



Impact of Foliar Application of Nano Nitrogen and Nano Zinc on Soil Properties of Mustard (*Brassica juncea* L.) Crop

Kriti Sharma^{a++*}, R. H. Meena^{a#}, Kishan Kumar^{a++},
Yash Vardhan Singh^{a++}, Pramod Kumar^{a++},
Deshraj Meena^{a++} and Hansa Kumawat^{a++}

^a Department of Soil Science and Agricultural Chemistry, Rajasthan College of Agriculture, MPUAT, Udaipur - 313001, Rajasthan, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The utilization of nano-sized nitrogen (N) and zinc (Zn) fertilizers through foliar application has gained considerable attention in agricultural research. This study focuses on investigating the effects of such foliar applications on soil properties, including both chemical and biological aspects, after the harvest of mustard (*Brassica juncea* L.). The field experiment was carried out during October to March 2022 season at Instructional Farm, Rajasthan College of Agriculture, MPUAT, Udaipur which lies in agro-climatic zone IV-A of Rajasthan, India. The field was designed in a

⁺⁺ Research Scholar;

[#] Professor;

*Corresponding author: E-mail: kritisharma101095@gmail.com;

randomized block design having 10 treatments which were replicated thrice. The treatments include the various combination RDF and nano fertilizers of N and Zn. The application treatment T₆ (100% NPK Zn +1st spray of Nano N and Zn at 30 DAS +2nd spray of Nano N and Zn at 45 DAS) has significantly increased the availability of macronutrients (N, P, K), micronutrients (Zn, Fe, Cu and Mn), microbial population (bacteria, fungi and actinomycetes) as well as the dehydrogenase and acid phosphatase enzyme activity in post-harvest soil of mustard over control.

Keywords: Foliar application; nano fertilizer; mustard; microbial population; enzyme activity.

1. INTRODUCTION

“Mustard (*Brassica juncea* L.) holds a remarkable historical significance as one of the oldest condiments, and its cultivation has been prevalent worldwide for thousands of years. The origins of mustard cultivation can be traced back to 3000 B.C. In India, mustard is the most important oilseed crop, ranking first in terms of cultivated area and second in production, trailing only China. The total area dedicated to rapeseed-mustard cultivation in India is approximately 5.98 million hectares, with a production of 8.32 million tonnes and a productivity of 1397 kg per hectare” [1]. “Oilseeds, including rapeseed-mustard, hold a significant share of 14.1 percent of the total cropped area of the country. Specifically, rapeseed-mustard alone occupies 3 percent of the total cropped area. Among the seven edible oilseeds cultivated in India, mustard is the principal edible oilseed crop, contributing 28.6 percent to the overall oilseed production. It stands as the second-largest oilseed crop in the country, following groundnut, which accounts for 27.8 percent of India's oilseed economy. The cultivation of mustard is primarily concentrated in states such as Rajasthan, Uttar Pradesh, Haryana, Madhya Pradesh, Gujarat, and certain non-traditional regions in southern India. These regions play a vital role in mustard production and contribute significantly to the overall oilseed sector in the country” [2].

“Nitrogen plays a vital role in plant growth and development, making it an essential nutrient for plants. It is an integral component of amino acids, proteins, chlorophyll, and nucleic acids, which are crucial for various metabolic processes. Nitrogen availability in the soil greatly influences plant productivity and overall crop yield” [3]. In Indian soil, nitrogen holds significant importance due to its impact on agricultural sustainability and food security. However, many Indian soils are inherently low in nitrogen content, necessitating external nitrogen inputs through fertilizers to meet the demands of high-

yielding crop varieties. The efficient management of nitrogen is crucial to optimize crop production while minimizing environmental impacts such as nitrate leaching and greenhouse gas emissions [4]. Nitrogen is a critical element that significantly influences agricultural production on a global scale. Despite numerous efforts, the efficiency of nitrogen use (NUE) in agriculture remains relatively low, typically falling below 50%. Among all mineral nutrients, nitrogen stands out as the foremost requirement for crop plants. It serves as a vital component of chlorophyll, proteins, and enzymes, playing a pivotal role in promoting vegetative growth in crops. Unfortunately, nitrogen losses occur through various processes, including nitrate leaching, denitrification, and ammonia volatilization. These losses not only result in economic losses but also raise concerns regarding environmental pollution. The loss of mineral nutrients through leaching and runoff, coupled with significant volatilization, is particularly alarming. Furthermore, nitrogen volatilization leads to the release of nitrous oxides, contributing to the greenhouse effect and global warming. It is disheartening to observe that modern profit-driven farming systems exhibit nitrogenous fertilizer use efficiency of only 45-50%, highlighting the need for improved practices and sustainable approaches in nitrogen management [5].

Zinc is recognized as the fourth most crucial nutrient that limits crop yield, following nitrogen, phosphorus, and potassium, both globally and in Indian soils [6]. It has been estimated that approximately 36.5% of Indian soils suffer from zinc deficiency [7]. Zinc is an essential micronutrient for crop nutrition as it plays a pivotal role in various metabolic processes, including the synthesis and degradation of carbohydrates, nucleic acids, lipids, and proteins. It serves as a fundamental component of nearly 200 enzymes in plants. Additionally, zinc is involved in the synthesis of Indole Acetic Acid (IAA), a phytohormone that exerts significant control over plant growth, chlorophyll synthesis, pollen formation, and tolerance to environmental

stress. Moreover, zinc influences water uptake and transport within the plant. Given its multifaceted roles, ensuring an adequate supply of zinc is critical for optimizing plant growth and development, enhancing crop productivity, and mitigating the effects of environmental stressors.

Foliar application is a technique that involves the direct spraying of liquid fertilizers onto plant leaves, enabling better absorption in the aerial parts [8 and 9]. This method has proven to be more effective than soil fertilizer application, particularly under conditions of drought and salinity. The foliar application allows nutrients to be supplied directly to the leaves, facilitating rapid absorption. It is independent of root activity and the availability of soil water [10]. When it comes to grain crops, such as wheat, the application of foliar nano zinc, copper, and iron fertilizers has been shown to enhance growth parameters when compared to other fertilizer sources [11].

Nano fertilizers have emerged as a promising approach to promoting plant growth and enhancing crop production. These fertilizers deliver essential nutrients in nano form, offering advantages such as high fertilizers use efficiency, ultrahigh absorption due to their small size, and the ability to minimize negative effects associated with over-dosage. By utilizing nano fertilizers, the frequency of fertilizer application can be reduced, leading to cost savings. Additionally, the decline in environmental protection costs further contributes to their cost-effectiveness. Moreover, nano fertilizers help maintain soil fertility and health, making them an eco-friendly alternative to conventional fertilizers. They hold great potential for sustainable agriculture and the production of high-quality food, while minimizing adverse impacts on human health and the environment [12]. Nano fertilizers are a cutting-edge innovation in the field of agriculture and have shown great promise in revolutionizing crop production and sustainable agriculture practices. These fertilizers are designed to deliver essential nutrients to plants in the form of nanoparticles. Their small size grants them several advantages over traditional fertilizers, making them a potential solution to many challenges faced in modern farming [13 and 14]. Another significant advantage of using nano fertilizers is their positive impact on soil health and fertility. Conventional fertilizers can sometimes degrade soil quality over time, leading to issues like soil compaction, decreased microbial activity,

and nutrient depletion. In contrast, nano fertilizers can improve soil structure and promote beneficial microbial activity, fostering a healthier soil ecosystem. This, in turn, contributes to long-term sustainable agriculture by ensuring the soil's ability to support continuous crop growth [15].

Given the challenges posed by a growing population and increasing food demand within limited land resources, improving nutrient use efficiency and adopting innovative technologies are crucial for ensuring food availability [16]. Nano-fertilizers offer a controlled and targeted release of nutrients into the soil, minimizing nutrient losses and soil toxicity. By utilizing nano-fertilizers, the sustainability and protection of agriculturally produced food can be maintained while reducing environmental impacts [17]. The application of nano-fertilizers provides an opportunity to address the challenges of agricultural productivity, food security, and environmental sustainability in a more efficient and responsible manner.

In light of the aforementioned information, the current study was conducted to assess the effects of foliar applications of nano nitrogen- and zinc on soil properties after the harvest of mustard crop in the sub-humid southern plains of Rajasthan.

2. MATERIALS AND METHODS

2.1 Study Area

The experiment was conducted during rabi 2021-22 at the Instructional Farm, Rajasthan College of Agriculture, Udaipur. The region falls under the agro-climatic zone-IVA (Sub-humid Southern Plains and Aravalli Hills) of Rajasthan. The climate of the study area is sub-humid with an average minimum and maximum temperature (October-February) ranging between 3.2° to 30.4°C.

To ascertain the physico-chemical characteristics of the experimental field, soil samples up to 0-15 cm depth were drawn from different spots of the field and a representative composite sample was prepared by mixing, which was subjected to mechanical, physical, chemical and biological analysis using standard methods. Table 1 presents the results of the soil analysis along with the protocol used. The data indicate that the soil of the experimental site was clay loam, neutral alkaline in reaction, medium in available

nitrogen and phosphorus and high in available potassium and sufficient in DTPA extractable micronutrients.

2.2 Experimental Design and Treatments

The experiment was laid out in a randomized block design with three replications. The gross plot size was 15 m² (5 x 3 m). The experiment consisted of ten treatments viz., T₁ (Control), T₂ (100% NPK Zn), T₃ (75% N Zn + 100 % PK), T₄ (50% N Zn + 100 % PK), T₅ (T₂+1st spray of Nano N and Zn at 30 DAS), T₆ (100% NPK Zn +1st spray of Nano N and Zn at 30 DAS +2nd spray of Nano N and Zn at 45 DAS), T₇ (75% N Zn + 100 % PK +1st spray of Nano N and Zn at 30 DAS), T₈ (75% N Zn + 100 % PK +1st spray of Nano N and Zn at 30 DAS +2nd spray of Nano N and Zn at 45 DAS), T₉ (50% N Zn + 100 % PK +1st spray of Nano N and Zn at 30 DAS), T₁₀ (50% N Zn + 100 % PK +1st spray of Nano N and Zn at 30 DAS +2nd spray of Nano N and Zn at 45 DAS) was applied to mustard var. Giriraj (DRMRIJ 31) in *rabi* session, 2021-22. In accordance with the recommended practices outlined in the Package of Practices by the Government of Rajasthan, the fertilizer application was carried out using the recommended dosage. For the specified area, the recommended fertilizer doses were 60 kg of nitrogen (N), 40 kg of phosphorus pentoxide (P₂O₅), 40 kg of potassium oxide (K₂O), and 5 kg of zinc sulfate (ZnSO₄) per hectare (ha). These doses were applied to meet the nutrient requirements of the crops effectively.

2.3 Application Protocol of Foliar Spray

The foliar sprays were administered in the selected treatments by utilizing a knapsack sprayer equipped with a flat fan nozzle. The application schedule involved two sprays: the first spray was applied 30 days after sowing, while the second spray was administered at 45 days after sowing. For the specified treatments, the foliar spray consisted of Nano N at a rate of 4 ml per liter of water, while Nano Zn was applied at a rate of 2 ml per liter of water. The sprays were applied according to the predetermined treatment schedule.

2.4 Soil Chemical Properties

To assess the fertility status of soil, the soil sample (0-15 cm depth) from each plot at harvest of the crop was taken. The samples were passed

through a 2 mm plastic sieve to avoid metallic contamination. The soil sample was analyzed for available N, P, K and available micronutrients (Zn, Fe, Mn and Cu) as per the method given below.

Chemical determinations		
(a)	Available nitrogen	By alkaline permanganate method [21]
(b)	Available Phosphorus	Extraction of soil with 0.5 M NaHCO ₃ at pH 8.5 and development of blue colour with SnCl ₂ and measurement through colorimetrically [22]
(c)	Available potassium	Extraction was done with 1 N neutral ammonium acetate at pH 7.0 and determined by flame photometer [23]
(d)	Available Zn, Fe, Mn and Cu	Analysis of suitable aliquot of DTPA extract with the help of atomic absorption spectrophotometer (Varian techtron AAS-120) [24]

2.5 Soil Microbial Properties

“Soil samples (0-15 cm depth) were collected at harvest of the crop from each treatment plot for analysis. The samples were stored in plastic bags and taken to the laboratory, where the soil was sieved (2 mm mesh size), homogenized and stored at 4°C. The fungal, bacterial and actinomycetes populations was estimated by standard plate count method using Marten’s for fungi” [29], and “nutrient agar medium for bacteria and actinomycetes” [27]. The microbial population was calculated and expressed as a number of cells per gram of soil. Dehydrogenase enzyme activity in soil was evaluated by Anthrone extraction method [30]. Acid phosphatase activity in soil was determined by β-nitrophenol phosphate by spectrophotometry method [31].

2.6 Statistical Analysis

The statistical analysis of the obtained data was conducted using the analysis of variance (ANOVA) techniques, following the methodology outlined by Steel and Torrie [32]. To compare the treatment means, the critical difference (CD) test was employed at a significance level of 5% (P=0.05). The critical difference test helps determine the minimum significant difference between treatment means that indicates a statistically significant variation.

Table 1. Mechanical, physic-chemical and biological properties of soil of the experimental field

Characteristics	Value	Method of analysis	Reference	
A. Mechanical composition				
Sand (%)	38.25%	By International Pipette Method	Bouyoucos [18]	
Silt (%)	26.94%			
Clay (%)	34.47%			
Soil texture	Clay loam		Piper [19]	
B. Physical properties				
Bulk density (Mg m^{-3})	1.29	Core sampler method	Piper [19]	
Particle density (Mg m^{-3})	2.54		Black [20]	
Porosity (%)	49.21			
C. Chemical properties				
Available N (kg ha^{-1})	250.13	Alkaline KMnO_4 method	Subbiah and Asija [21]	
Available P_2O_5 (kg ha^{-1})	26.05	Olsen's method	Olsen et al. [22]	
Available K_2O (kg ha^{-1})	415.04	Flame photometer	Jackson [23]	
Available Zn (mg kg^{-1})	0.52	DTPA-extract with AAS	Lindsay and Norvell [24]	
Available Fe (mg kg^{-1})	3.96			
Available Mn (mg kg^{-1})	8.70			
Available Cu (mg kg^{-1})	1.42			
Organic carbon (%)	0.52		Walkley and Black's rapid titration method	Walkley and Black [25]
Electric Conductivity (dS m^{-1} at 25°C)	0.78		Using saltbridge	Richards [26]
pH (1:2 soil water suspension)	8.3	Glass electrode pH meter	Richards [26]	
D. Biological properties				
Bacterial population (cfu g^{-1} soil)	49.30×10^7	Standard serial dilution and plate count method	Allen [27]	
Fungal population (cfu g^{-1} soil)	20.56×10^4			
Actinomycetes population (cfu g^{-1} soil)	30.12×10^6			
Microbial biomass carbon (mg kg^{-1})	340 mg kg^{-1}	An extraction method for measuring soil microbial biomass carbon	Vance et al. [28]	

3. RESULTS AND DISCUSSION

3.1 Chemical Properties

The application of foliar spray consisting of nano-sized nitrogen and zinc fertilizers has been found to have a significant impact on increasing the availability of nutrients such as nitrogen (N), phosphorus (P), potassium (K), zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) in the soil after the mustard crop is harvested. This information is presented in Table 2 and Table 3. Maximum available nutrient content in soil was observed under treatment T_6 (100% NPK Zn +1st spray of Nano N and Zn at 30 DAS +2nd spray of Nano N and Zn at 45 DAS) which was statistically at par with T_8 (75% N Zn + 100 % PK +1st spray of Nano N and Zn at 30 DAS +2nd spray of Nano N and Zn at 45 DAS) as compared to control. Nano-scale particles have a

significantly larger surface area compared to their bulk counterparts. This increased surface area allows for greater interaction with soil particles and enhances the contact between the nanoparticles and soil nutrients. As a result, the release and availability of nutrients in the soil can be improved. Nano-scale particles can exhibit unique chemical properties compared to bulk materials [33]. Nano nitrogen and nano zinc particles can increase the solubility of nitrogen and zinc, respectively, in the soil. This increased solubility promotes the release of these nutrients, making them more accessible to plants and microorganisms [34]. Nano nitrogen and nano zinc can interact with organic matter in the soil, such as humic and fulvic acids. These interactions can promote the decomposition of organic matter, thereby releasing bound nutrients and making them available to plants [35]. The increased availability of nutrients can be

attributed to the unique properties of nano-sized nitrogen and zinc particles. These particles have a significantly larger surface area, allowing for enhanced absorption and utilization by plant roots. The foliar spray application facilitates direct contact between the nanoparticles and the plant surfaces, promoting efficient nutrient uptake [36]. According to Abdelsalam *et al.* [37], their study on soybean demonstrated that the utilization of nano-sized nitrogen and zinc can enhance the efficiency of nutrient uptake in plants. These nanoparticles can increase the accessibility and availability of nutrients to plant roots, thereby improving nutrient absorption and utilization throughout the crop growth cycle. Consequently, this improved nutrient uptake can contribute to higher levels of nutrient content remaining in the soil following harvest. Abdel-Aziz *et al.* [38] conducted a study that yielded similar findings, supporting the notion that foliar spray application of NPK (nitrogen, phosphorus, and potassium) can enhance the availability of nitrogen, potassium, and micronutrients. This improvement can be attributed to the ability of nano particles to facilitate the release of nutrients from organic matter or mineral compounds present in the soil. The enhanced release of nutrients contributes to a greater availability of nutrients for uptake by plants, ultimately resulting in higher nutrient content in the soil following harvest. Johnson *et al.* [39] demonstrated that nano fertilizers, through their slow-release mechanism, have the capacity to improve the nutrient status of the soil. This enhancement is achieved by minimizing nutrient losses due to leaching, fixation, atmospheric losses, and microbial conversion.

3.2 Biological Properties

Foliar application of nano nitrogen and nano zinc significantly increased the soil microbial population (bacteria, fungi and actinomycetes) in the soil after the mustard harvest (Table 4). The maximum microbiological population of bacteria (60.00×10^7 cfu g^{-1} of soil), fungi (26.67×10^5 cfu g^{-1} of soil) and actinomycetes (34.97×10^6 cfu g^{-1} of soil) were found under treatment T₆ (100% NPK Zn +1st spray of Nano N and Zn at 30 DAS +2nd spray of Nano N and Zn at 45 DAS). "Nano-fertilizers stimulated the growth of microbes by providing nutrients in available soluble forms and directly increased the population. Nano-fertilizers stimulated the growth of microbes by providing nutrients in available soluble forms and directly increased the population. The application of nano-fertilizers

appears to be safer and due to proper availability of nutrients improved both plant and microbial biomass. Microbial activity of a soil system is affected by anthropogenic activities such as indiscriminate use of chemical. The microbial population decreases with an increase in levels of contaminants" [40]. "The enhancement in microbial population and activity in rhizosphere may also enhance nutrient mobilization and availability of nutrients for plant uptake" [41]. A similar result was shown by Meena *et al.* [42] that "a significant maximum microbial count of bacteria (78.54×10^6), fungi (34.25×10^4), and microbial biomass-C ($259.33 \text{ mg kg}^{-1}$) was obtained under foliar application of nano nutrients". According to Nibin *et al.* [43] research, nano NPK was applied foliarly to bhindi, which increased the microbial population's activity. According to Rajput *et al.* [44], nano fertilizers improved the amount of accessible nutrients and microbial population in soil following crop harvest. According to the findings of Hu *et al.* [45], the application of nano-sized zinc and nitrogen has been shown to have a significant impact on plant health and growth. This improved plant health can result in the secretion of root exudates and increased organic matter production, which serve as a food source for soil microbes. The enhanced plant growth resulting from the application of nanomaterials can indirectly contribute to the proliferation of microbial populations by creating a more favorable environment for microbial colonization and activity.

The application of foliar spray of nano-fertilizer significantly influenced the dehydrogenase activity and acid phosphatase activity in the soil after the harvest of the mustard crop (Table 5). The significant maximum dehydrogenase activity ($20.83 \mu\text{g TPF g}^{-1} 24\text{h}^{-1}$ soil) and acid phosphatase activity ($11.91 \mu\text{g PNP g}^{-1} \text{h}^{-1}$ soil) in the soil after harvest was found under treatment T₆ (100% NPK Zn +1st spray of Nano N and Zn at 30 DAS +2nd spray of Nano N and Zn at 45 DAS). Arif *et al.* [46] found that increased microbial population activity has a direct positive impact on the activity of soil enzymes. The presence of nano-scale particles can stimulate the growth and activity of soil microbial populations, subsequently leading to elevated enzyme activity. Dehydrogenase and acid phosphatase enzymes, which play crucial roles in soil processes, are primarily produced by microbes. The application of nanomaterials creates a more conducive environment for microbial growth, thus promoting higher enzyme

Table 2. Effect of foliar application of nano nitrogen and nano zinc on available N, P and K in soil after harvest of mustard

Treatments	Available nitrogen (kg ha⁻¹)	Available phosphorus (kg ha⁻¹)	Available potassium (kg ha⁻¹)
T ₁ : Control	245.33	17.88	265.57
T ₂ : 100% NPK Zn	410.22	28.22	443.75
T ₃ : 75% N Zn + 100% PK	364.34	26.00	393.25
T ₄ : 50% N Zn + 100% PK	321.99	22.18	391.30
T ₅ : 100% NPK Zn +1 st spray of Nano N and Zn at 30 DAS	457.55	30.16	463.11
T ₆ : 100% NPK Zn +1 st spray of Nano N and Zn at 30 DAS +2 nd spray of Nano N and Zn at 45 DAS	466.99	30.18	465.00
T ₇ : 75% N Zn + 100% PK +1 st spray of Nano N and Zn at 30 DAS	450.25	29.80	461.81
T ₈ : 75% N Zn + 100% PK +1 st spray of Nano N and Zn at 30 DAS +2 nd spray of Nano N and Zn at 45 DAS	458.00	30.12	463.20
T ₉ : 50% N Zn + 100% PK +1 st spray of Nano N and Zn at 30 DAS	425.68	29.74	458.00
T ₁₀ : 50% N Zn + 100% PK +1 st spray of Nano N and Zn at 30 DAS +2 nd spray of Nano N and Zn at 45 DAS	433.00	29.88	459.61
SEm±	5.207	0.519	6.524
CD (P =0.05)	15.471	1.542	19.383

Table 3. Effect of foliar application of nano nitrogen and nano zinc on available micronutrients in soil after harvest of mustard

Treatments		Available micronutrients (mg kg ⁻¹)			
		Zinc	Iron	Manganese	Copper
T ₁	: Control	2.18	4.02	9.02	1.86
T ₂	: 100% NPK Zn	3.64	4.41	9.89	1.92
T ₃	: 75% N Zn + 100% PK	3.22	4.21	9.23	1.98
T ₄	: 50% N Zn + 100% PK	2.89	4.15	9.10	2.00
T ₅	: 100% NPK Zn +1 st spray of Nano N and Zn at 30 DAS	4.07	4.22	10.02	2.26
T ₆	: 100% NPK Zn +1 st spray of Nano N and Zn at 30 DAS +2 nd spray of Nano N and Zn at 45 DAS	4.18	5.62	10.22	2.20
T ₇	: 75% N Zn + 100% PK +1 st spray of Nano N and Zn at 30 DAS	4.07	5.21	10.01	2.10
T ₈	: 75% N Zn + 100% PK +1 st spray of Nano N and Zn at 30 DAS +2 nd spray of Nano N and Zn at 45 DAS	4.09	5.02	10.25	2.17
T ₉	: 50% N Zn + 100% PK +1 st spray of Nano N and Zn at 30 DAS	3.86	4.27	10.00	2.03
T ₁₀	: 50% N Zn + 100% PK +1 st spray of Nano N and Zn at 30 DAS +2 nd spray of Nano N and Zn at 45 DAS	3.86	4.52	9.98	2.05
SEm±		0.04	0.05	0.12	0.02
CD(P= 0.05)		0.12	0.17	0.37	0.06

Table 4. Effect of foliar application of nano nitrogen and nano zinc on soil microbial population at harvest of mustard

Treatments		Microbial population (cfu g ⁻¹ of soil)		
		Bacteria (1 × 10 ⁷)	Fungi (1 × 10 ⁵)	Actinomycetes (1 × 10 ⁶)
T ₁	: Control	53.93	23.06	31.48
T ₂	: 100% NPK Zn	58.11	24.63	32.67
T ₃	: 75% N Zn + 100 % PK	58.67	24.90	32.92
T ₄	: 50% N Zn + 100 % PK	59.42	25.00	34.01
T ₅	: 100% NPK Zn +1 st spray of Nano N and Zn at 30 DAS	59.62	25.20	34.69
T ₆	: 100% NPK Zn +1 st spray of Nano N and Zn at 30 DAS +2 nd spray of Nano N and Zn at 45 DAS	60.00	26.17	34.97
T ₇	: 75% N Zn + 100 % PK +1 st spray of Nano N and Zn at 30 DAS	59.40	24.11	33.68
T ₈	: 75% N Zn + 100 % PK +1 st spray of Nano N and Zn at 30 DAS +2 nd spray of Nano N and Zn at 45 DAS	59.22	24.19	33.92
T ₉	: 50% N Zn + 100 % PK +1 st spray of Nano N and Zn at 30 DAS	58.10	23.92	33.85
T ₁₀	: 50% N Zn + 100 % PK +1 st spray of Nano N and Zn at 30 DAS +2 nd spray of Nano N and Zn at 45 DAS	58.94	23.98	33.99
SEm±		0.608	0.225	0.608
CD(P= 0.05)		1.807	0.669	1.807

Table 5. Effect of foliar application of nano nitrogen and nano zinc on soil enzymic activity at harvest of mustard

Treatments		Dehydrogenase ($\mu\text{g TPF g}^{-1}$ $24 \text{ h}^{-1} \text{ soil}$)	Acid phosphatase ($\mu\text{g of PNP}$ $\text{g}^{-1} \text{ h}^{-1} \text{ soil}$)
T ₁	: Control	19.30	9.96
T ₂	: 100% NPK Zn	20.03	11.63
T ₃	: 75% N Zn + 100% PK	20.12	11.66
T ₄	: 50% N Zn + 100% PK	20.50	11.79
T ₅	: 100% NPK Zn +1 st spray of Nano N and Zn at 30 DAS	20.74	11.88
T ₆	: 100% NPK Zn +1 st spray of Nano N and Zn at 30 DAS +2 nd spray of Nano N and Zn at 45 DAS	20.81	11.91
T ₇	: 75% N Zn + 100% PK +1 st spray of Nano N and Zn at 30 DAS	20.40	11.75
T ₈	: 75% N Zn + 100% PK +1 st spray of Nano N and Zn at 30 DAS +2 nd spray of Nano N and Zn at 45 DAS	20.47	11.78
T ₉	: 50% N Zn + 100% PK +1 st spray of Nano N and Zn at 30 DAS	20.44	11.77
T ₁₀	: 50% N Zn + 100% PK +1 st spray of Nano N and Zn at 30 DAS +2 nd spray of Nano N and Zn at 45 DAS	20.49	11.79
SEm±		0.143	0.053
CD(P= 0.05)		0.426	0.158

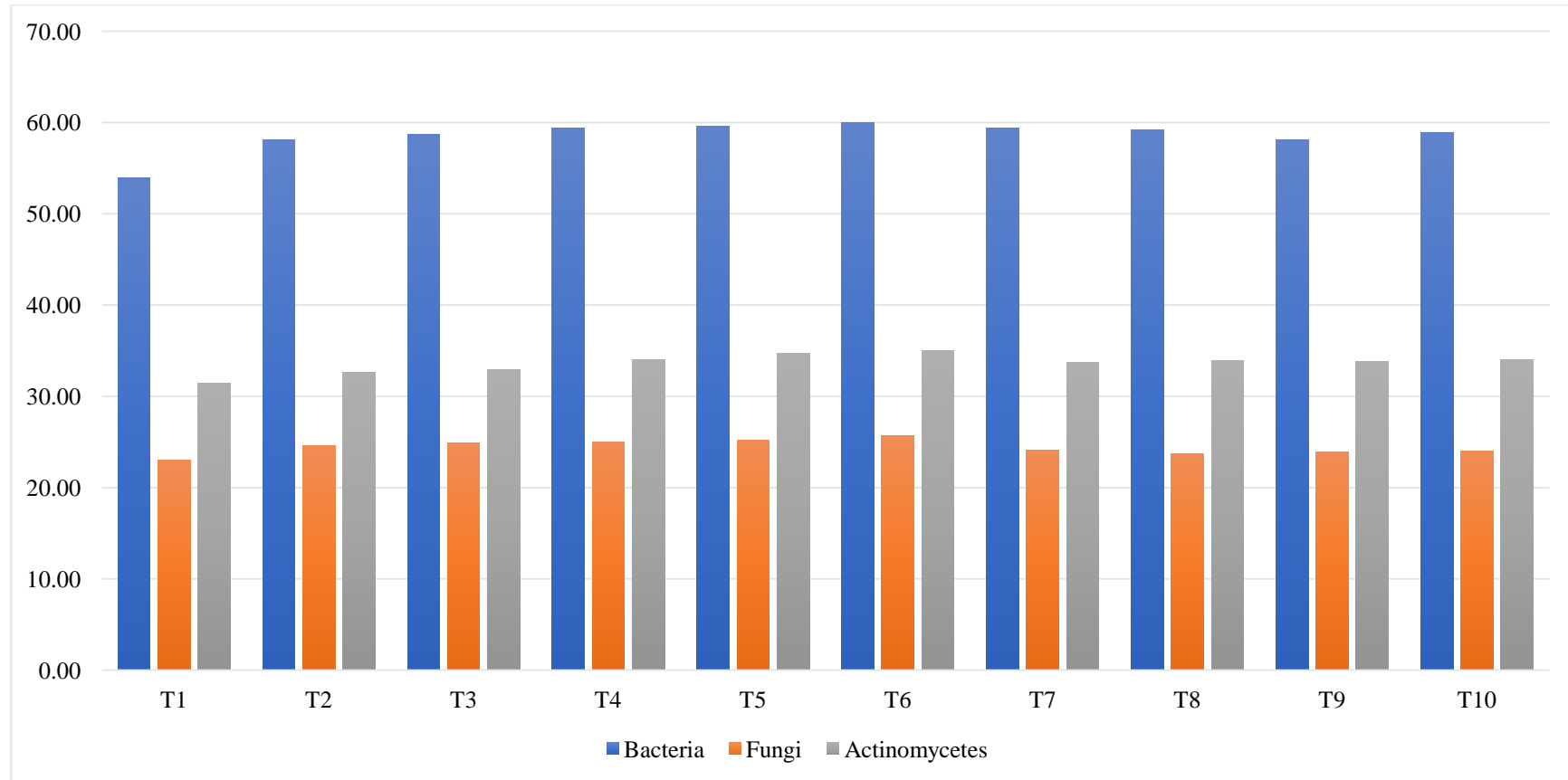


Fig. 1. Effect of nano nitrogen and nano zinc on soil microbial population in soil after harvest of mustard

production and activity in the soil. Rai and Tripathi [47] concluded that nano zinc and nano nitrogen application can improve plant growth and health. Healthy plants release root exudates that provide a carbon source for soil microbes, promoting microbial growth and enzyme production. Increased microbial activity due to nanomaterial application can subsequently enhance dehydrogenase and acid phosphatase activity in the soil. Similar finding was concluded by Khardia *et al.* [48] that “the plots treated with nano fertilizers found better nutrient and biological status in post-harvest soil”.

4. CONCLUSION

Based on the aforementioned findings, it can be inferred that the foliar application of nano nitrogen and nano zinc not only enhances the availability of nutrients but also improves the population of soil microorganisms and their enzymatic activity in the post-harvest condition of the soil. Nano-fertilizers exhibit potential as an effective nutrient delivery system, thereby reducing the overall nutrient requirement. Soil enzymes are regarded as reliable indicators of microbial diversity in soil and their presence enhances the efficacy of applied nutrients as well as nutrients present in the labile pool. These results shed light on the potential utilization of nano-fertilizers for the safer and more efficient delivery of essential nutrients to crop plants in an environmentally favorable manner.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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