mineralization and solubility through enhanced microbial activity (Bhati *et al*., 2018) [9]. Sulfur from bentonite-S has been showed to positively influence soil structure and microbial communities, facilitating the release of phosphorus from organic and mineral complexes, while micronutrients like boron in T_5 may further support root development, enabling better phosphorus uptake from the soil (Singh *et al*., 1999) [16]. The absolute control, with an average of 14.48 kg/ha, showed the lowest phosphorus levels, illustrating the significant role of amendments in promoting phosphorus availability. Potassium, T_6 once again showed the highest values, averaging 411.18 kg/ha, followed by T_5 at 404.75 kg/ha. The elevated potassium levels in T_6 can be attributed to the improved soil structure from bentonite-S, which supports nutrient retention and enhances root access to soil potassium reserves (Gererufael *et al.*, 2020) [11]. Additionally, Vegetable Special likely contains nutrient-rich organic compounds that increase cation exchange capacity (CEC), essential for retaining potassium in soil and making it accessible to plants. The absolute control, with an average potassium content of 367.85 kg/ha, had the lowest potassium levels, emphasizing how nutrient management and organic amendments improve potassium availability. Micronutrients like boron also play a role in nutrient transport within the plant, which may further contribute to improved potassium utilization in treatments like T_6 and T_5 (Jawadagi *et al*., 2012) [12].

The data on exchangeable calcium, magnesium, and available sulfur (Table 3) for the years 2022 and 2023 reveal that T_6 (RPP + bentonite-S with sulfur and Vegetable Special) consistently achieved the highest values for these nutrients. T_6 recorded average calcium, magnesium, and sulfur levels of 31.27 cmol (p+) kg^{-1}, 15.78 cmol (p+) kg^{-1}, and 22.45 mg kg^{-1}, respectively. This performance can be attributed to bentonite-S high cation exchange capacity, which enhances nutrient retention and availability. Additionally, sulfur from bentonite-S not only supplies sulfur but also improves soil structure and facilitates microbial activity, which is critical for nutrient bioavailability (Singh *et al*., 1999) [16]. The organic amendments in Vegetable Special may further support nutrient cycling and microbial activity, providing essential nutrients through enhanced biochemical processes. Treatment T_5 (RPP + bentonite-S with micronutrients) also showed high levels for these nutrients, reflecting the benefits of combining bentonite-S with boron, zinc and iron, which together support nutrient uptake and physiological processes essential for plant growth (Shaheen *et al*., 2007; Yohannes *et al*., 2017) [14, 19]. The absence of such amendments in the absolute control (T_{13}), with consistently lower nutrient levels, highlights the importance of soil management in maintaining adequate nutrient availability and preventing leaching losses and reduced nutrient cycling.

The data on zinc, iron, manganese and copper concentrations (Tables 4 and 5) for 2022 and 2023 revealed significant variations across treatments, with T_6 (RPP + bentonite-S + Vegetable Special) consistently achieving the highest levels of these essential micronutrients. T_6 recorded the highest average zinc (0.68 mg kg^{-1}), iron (4.02 mg kg^{-1}), manganese (0.91 mg kg^{-1}), and copper (2.25 mg kg^{-1}) concentrations over the two years. This increase in micronutrient availability can be attributed to the role of bentonite-S in enhancing the soil cation exchange capacity, which facilitates nutrient retention and availability. Bentonite interactions with organic matter, especially through the application of Vegetable Special, likely improve soil structure and microbial activity, thus supporting the mobilization of these nutrients within the soil matrix (Barrales-Heredia *et al*., 2023) [8]. Zinc and iron are essential for enzymatic processes, protein synthesis and chlorophyll production, making them crucial for plant growth and resilience. Similarly, manganese and copper are vital co-factors in photosynthesis and oxidative stress responses, further enhancing plant vigor when present in adequate amounts (Kumar *et al*., 2021) [13]. Treatment T_5 (RPP + bentonite-S with additional micronutrients such as boron, zinc sulphate and ferrous sulphate) also recorded high levels of these nutrients, highlights the value of a multi-nutrient approach that can boost uptake and utilization efficiency, as seen in the synergistic effects of boron and manganese on nutrient mobilization (Al-Fraihat *et al.*, 2010) [3]. The absolute control (T_{13}) consistently recorded the lowest concentrations for these micronutrients, highlighting the adverse effects of nutrient deficiency on crop productivity and physiological health, including stunted growth, chlorosis and poor metabolic function.

Table 1: Effect of ICM practices with different levels of conventional and Nano fertilizers on pH, Electrical Conductivity (dS m-1) and Organic carbon (%) status of soil after the harvest of onion

Treatments	Details	pH			Electrical Conductivity (dS m^{-1})			Organic carbon (g kg^{-1})		
		2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled
T_1	Recommended Package of Practice (RPP)	8.14	8.16	8.15	0.41	0.41	0.41	0.48	0.49	0.49
T_2	T_1 + Bentonite-S (Sulphur, 50 kg S/ha)	7.83	7.90	7.86	0.38	0.39	0.38	0.49	0.50	0.50
T_3	T_2 + Boron @ 2. 5 kg/ha + ZnSO4 @ 25 kg/ha	7.95	7.98	7.97	0.38	0.45	0.41	0.49	0.50	0.49
T_4	T_2 + Boron @ 2. 5 kg/ha+ FeSO4 @ 25 kg/ha	7.99	8.04	8.02	0.39	0.39	0.39	0.50	0.51	0.51
T_5	T_2 + Boron @ 2. 5 kg/ha + ZnSO4 + FeSO4 each at 25 kg/ha	8.02	8.07	8.05	0.38	0.39	0.38	0.52	0.53	0.53
T_6	T_2 +Vegetable Special at 5 g per litter (Twice at 45 and 60 DAS)	7.98	8.04	8.01	0.37	0.38	0.38	0.50	0.52	0.51
T_7	50% Recommended N P + 100% Recommended K and spray of Nano-Urea & DAP @ 4 ml/L, twice at 45 and 60 DAS)	8.13	8.16	8.15	0.37	0.37	0.37	0.49	0.50	0.49
T_8	T_7 + Bentonite-S (Sulphur, 50 kg S/ha)	8.00	8.07	8.03	0.37	0.37	0.37	0.47	0.49	0.48
T_9	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Zn at 2 ml per litter (Twice at 45 and 60 DAS)	8.08	8.10	8.09	0.39	0.40	0.39	0.49	0.51	0.50
T_{10}	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Fe at 2 ml per litter (Twice at 45 and 60 DAS)	8.09	8.09	8.09	0.45	0.44	0.45	0.48	0.49	0.49
T_{11}	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Zn & Fe each at 2 ml per liter (Twice at 45 and 60 DAS)	8.12	8.12	8.12	0.37	0.36	0.36	0.48	0.50	0.49
T_{12}	T_8 +Vegetable Special at 5 g per litter (Twice at 45 & 60 DAS)	7.95	8.00	7.98	0.39	0.41	0.40	0.48	0.50	0.49
T_{13}	Absolute control	8.22	8.21	8.22	0.45	0.46	0.46	0.44	0.41	0.43
	Mean	8.04	8.07	8.06	0.39	0.40	0.40	0.49	0.50	0.49
	S.Em ±	0.40	0.38	0.29	0.02	0.02	0.02	0.02	0.02	0.02
	CD @ 5%	NS	NS	NS	0.05	0.05	0.05	NS	NS	NS

Table 2: Effect of ICM practices with different levels of conventional and Nano fertilizers on available major nutrient (Nitrogen, Phosphorus and Potassium) (kg ha^{-1}) status of soil after the harvest of onion

Treatments	Details	Available Nitrogen (kg ha^{-1})			Available Phosphorus (kg ha^{-1})			Available Potassium (kg ha^{-1})		
		2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled
T_1	Recommended Package of Practice (RPP)	218.83	221.10	219.97	17.33	17.73	17.53	374.93	377.00	375.97
T_2	T_1 + Bentonite-S (Sulphur, 50 kg S/ha)	222.73	224.23	223.48	17.67	17.93	17.80	386.43	388.13	387.28
T_3	T_2 + Boron @ 2. 5 kg/ha + ZnSO4 @ 25 kg/ha	223.83	225.33	224.58	18.83	19.03	18.93	386.70	386.03	386.37
T_4	T_2 + Boron @ 2. 5 kg/ha+ FeSO4 @ 25 kg/ha	231.07	232.33	231.70	18.50	19.20	18.85	390.50	391.90	391.20
T_5	T_2 + Boron @ 2. 5 kg/ha + ZnSO4 + FeSO4 each at 25 kg/ha	232.37	233.20	232.78	19.53	20.30	19.92	404.23	405.27	404.75
T_6	T_2 +Vegetable Special at 5 g per litter (Twice at 45 and 60 DAS)	223.00	224.17	223.58	19.63	20.47	20.05	410.37	412.00	411.18
T_7	50% Recommended N P + 100% Recommended K and spray of Nano-Urea & DAP @ 4 ml/L, twice at 45 and 60 DAS)	200.47	201.47	200.97	15.67	16.23	15.95	362.70	363.93	363.32
T_8	T_7 + Bentonite-S (Sulphur, 50 kg S/ha)	203.03	204.17	203.60	15.97	17.00	16.48	362.20	363.07	362.63
T_9	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Zn at 2 ml per litter (Twice at 45 and 60 DAS)	204.37	205.47	204.92	16.63	17.47	17.05	367.23	369.07	368.15
T_{10}	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Fe at 2 ml per litter (Twice at 45 and 60 DAS)	209.43	210.23	209.83	17.43	17.93	17.68	379.27	379.70	379.48
T_{11}	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Zn & Fe each at 2 ml per liter (Twice at 45 and 60 DAS)	210.77	212.07	211.42	16.97	17.43	17.20	377.17	379.30	378.23
T_{12}	T_8 +Vegetable Special at 5 g per litter (Twice at 45 & 60 DAS)	215.60	216.70	216.15	17.50	18.03	17.77	378.03	379.07	378.55
T_{13}	Absolute control	189.93	181.67	185.80	14.57	14.40	14.48	370.70	365.00	367.85
	Mean	214.26	214.78	214.52	17.40	17.94	17.67	380.81	381.50	381.15
	S.Em ±	8.50	8.87	8.03	0.99	1.09	0.99	15.61	16.33	15.47
	CD @ 5%	24.82	25.90	23.43	2.89	3.18	2.89	NS	NS	NS

Table 3: Effect of ICM practices with different levels of conventional and Nano fertilizers on secondary nutrients (Exchangeable Calcium, Magnesium (c mol (p^+) kg^{-1}) and Available Sulphur (mg kg^{-1}) status of soil after the harvest of onion

Treatments	Details	Ex. Calcium (c mol (p^+) kg^{-1})			Ex. Magnesium (c mol (p^+) kg^{-1})			Available Sulphur (mg kg^{-1})		
		2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled
T_1	Recommended Package of Practice (RPP)	27.53	28.60	28.07	13.00	13.43	13.22	17.37	17.87	17.62
T_2	T_1 + Bentonite-S (Sulphur, 50 kg S/ha)	27.50	28.57	28.03	13.90	14.63	14.27	20.13	20.97	20.55
T_3	T_2 + Boron @ 2. 5 kg/ha + ZnSO4 @ 25 kg/ha	28.50	29.50	29.00	14.03	14.30	14.17	21.07	21.83	21.45
T_4	T_2 + Boron @ 2. 5 kg/ha+ FeSO4 @ 25 kg/ha	28.60	29.67	29.13	14.00	15.47	14.73	21.53	22.10	21.82
T_5	T_2 + Boron @ 2. 5 kg/ha + ZnSO4 + FeSO4 each at 25 kg/ha	28.97	30.20	29.58	15.10	15.70	15.40	21.83	22.47	22.15
T_6	T_2 +Vegetable Special at 5 g per litter (Twice at 45 and 60 DAS)	30.87	31.67	31.27	15.43	16.13	15.78	22.07	22.83	22.45
T_7	50% Recommended N P + 100% Recommended K and spray of Nano-Urea & DAP @ 4 ml/L, twice at 45 and 60 DAS)	26.27	27.27	26.77	12.93	13.57	13.25	19.40	20.40	19.90
T_8	T_7 + Bentonite-S (Sulphur, 50 kg S/ha)	27.27	27.77	27.52	13.27	14.23	13.75	19.70	20.87	20.28
T_9	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Zn at 2 ml per litter (Twice at 45 and 60 DAS)	27.60	28.53	28.07	13.20	13.77	13.48	20.07	21.33	20.70
T_{10}	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Fe at 2 ml per litter (Twice at 45 and 60 DAS)	27.70	29.00	28.35	13.67	14.30	13.98	19.23	19.93	19.58
T_{11}	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Zn & Fe each at 2 ml per liter (Twice at 45 and 60 DAS)	26.40	27.27	26.83	13.20	13.97	13.58	19.70	20.83	20.27
T_{12}	T_8 +Vegetable Special at 5 g per litter (Twice at 45 & 60 DAS)	27.73	28.27	28.00	13.67	14.67	14.17	20.07	21.03	20.55
T_{13}	Absolute control	20.47	17.53	19.00	10.63	9.83	10.23	14.97	14.50	14.73
	Mean	27.34	27.99	27.66	13.54	14.15	13.85	19.78	20.54	20.16
	S.Em ±	1.92	1.98	1.94	1.08	1.16	1.07	1.39	1.47	1.41
	CD @ 5%	NS	5.79	NS	NS	NS	NS	NS	NS	NS

Table 4: Effect of ICM practices with different levels of conventional and Nano fertilizers on DTPA extractable micronutrient (Zinc and Iron) (mg kg^{-1}) status of soil after the harvest of onion

Treatments	Details	Zinc (mg kg^{-1})			Iron (mg kg^{-1})		
		2022	2023	Pooled	2022	2023	Pooled
T_1	Recommended Package of Practice (RPP)	0.58	0.60	0.59	3.67	3.68	3.68
T_2	T_1 + Bentonite-S (Sulphur, 50 kg S/ha)	0.59	0.62	0.61	3.80	3.89	3.85
T_3	T_2 + Boron @ 2. 5 kg/ha + ZnSO4 @ 25 kg/ha	0.60	0.62	0.61	3.85	3.89	3.87
T_4	T_2 + Boron @ 2. 5 kg/ha+ FeSO4 @ 25 kg/ha	0.62	0.64	0.63	3.87	3.93	3.90
T_5	T_2 + Boron @ 2. 5 kg/ha + ZnSO4 + FeSO4 each at 25 kg/ha	0.67	0.68	0.68	3.88	3.96	3.92
T_6	T_2 +Vegetable Special at 5 g per litter (Twice at 45 and 60 DAS)	0.67	0.69	0.68	4.00	4.04	4.02
T_7	50% Recommended N P + 100% Recommended K and spray of Nano-Urea & DAP @ 4 ml/L, twice at 45 and 60 DAS)	0.55	0.56	0.56	3.57	3.60	3.59
T_8	T_7 + Bentonite-S (Sulphur, 50 kg S/ha)	0.55	0.56	0.56	3.61	3.69	3.65
T_9	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Zn at 2 ml per litter (Twice at 45 and 60 DAS)	0.57	0.59	0.58	3.62	3.67	3.65
T_{10}	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Fe at 2 ml per litter (Twice at 45 and 60 DAS)	0.57	0.59	0.58	3.63	3.70	3.67
T_{11}	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Zn & Fe each at 2 ml per liter (Twice at 45 and 60 DAS)	0.58	0.59	0.59	3.65	3.71	3.68
T_{12}	T_8 +Vegetable Special at 5 g per litter (Twice at 45 & 60 DAS)	0.60	0.61	0.60	3.49	3.55	3.52
T_{13}	Absolute control	0.50	0.48	0.49	2.52	2.37	2.45
	Mean	0.59	0.60	0.60	3.63	3.67	3.65
	S.Em ±	0.03	0.04	0.03	0.18	0.19	0.17
	CD @ 5%	0.08	0.11	0.09	0.52	0.56	0.50

Table 5: Effect of ICM practices with different levels of conventional and Nano fertilizers on DTPA extractable micronutrient (Manganese and Copper) (mg kg^{-1}) status of soil after the harvest of onion

Treatments	Details	Manganese (mg kg^{-1})			Copper (mg kg^{-1})		
		2022	2023	Pooled	2022	2023	Pooled
T_1	Recommended Package of Practice (RPP)	0.83	0.84	0.84	1.77	1.79	1.78
T_2	T_1 + Bentonite-S (Sulphur, 50 kg S/ha)	0.85	0.87	0.86	1.63	1.67	1.65
T_3	T_2 + Boron @ 2. 5 kg/ha + ZnSO4 @ 25 kg/ha	0.87	0.90	0.89	1.65	1.71	1.68
T_4	T_2 + Boron @ 2. 5 kg/ha+ FeSO4 @ 25 kg/ha	0.88	0.90	0.89	1.79	1.88	1.84
T_5	T_2 + Boron @ 2. 5 kg/ha + ZnSO4 + FeSO4 each at 25 kg/ha	0.89	0.90	0.90	1.96	2.02	1.99
T_6	T_2 +Vegetable Special at 5 g per litter (Twice at 45 and 60 DAS)	0.90	0.91	0.91	2.22	2.29	2.25
T_7	50% Recommended N P + 100% Recommended K and spray of Nano-Urea & DAP @ 4 ml/L, twice at 45 and 60 DAS)	0.73	0.75	0.74	1.53	1.62	1.57
T_8	T_7 + Bentonite-S (Sulphur, 50 kg S/ha)	0.76	0.77	0.76	1.55	1.62	1.59
T_9	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Zn at 2 ml per litter (Twice at 45 and 60 DAS)	0.79	0.81	0.80	1.55	1.64	1.59
T_{10}	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Fe at 2 ml per litter (Twice at 45 and 60 DAS)	0.79	0.81	0.80	1.58	1.67	1.63
T_{11}	T_8 + Boron @ 2.5 kg/ha + Spray with Nano Zn & Fe each at 2 ml per liter (Twice at 45 and 60 DAS)	0.81	0.82	0.82	1.74	1.80	1.77
T_{12}	T_8 +Vegetable Special at 5 g per litter (Twice at 45 & 60 DAS)	0.89	0.90	0.89	1.81	1.89	1.85
T_{13}	Absolute control	0.55	0.54	0.55	1.24	1.18	1.21
	Mean	0.81	0.83	0.82	1.69	1.75	1.72
	S.Em ±	0.06	0.06	0.06	0.12	0.12	0.12
	CD @ 5%	0.17	0.16	0.17	0.35	0.36	0.35

Conclusion

The incorporation of bentonite-S, Vegetable Special and strategic micronutrient applications significantly improve soil health and nutrient availability, enhancing crop productivity compared to the absolute control (T_{13}). Among the treatments, T_6 (RPP + bentonite-S + Vegetable Special) consistently performed best across key metrics, including soil pH, EC, OC and levels of essential macro- and micronutrients. This treatment beneficial effect is likely due to the high cation exchange capacity (CEC) of bentonite-S, which supports nutrient retention and the gradual release of sulfur, thereby lowering soil pH and enhancing nutrient bioavailability. The addition of organic inputs like Vegetable Special also stimulates microbial activity, which aids in nutrient cycling, soil structure improvement and the solubilization of phosphorus and micronutrients. High concentrations of nitrogen, phosphorus, potassium and essential micronutrients (zinc, iron, manganese and copper) in T_6 emphasise the effectiveness of integrated nutrient management in promoting optimal plant growth. T_5 (RPP + bentonite-S with additional micronutrients) also showed favorable results, highlighting the importance of a multi-nutrient approach. The study highlights that nutrient-enriched amendments and sulfur-based treatments can address nutrient limitations, enhance soil organic matter, and improve the bioavailability of critical micronutrients, providing a sustainable approach to enhancing soil fertility and agricultural productivity in onion cultivation.

Conflict of Interest

The authors declare no conflict of interest

Reference

1. Abbey L, Kanton R. Fertilizer type, but not time of cessation of irrigation, affect onion development and yield in semi-arid region. Journal of Vegetable Crop Production. 2003;9(2):41-48.
2. Abbey L, Joyce DC, Aked J, Smith B. Genotype, sulphur nutrition and soil type effect on growth and dry matter production of spring onion. Journal of Horticultural Science and Biotechnology. 2000;77(3):340-345.
3. Al-Fraihat AH. Effect of different nitrogen and sulphur fertilizer levels on growth, yield and quality of onion (*Allium cepa* L.). Jordan Journal of Agricultural Sciences. 2010;5:155-169.
4. Ayamba BE, Abaidoo RC, Opoku A, Ewusi-Mensah N. Mechanisms for nutrient interactions from organic amendments and mineral fertilizer inputs under cropping systems: A review. PeerJ. 2023;11(2):e15135.
5. Babajide PA, Olabode OS, Akanbi WB, Olatunji OO, Ewetola EA. Influence of composted *Tithonia*-biomass and N-mineral fertilizer on soil physico-chemical properties and performance of tomato (*Lycopersicon esculentum* Mill.). Research Journal of Agronomy. 2008;2(4):101-106.
6. Bairagi P, Yadav SR, Dinesh K. Response of onion (*Allium cepa* L.) to different levels of NPK and FYM under arid condition of Rajasthan. An Asian Journal of Soil Science. 2015;10(1):42-46.
7. Barakade AJ, Lokhande TN, Todkari GU. Economics of onion cultivation and its marketing pattern in Satara district of Maharashtra. International Journal of Agricultural Sciences. 2011;3(3):110-117.
8. Barrales-Heredia SM, Grimaldo-Juarez O, Suarez-Hernandez AM, Gonzalez-Vega RI, Diaz-Ramirez J, Garcia-Lope AM, *et al.* Effects of different irrigation regimes and nitrogen fertilization on the physicochemical and bioactive characteristics of onion (*Allium cepa* L.). Horticulturae. 2023;9:344-358.
9. Bhati V, Yadav PK, Kumar R. Effect of levels of inorganic fertilizers, organic manure and bio-fertilizers on plant growth attributes of onion (*Allium cepa* L.) cv. N-53 under hot arid region of western Rajasthan, India.

International Journal of Current Microbiology and Applied Sciences. 2018;7(2):3593-3601.

10. FAO. Food and Agriculture Organization of the United Nations, FAOSTAT Database [Internet]; 2022. Available from: https://www.fao.org/faostat/en/#data
11. Gererufael LA, Abraham NT, Reda TB. Growth and yield of onion (*Allium cepa* L.) as affected by farmyard manure and nitrogen fertilizer application in Tahtay Koraro District, Northwestern Zone of Tigray, Ethiopia. Vegetos. 2020;33:3617-3627.
12. Jawadagi RS, Jasavaraj N, Patil BN, Hemla NB, Channappagoudar BB. Effect of different sources of nutrients on growth, yield, and quality of onion cv. Bellary red. Karnataka Journal of Agricultural Sciences. 2012;25(2):232-235.
13. Kumar S, Kumar M, Kumar V. Effect of micronutrients on yield and quality of onion. The Pharma Innovation Journal. 2021;10(10):2261-2264.
14. Shaheen AM, Rizk FA, Singer SM. Growing onion plants without chemical fertilization. Research Journal of Agriculture and Biological Science. 2007;3(2):95-104.
15. Sharma GP, Dhaka RS, Shankar UT, Meena VS. Effect of nitrogen and sulphur levels on growth and yield of *Rabi* onion (*Allium cepa* L.). The Pharma Innovation Journal. 2022;11:5697-5701.
16. Singh T, Singh SB, Singh BN. Effect of nitrogen, potassium and green manuring on growth and yield of rainy season onion (*Allium cepa* L.). Narendra Deva Journal of Agricultural Research. 1999;4(1):57-60.
17. Tekalign AT, Pant LM. Growth, bulb yield and quality of onion (*Allium cepa* L.) as influenced by nitrogen and phosphorus fertilization on vertisol, growth attributes, biomass production and bulb yield. African Journal of Agricultural Research. 2011;6(14):3252-3258.
18. Thakur O, Kumar V. Review on impact of micronutrients (zinc and boron) in relation to growth, yield and quality of onion. International Journal of Current Microbiology and Applied Sciences. 2021;10(3):1733-1740.
19. Yohannes GK, Kebede W, Arvind C, Fikreyohannes G. Effect of integrated nutrient management on growth, bulb yield and storability of onion (*Allium cepa* L.) under irrigation at Selekeleka, Northern Ethiopia. International Journal of Life Sciences. 2017;5(2):151-160.
20. Jackson WA, Flesher D, Hageman RH. Nitrate uptake by dark-grown corn seedlings: some characteristics of apparent induction. Plant Physiology. 1973 Jan 1;51(1):120-127.
21. Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil science. 1934 Jan 1;37(1):29-38.
22. Gomez KA, Gomez AA. Statistical procedures for agricultural research. John wiley & sons; 1984 Feb 17.