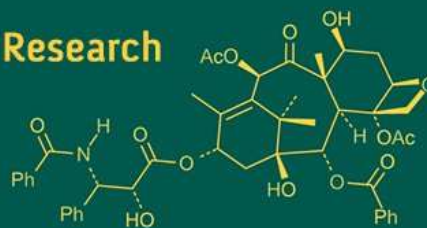
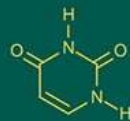
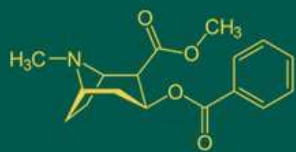


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Impact of integrated use of soil amendments and nano fertilizers on soil properties under temperate conditions of Kashmir

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Abstract

A pot experiment was conducted during Rabi 2022 at the Faculty of Horticulture, SKUAST-Kashmir, Shalimar, Srinagar. Among the treatments, T₈ proved to be the most promising treatment and recorded significantly superior values for most of the soil physicochemical and nutrient parameters. Treatment T₈ recorded the highest soil porosity (49.35%), infiltration rate (0.48 cm/s), pH (7.24), electrical conductivity (0.69 dS/m), organic carbon (0.51%), available nitrogen (306.99 kg/ha), available phosphorus (20.45 kg/ha), available potassium (292.46 kg/ha), zinc (0.77 ppm), iron (2.63 ppm), copper (0.32 ppm) and manganese (2.60 ppm). In contrast, the untreated control (T₁₀) recorded the highest bulk density (1.35 g/cm³) and particle density (2.61 g/cm³), whereas T₈ recorded the lowest bulk density (1.25 g/cm³) and particle density (2.45 g/cm³). The reduction in bulk density under T₈ may be attributed to the combined application of neem cake and nano zeolite, which improved soil aggregation, increased pore space and enhanced soil structural conditions. The untreated control (T₁₀) recorded the lowest values for porosity (47.57%), infiltration rate (0.24 cm/s), pH (6.43), electrical conductivity (0.25 dS/m), organic carbon (0.26%), available nitrogen (234.41 kg/ha), available phosphorus (11.96 kg/ha), available potassium (183.45 kg/ha), zinc (0.46 ppm), iron (2.02 ppm), copper (0.18 ppm) and manganese (1.94 ppm). It can therefore be concluded that the combined application of neem cake and nano zeolite along with nano fertilizers proved superior to the recommended dose of fertilizers (RDF) and untreated control in improving soil physical, chemical and nutrient status. Treatment T₈ emerged as the most effective treatment, demonstrating its potential for improving soil quality and nutrient availability.

Keywords: Nutrient, zeolite, organic, soil, fertilizer, manganese

1. Introduction

Conventional agriculture has exerted considerable pressure on soil quality and its capacity to function sustainably. The post-Green Revolution challenges confronting Indian agriculture have raised serious concerns regarding long-term agricultural sustainability and national food security. The widespread and indiscriminate use of high-analysis chemical fertilizers has contributed to the depletion of soil organic matter, increased salinity and sodicity, soil contamination, and an overall decline in soil health (Shambhavi *et al.*, 2017) [26]. Over the past three decades, the consumption of inorganic fertilizers has increased substantially to meet the growing demand for food. However, excessive and imbalanced fertilizer application can adversely affect soil, water and atmospheric environments. Continuous overuse of chemical fertilizers may alter soil organic matter, microbial populations and soil reaction, thereby negatively influencing overall soil health (Erisman *et al.*, 2008) [9]. Moreover, excessive fertilizer application can contaminate surface and groundwater resources through leaching and surface runoff.

The integrated use of organic and inorganic nutrient sources has emerged as an effective approach for improving crop productivity while maintaining soil fertility and sustainability. Unlike the sole application of either chemical fertilizers or organic manures, integrated nutrient management can provide a more balanced supply of essential nutrients and improve soil physical, chemical and biological properties.

Such an approach not only enhances crop productivity but can also sustain soil productivity and provide a cost-effective nutrient management strategy, particularly for developing countries. Organic amendments contribute to the improvement of soil structure, organic carbon content and microbial activity, while mineral fertilizers provide nutrients in readily available forms, including nitrate, phosphate, exchangeable calcium and soluble potassium. Therefore, the combined application of organic and inorganic nutrient sources can exert a more beneficial influence on plant growth, yield and soil physicochemical properties than the sole application of inorganic fertilizers. Furthermore, decomposition of organic amendments and the subsequent release of nutrients are influenced by temperature, moisture regimes, season and management practices. The incorporation of organic materials can also contribute to climate-change mitigation by enhancing soil carbon sequestration (Ryals and Silver, 2013) ^[25]. In recent years, advances in nanotechnology have introduced nano-fertilizers as an innovative approach to improving nutrient-use efficiency and sustainable crop production. Nano-fertilizers can be applied directly to the soil, through irrigation water, or as foliar sprays to improve nutrient availability and plant growth. Their nanoscale properties may facilitate more efficient nutrient delivery and uptake, potentially reducing nutrient losses and improving fertilizer-use efficiency. Nano-fertilization has also been associated with enhanced physiological and biochemical processes in plants, including carbon metabolism and antioxidant enzyme activity, which can positively influence crop productivity and quality (Gerdini, 2016) ^[10]. Thus, nanotechnology offers considerable potential for addressing some of the limitations associated with conventional fertilizer practices and promoting sustainable soil health and crop production (Lal, 2008) ^[14]. In strawberry, the application of nano-fertilizers has been reported to improve fruit quality attributes,

including phenolic content and aroma (Cvelbar *et al.*, 2021) ^[8], while nano-based approaches have also demonstrated potential in enhancing tolerance to environmental stresses such as fluoride toxicity (Mozafari *et al.*, 2018) ^[21]. Nano-fertilizers are designed to supply essential nutrients in a controlled and efficient manner, with nutrients and, in some formulations, growth-promoting substances delivered through nanoscale carriers or formulations. Consequently, their integration with organic amendments and conventional fertilizers may provide a promising strategy for improving nutrient availability, soil health, crop productivity and produce quality in sustainable horticultural production systems.

2. Materials and Methods

2.1 Experimental location

The study was conducted at Faculty of Horticulture, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shalimar, Srinagar (J&K) India

2.2 Pot Experiment

2.2.1 Soil Collection for pots

Bulk soil collected from the research field of Soil Science, Faculty of Horticulture, SKUAST-Kashmir Shalimar was crushed and passed through a 5.0 mm sieve, which reduce the particle size even further. Soil was loaded into each pot and then total volume of the soil in pot was calculated.

2.3 Soil Characteristics

2.3.1 Mechanical and chemical properties

Mechanical and chemical analyses were performed on the samples under investigation. According to the results mentioned in Table 1 the soil analyzed was a sandy clay loam, slightly alkaline reaction, electrical conductivity within safe limits, low organic carbon, nitrogen and medium phosphorus and potassium.

Table 1: Initial soil properties of the experimental soil.

S. No	Soil Properties	Observation	Analytical method used
A	Physical properties		
1	Texture		
	Sand (%)	45	Bouyoucous hydrometer method
	Silt (%)	29	
	Clay (%)	25	
	Textural Class	Clay Loam	Textural diagram
2	Bulk Density (g cm ⁻³)	1.34	Core sampler method
3	Particle Density (g cm ³)	2.59	Parihar and Sandhu, 1968) ^[30] .
4	Porosity (%)	48.23	Majumdar and Singh, 2005) ^[31] .
B	Chemical properties		
1	pH	7.23	1:2 Soil water suspension measured with glass electrode pH meter (Jackson, 1973) ^[13]
2	EC (dSm ⁻¹)	0.26	1:2 Soil water suspension measured with glass electrode pH meter (Jackson, 1973) ^[13]
3	Organic Carbon (%)	0.25	Walkley and Black's rapid titration method (Jackson, 1973) ^[13]
4	Available N (kg ha ⁻¹)	235.76	Modified alkaline potassium permanganate method (Subbiah and Asija, 1956) ^[27]
5	Available P (kg ha ⁻¹)	11.98	0.5 M Sodium bicarbonate extractable P method (Olsen <i>et al.</i> , 1954) ^[22]
6	Available K (kg ha ⁻¹)	184.72	Ammonium acetate extractable K method (Jackson, 1973) ^[13]
7	Zinc (mg kg ⁻¹)	0.45	Lindsay and Norvell. 1978. ^[16]
8	Iron (mg kg ⁻¹)	2.03	
9	Copper (mg kg ⁻¹)	0.19	
10	Manganese (mg kg ⁻¹)	1.96	

2.4 Experimental Details

There were a total of ten treatment combinations with 3 replications taking the number of pots to thirty (30). Statistical design was Completely Randomized Design (CRD).

2.5 Soil Chemical Parameters

2.5.1 Soil pH

The pH of the soil was tested by mixing soil and water (1:2) in a glass-calomel electrode (Jackson, 1973) ^[13].

2.5.2 Soil EC (dS m^{-1})

The EC was calculated by measuring the salt bridge in the suspension used to evaluate the EC. (Jackson, 1973) ^[13].

2.5.3 Organic Carbon (g kg^{-1})

Walkley and Black's rapid titration test was used to estimate organic carbon (Jackson, 1973) ^[13].

2.5.4 Available nitrogen (kg ha^{-1})

The available nitrogen concentration was determined using a modified alkaline potassium permanganate method (Subbiah and Asija, 1956) ^[27], and the results were expressed in kilograms per hectare.

2.5.5 Available phosphorus (kg ha^{-1})

The extractable P method with 0.5M sodium bicarbonate was used to determine the available phosphorus. (Olsen *et al.*, 1954) ^[22]. The colour intensity created by stannous chloride was determined using a spectrophotometer at 660 nm and quantified as phosphorus kilograms per hectare.

2.5.6 Available potassium (kg ha^{-1})

The ammonium acetate extractable K technique was used to extract the available potassium (Jackson, 1973) ^[13], and the potassium concentration was determined using a flame photometer and quantified as kilograms per hectare.

2.5.7 DTPA-extractable micronutrient cations

Availability of DTPA-extractable micronutrient cations (Zn, Fe, Cu and Mn) was assessed by extracting 10g of soil sample with 20 mL of diethylene triamine penta acetic acid (DTPA) extractant as described by Lindsay and Norvell (1978) ^[16]. The extract was fed to Atomic Absorption Spectrophotometer (Thermo).

3. Results and Discussion

3.1 Effect of nano fertilizers and soil amendments on physical properties of soil

3.1.1 Bulk Density

The data presented in Table 2 revealed that the application of nano fertilizers and soil amendments significantly influenced the bulk density of soil. The lowest bulk density (1.24 g cm^{-3}) was recorded in T₈ (Neem cake @ 50% + nano zeolite @ 5 g kg^{-1} soil + RDF @ 50%), followed by T₇ (1.26 g cm^{-3}), T₅ (1.27 g cm^{-3}), T₄ (1.28 g cm^{-3}), T₃ (1.29 g cm^{-3}), T₂ (1.30 g cm^{-3}), T₁ (1.31 g cm^{-3}) and T₉ (1.33 g cm^{-3}). The highest bulk density (1.35 g cm^{-3}) was recorded in T₁₀ (control).

Overall, the combined application of neem cake, nano zeolite and RDF resulted in a greater reduction in soil bulk density compared with the control. Among the treatments, T₈ exhibited the most favourable effect, indicating improved soil structural condition and greater pore space.

3.1.2 Particle Density

The results presented in Table 2 indicated that the application of nano fertilizers and soil amendments influenced soil particle density. The lowest particle density among the treated plots was recorded in T₈ (2.45 g cm^{-3}), followed by T₇ (2.46 g cm^{-3}), T₆ (2.47 g cm^{-3}), T₅ (2.48 g cm^{-3}), T₂ (2.49 g cm^{-3}), T₁ (2.50 g cm^{-3}), T₄ (2.52 g cm^{-3}), T₃ (2.54 g cm^{-3}) and T₉ (2.57 g cm^{-3}). The highest particle density (2.61 g cm^{-3}) was recorded in T₁₀ (control).

The results suggest that the incorporation of organic amendments, particularly neem cake, in combination with nano zeolite and reduced levels of RDF, favourably modified

soil physical characteristics. T₈ recorded the lowest particle density, whereas the control exhibited the highest value.

3.1.3 Porosity

The data pertaining to the effect of nano fertilizers and soil amendments on soil porosity are presented in Table 2. The highest soil porosity was recorded in T₆ (49.36%), closely followed by T₈ (49.35%), T₄ (49.17%), T₃ (49.18%), T₇ (48.75%), T₅ (48.76%), T₉ (48.22%), T₂ (47.76%) and T₁ (47.56%). The lowest porosity (48.24%) was recorded in T₁₀ (control).

The higher porosity observed under the amended treatments may be attributed to the incorporation of organic matter and the improvement in soil aggregation and pore-space distribution. The combined application of neem cake and nano zeolite, particularly when integrated with RDF, resulted in comparatively higher porosity than the control.

3.1.4 Infiltration Rate

The data presented in Table 2 revealed a significant improvement in soil infiltration rate following the application of nano fertilizers and soil amendments. The highest infiltration rate (0.48 cm s^{-1}) was recorded in T₈ (Neem cake @ 50% + nano zeolite @ 5 g kg^{-1} soil + RDF @ 50%), followed by T₇ (0.46 cm s^{-1}), T₆ (0.44 cm s^{-1}), T₅ (0.42 cm s^{-1}), T₄ (0.40 cm s^{-1}), T₃ (0.37 cm s^{-1}), T₂ (0.35 cm s^{-1}), T₁ (0.33 cm s^{-1}) and T₉ (0.30 cm s^{-1}). The lowest infiltration rate (0.24 cm s^{-1}) was recorded in T₁₀ (control).

The higher infiltration rate under the amended treatments indicates improved soil structure, aggregation and pore continuity. T₈ showed the most pronounced improvement, suggesting that the combined application of neem cake, nano zeolite and RDF at the specified rates was effective in improving soil water movement.

3.2 Effect of Nano Fertilizers and Soil Amendments on Chemical Properties of Soil

3.2.1 pH

The results presented in Table 3 revealed that the application of nano fertilizers and soil amendments improved soil pH compared with the control. The highest soil pH (6.97) was recorded in T₈ (Neem cake @ 50% + nano zeolite @ 5 g kg^{-1} soil + RDF @ 50%), followed by T₇ (6.86), T₆ (6.81), T₅ (6.78), T₂ (6.71), T₁ (6.69), T₄ (6.67), T₃ (6.65) and T₉ (6.47). The lowest soil pH (6.43) was recorded in T₁₀ (control).

The results indicate that the combined application of neem cake and nano zeolite along with RDF was more effective in maintaining a favourable soil pH than the control. T₈ recorded the highest pH value, indicating a positive influence of the integrated nutrient and soil amendment treatment on soil chemical conditions.

3.2.2 Electrical Conductivity

The data pertaining to the effect of nano fertilizers and soil amendments on soil electrical conductivity are presented in Table 3. The highest electrical conductivity (0.69 dS m^{-1}) was recorded in T₈ (Neem cake @ 50% + nano zeolite @ 5 g kg^{-1} soil + RDF @ 50%), followed by T₇ (0.61 dS m^{-1}), T₆ (0.56 dS m^{-1}), T₅ (0.53 dS m^{-1}), T₂ (0.50 dS m^{-1}), T₁ (0.48 dS m^{-1}), T₄ (0.44 dS m^{-1}), T₃ (0.40 dS m^{-1}) and T₉ (0.36 dS m^{-1}). The lowest electrical conductivity (0.25 dS m^{-1}) was recorded in T₁₀ (control).

The comparatively higher electrical conductivity under the amended treatments may be associated with greater availability of soluble nutrients and other ionic constituents released through the decomposition of organic amendments

and application of fertilizers. Nevertheless, the recorded EC values remained within a relatively low range, indicating that the treatments did not result in excessive salt accumulation.

3.2.3 Organic Carbon

The data presented in Table 3 revealed that the application of nano fertilizers and soil amendments significantly enhanced soil organic carbon content compared with the control. The highest organic carbon content (0.51%) was recorded in T₈ (Neem cake @ 50% + nano zeolite @ 5 g kg⁻¹ soil + RDF @ 50%), followed by T₇ (0.49%), T₆ (0.46%), T₅ (0.44%), T₂ (0.41%), T₁ (0.39%), T₄ (0.34%), T₃ (0.35%) and T₉ (0.34%). The lowest organic carbon content (0.26%) was recorded in T₁₀ (control).

The increase in organic carbon under the amended treatments may be attributed primarily to the addition and decomposition of neem cake, which contributed organic residues to the soil. The combined application of neem cake and nano zeolite with RDF, particularly in T₈, resulted in the highest accumulation of organic carbon, indicating improved soil organic matter status and overall soil quality.

3.3 Effect of nano fertilizers and soil amendments on organic carbon

3.3.1 Available Nitrogen

The results from Table 3 confirmed that the application of nano fertilizers and soil amendments boosted available nitrogen as compared to control. T₈ (Neem Cake @ 50% + Nano Zeolite @ 5 g kg⁻¹ soil + RDF 50%) recorded significantly highest values for available nitrogen i.e 306.99 kg/ha, 301.71 kg/ha, 294.18 kg/ha, 290.16 kg/ha, 285.63 kg/ha, 281.35 kg/ha, 277.97 kg/ha, 276.49 kg/ha, 273.65 kg/ha, and T₁₀ (control) recorded lowest values for available nitrogen of 234.41 kg/ha. The highest to lowest order of treatments are as T₈ (Neem Cake @ 50% + Nano Zeolite @ 5 g kg⁻¹ soil + RDF 50%) > T₇ (Neem Cake @ 50% + Nano Zeolite @ 2 g kg⁻¹ soil + RDF 50%) > T₆ (Neem Cake @ 25% + Nano Zeolite @ 5g kg⁻¹ soil + RDF 75%) > T₅ (Neem Cake @ 25% + Nano Zeolite @ 2g kg⁻¹ soil + RDF 75%) > T₂ (Neem Cake @ 50% + RDF @ 50%) > T₁ (Neem Cake @ 25% + RDF @ 75%) > T₄ (Nano Zeolite @ 5 g kg⁻¹ soil + RDF @ 100%) > T₃ (Nano Zeolite @ 2 g kg⁻¹ soil + RDF @ 100%) > T₉ (100% RDF through Nano fertilizer).

3.3.2 Available Phosphorus

Data pertaining to the effect of nano fertilizers and soil amendments on available phosphorus content is presented in Table 3. Among all treatments, the significantly highest available phosphorus (20.45 kg/ha,) was observed in T₈ (Neem Cake @ 50% + Nano Zeolite @ 5 g kg⁻¹ soil + RDF 50%) followed by 19.87 kg/ha, in T₇ (Neem Cake @ 50% + Nano Zeolite @ 2 g kg⁻¹ soil + RDF 50%) > 18.84 kg/ha, in T₆ (Neem Cake @ 25% + Nano Zeolite @ 5g kg⁻¹ soil + RDF 75%) > 18.01 kg/ha, in T₅ (Neem Cake @ 25% + Nano Zeolite @ 2g kg⁻¹ soil + RDF 75%) > 17.70 kg/ha, in T₂ (Neem Cake @ 50% + RDF @ 50%) > 17.07 kg/ha, in T₁ (Neem Cake @ 25% + RDF @ 75%) > 16.09 kg/ha, in T₄ (Nano Zeolite @ 5 g kg⁻¹ soil + RDF @ 100%) > 15.94 kg/ha, in T₃ (Nano Zeolite @ 2 g kg⁻¹ soil + RDF @ 100%) > 15.00 kg/ha, in T₉ (100% RDF through Nano fertilizer). The lowest values for available phosphorus (11.96 kg/ha) were recorded in T₁₀ (control).

3.3.3 Available Potassium

The perusal of data in Table 3 revealed that treatment T₈ (Neem Cake @ 50% + Nano Zeolite @ 5 g kg⁻¹ soil + RDF

50%) recorded significantly highest available potassium (292.46 kg/ha) followed by 281.40 kg/ha in T₇ (Neem Cake @ 50% + Nano Zeolite @ 2 g kg⁻¹ soil + RDF 50%) > 267.21 kg/ha in T₆ (Neem Cake @ 25% + Nano Zeolite @ 5g kg⁻¹ soil + RDF 75%) > 258.92 kg/ha in T₅ (Neem Cake @ 25% + Nano Zeolite @ 2g kg⁻¹ soil + RDF 75%) > 237.78 kg/ha in T₂ (Neem Cake @ 50% + RDF @ 50%) > 232.51 kg/ha in T₁ (Neem Cake @ 25% + RDF @ 75%) > 249.77 kg/ha in T₄ (Nano Zeolite @ 5 g kg⁻¹ soil + RDF @ 100%) > 241.66 kg/ha in T₃ (Nano Zeolite @ 2 g kg⁻¹ soil + RDF @ 100%) > 222.01 kg/ha in T₉ (100% RDF through Nano fertilizer). The lowest values for available potassium (183.45 kg/ha) was recorded in T₁₀ (control).

3.4 Effect of nano fertilizers and soil amendments on micro nutrient status of soil

3.4.1 Zinc

The perusal of data in Table 4 revealed that treatment T₈ (Neem Cake @ 50% + Nano Zeolite @ 5 g kg⁻¹ soil + RDF 50%) recorded significantly highest zinc (0.77 ppm), followed by 0.75 ppm in T₇ (Neem Cake @ 50% + Nano Zeolite @ 2 g kg⁻¹ soil + RDF 50%) > 0.72 ppm in T₆ (Neem Cake @ 25% + Nano Zeolite @ 5g kg⁻¹ soil + RDF 75%) > 0.71 ppm in T₅ (Neem Cake @ 25% + Nano Zeolite @ 2g kg⁻¹ soil + RDF 75%) > 0.69 ppm in T₂ (Neem Cake @ 50% + RDF @ 50%) > 0.67 ppm in T₁ (Neem Cake @ 25% + RDF @ 75%) > 0.65 ppm in T₄ (Nano Zeolite @ 5 g kg⁻¹ soil + RDF @ 100%) > 0.63 ppm in T₃ (Nano Zeolite @ 2 g kg⁻¹ soil + RDF @ 100%) > 0.60 ppm in T₉ (100% RDF through Nano fertilizer). The lowest values for zinc (0.46 ppm) was recorded in T₁₀ (control).

3.4.2 Iron

The results from Table 4 confirmed that the application of nano fertilizers and soil amendments boosted the iron of Strawberry compared to control. T₈ (Neem Cake @ 50% + Nano Zeolite @ 5 g kg⁻¹ soil + RDF 50%) recorded significantly highest value for iron i.e. 2.63 ppm, 2.61 ppm, 2.57 ppm, 2.55 ppm, 2.53 ppm, 2.51 ppm, 2.47 ppm, 2.45 ppm, 2.41 ppm and T₁₀ (control) recorded lowest values for iron of 2.02 ppm. The highest to lowest order of treatments are as T₈ (Neem Cake @ 50% + Nano Zeolite @ 5 g kg⁻¹ soil + RDF 50%) > T₇ (Neem Cake @ 50% + Nano Zeolite @ 2 g kg⁻¹ soil + RDF 50%) > T₆ (Neem Cake @ 25% + Nano Zeolite @ 5g kg⁻¹ soil + RDF 75%) > T₅ (Neem Cake @ 25% + Nano Zeolite @ 2g kg⁻¹ soil + RDF 75%) > T₂ (Neem Cake @ 50% + RDF @ 50%) > T₁ (Neem Cake @ 25% + RDF @ 75%) > T₄ (Nano Zeolite @ 5 g kg⁻¹ soil + RDF @ 100%) > T₃ (Nano Zeolite @ 2 g kg⁻¹ soil + RDF @ 100%) > T₉ (100% RDF through Nano fertilizer).

3.4.3 Copper

Data pertaining to the effect of nano fertilizers and soil amendments on copper is presented in Table 4. Among all treatments, the significantly copper (0.32 ppm) was observed in T₈ (Neem Cake @ 50% + Nano Zeolite @ 5 g kg⁻¹ soil + RDF 50%) followed by 0.31 ppm in T₇ (Neem Cake @ 50% + Nano Zeolite @ 2 g kg⁻¹ soil + RDF 50%) > 0.30 ppm in T₆ (Neem Cake @ 25% + Nano Zeolite @ 5g kg⁻¹ soil + RDF 75%) > 0.29 ppm in T₅ (Neem Cake @ 25% + Nano Zeolite @ 2g kg⁻¹ soil + RDF 75%) > 0.28 ppm in T₂ (Neem Cake @ 50% + RDF @ 50%) > 0.26 ppm in T₁ (Neem Cake @ 25% + RDF @ 75%) > 0.25 ppm in T₄ (Nano Zeolite @ 5 g kg⁻¹ soil + RDF @ 100%) > 0.24 ppm in T₃ (Nano Zeolite @ 2 g

kg⁻¹ soil + RDF @ 100%) > 0.22 ppm in T₉ (100% RDF through Nano fertilizer). The lowest values for copper (0.18 ppm) were recorded in T₁₀ (control).

3.4.4 Manganese

The perusal of data in Table 4 revealed that treatment T₈ (Neem Cake @ 50% + Nano Zeolite @ 2 g kg⁻¹ soil + RDF 50%) recorded significantly highest manganese (2.60 ppm) followed by 2.58 ppm in T₇ (Neem Cake @ 50% + Nano

Zeolite @ 5 g kg⁻¹ soil + RDF 50%) > 2.54 ppm in T₆ (Neem Cake @ 25% + Nano Zeolite @ 5g kg⁻¹ soil + RDF 75%) > 2.52 ppm in T₅ (Neem Cake @ 25% + Nano Zeolite @ 2 g kg⁻¹ soil + RDF 75%) > 2.50 ppm in T₂ (Neem Cake @ 50% + RDF @ 50%) > 2.48 ppm in T₁ (Neem Cake @ 25% + RDF @ 75%) > 2.44 ppm in T₄ (Nano Zeolite @ 5 g kg⁻¹ soil + RDF @ 100%) > 2.42 ppm in T₃ (Nano Zeolite @ 2 g kg⁻¹ soil + RDF @ 100%) > 2.38 ppm in T₉ (100% RDF through Nano fertilizer). The lowest values for manganese (1.94 ppm) was recorded in T₁₀ (control).

Table 2: Effect of nano fertilizers and soil amendments on physical properties of soil

Treatment Code	Bulk Density (g/cm ³)	Particle Density (g/cm ³)	Porosity (%)	Infiltration rate (cm/s)
T ₁	1.31	2.50	47.57	0.33
T ₂	1.30	2.49	47.76	0.35
T ₃	1.29	2.54	49.18	0.37
T ₄	1.28	2.52	49.17	0.40
T ₅	1.27	2.48	48.76	0.42
T ₆	1.25	2.47	49.36	0.44
T ₇	1.26	2.46	48.75	0.46
T ₈	1.24	2.45	49.35	0.48
T ₉	1.33	2.57	48.22	0.30
T ₁₀	1.35	2.61	48.24	0.24
C.D (p<0.05)	0.045	0.058	0.002	0.043

T₁: Neem Cake @ 25% + RDF @ 75%

T₃: Nano Zeolite @ 2 g kg⁻¹ soil + RDF @ 100%

T₅: Neem Cake @ 25% + Nano Zeolite @ 2g kg⁻¹ soil + RDF 75%

T₇: Neem Cake @ 50% + Nano Zeolite @ 2g kg⁻¹ soil + RDF 50%

T₉: 100% RDF (through Nano fertilizer) T₁₀: Control (Untreated)

T₂: Neem Cake @ 50% + RDF @ 50%

T₄: Nano Zeolite @ 5 g kg⁻¹ soil + RDF @ 100%

T₆: Neem Cake @ 25% + Nano Zeolite @ 5g kg⁻¹ soil + RDF 75%

T₈: Neem Cake @ 25% + Nano Zeolite @ 5g kg⁻¹ soil + RDF 75%

Table 3: Effect of nano fertilizers and soil amendments on the soil fertility parameters

Treatment Code	pH	Electrical conductivity (dS/m)	Organic Carbon (%)	Available Nitrogen (kg/ha)	Available Phosphorus (kg/ha)	Available potassium (kg/ha)
T ₁	6.71	0.48	0.39	276.49	17.07	232.51
T ₂	6.67	0.50	0.41	277.97	17.70	237.78
T ₃	6.86	0.40	0.35	281.35	15.94	241.66
T ₄	6.81	0.44	0.36	285.63	16.09	249.77
T ₅	6.69	0.53	0.44	290.16	18.02	258.92
T ₆	6.65	0.56	0.46	294.18	18.84	267.21
T ₇	6.47	0.61	0.49	301.71	19.87	281.40
T ₈	6.43	0.69	0.51	306.99	20.45	292.46
T ₉	6.78	0.36	0.34	273.65	15.00	222.01
T ₁₀	7.24	0.25	0.26	234.41	11.96	183.45
C.D (p<0.05)	0.061	0.008	0.061	1.243	0.897	1.046

T₁: Neem Cake @ 25% + RDF @ 75%

T₃: Nano Zeolite @ 2 g kg⁻¹ soil + RDF @ 100%

T₅: Neem Cake @ 25% + Nano Zeolite @ 2g kg⁻¹ soil + RDF 75%

T₇: Neem Cake @ 50% + Nano Zeolite @ 2g kg⁻¹ soil + RDF 50%

T₉: 100% RDF (through Nano fertilizer) T₁₀: Control (Untreated)

T₂: Neem Cake @ 50% + RDF @ 50%

T₄: Nano Zeolite @ 5 g kg⁻¹ soil + RDF @ 100%

T₆: Neem Cake @ 25% + Nano Zeolite @ 5g kg⁻¹ soil + RDF 75%

T₈: Neem Cake @ 25% + Nano Zeolite @ 5g kg⁻¹ soil + RDF 75%

Table 4: Effect of nano fertilizers and soil amendments on micro nutrient status of soil

Treatment Code	Zinc (ppm)	Iron (ppm)	Copper (ppm)	Manganese (ppm)
T ₁	0.67	2.51	0.26	2.48
T ₂	0.69	2.53	0.28	2.50
T ₃	0.63	2.45	0.24	2.42
T ₄	0.65	2.47	0.25	2.44
T ₅	0.71	2.55	0.29	2.52
T ₆	0.72	2.57	0.30	2.54
T ₇	0.75	2.61	0.31	2.58
T ₈	0.77	2.63	0.32	2.60
T ₉	0.60	2.41	0.22	2.38
T ₁₀	0.46	2.02	0.18	1.94
C.D (p<0.05)	0.007	0.041	0.008	0.010

T₁: Neem Cake @ 25% + RDF @ 75%

T₃: Nano Zeolite @ 2 g kg⁻¹ soil + RDF @ 100%

T₅: Neem Cake @ 25% + Nano Zeolite @ 2g kg⁻¹ soil + RDF 75%

T₇: Neem Cake @ 50% + Nano Zeolite @ 2g kg⁻¹ soil + RDF 50%

T₉: 100% RDF (through Nano fertilizer) T₁₀: Control (Untreated)

T₂: Neem Cake @ 50% + RDF @ 50%

T₄: Nano Zeolite @ 5 g kg⁻¹ soil + RDF @ 100%

T₆: Neem Cake @ 25% + Nano Zeolite @ 5g kg⁻¹ soil + RDF 75%

T₈: Neem Cake @ 25% + Nano Zeolite @ 5g kg⁻¹ soil + RDF 75%

4. Discussion

Pursuant to the data presented in Tables 4.4-4.6, the application of neem cake, nano-zeolite and nano-fertilizers significantly influenced the physico-chemical properties and nutrient availability of the soil. Among the treatments, T₈ (Neem cake @ 50% + nano-zeolite @ 5 g kg⁻¹ soil + RDF 50%) generally recorded the most favourable values for the measured soil properties, indicating the beneficial effect of integrating organic amendments with nano-based inputs.

The lowest bulk density (1.25 g cm⁻³) and particle density (2.45 g cm⁻³) were recorded under T₈, whereas the highest porosity (49.35%) and infiltration rate (0.48 cm s⁻¹) were also observed in this treatment. In contrast, the control treatment recorded the highest bulk density (value to be inserted, if applicable) and particle density (value to be inserted), together with the lowest porosity (47.57%) and infiltration rate (0.24 cm s⁻¹). The improvement in soil physical properties under T₈ may be attributed to the combined effects of neem cake and nano-zeolite. The addition of organic matter from neem cake promotes soil aggregation and reduces compaction, while nano-zeolite, owing to its high surface area and ion-exchange capacity, contributes to improved soil structure and pore continuity. Consequently, enhanced pore space facilitates root penetration, aeration and movement of water through the soil profile.

Among the chemical properties, the lowest soil pH (6.43), EC (0.25 dS m⁻¹) and organic carbon (0.26%) were recorded in the treatment showing the minimum values, whereas T₈ recorded the highest values of pH (7.24), EC (0.69 dS m⁻¹) and organic carbon (0.51%). Similarly, T₈ recorded the highest availability of N (306.99 kg ha⁻¹), P (20.45 kg ha⁻¹), K (292.46 kg ha⁻¹), Zn (0.77 ppm), Fe (2.63 ppm), Cu (0.32 ppm) and Mn (2.60 ppm), compared with the corresponding minimum values of 234.41 kg ha⁻¹, 11.96 kg ha⁻¹, 183.45 kg ha⁻¹, 0.46 ppm, 2.02 ppm, 0.18 ppm and 1.94 ppm, respectively. These results demonstrate that the integrated application of neem cake, nano-zeolite and nano-fertilizers improved both soil physical conditions and nutrient availability.

Neem cake, being an organic amendment rich in carbon and other nutrients, can improve soil structure by stimulating aggregation and reducing compaction. Its decomposition provides a readily available energy source for soil microorganisms, thereby enhancing microbial activity and nutrient cycling. The decomposition and mineralization of organic matter gradually release nutrients into the soil solution, while also improving nutrient retention and reducing the likelihood of nutrient losses. Thus, neem cake acts not only as a nutrient source but also as a soil conditioner. The availability of individual nutrients is also governed by interactions among nutrients, changes in soil equilibrium, rhizosphere processes and nutrient transformation pathways (More and Ghonsikar, 1988; Bhandari *et al.*, 1989) [6, 20].

The beneficial effects of nano-based inputs may be related to their ability to regulate nutrient release and improve nutrient-use efficiency. Liu *et al.* (2006) [17] reported that organic materials associated with clay minerals can form nano- and sub-nano-composites capable of regulating nutrient release from fertilizer matrices. Similarly, Subramanian *et al.* (2008) [28] suggested that nano-fertilizers and nanocomposites can regulate nutrient release from fertilizer granules, thereby improving nutrient-use efficiency while reducing nutrient fixation and environmental losses.

Nano-zeolite further contributed to the improvement of soil properties owing to its high surface area, porous structure and cation-exchange capacity. Its incorporation can enhance aggregation, water retention and nutrient retention, thereby improving the soil environment for root growth. The increased infiltration rate observed under T₈ may therefore be associated with improved pore continuity and reduced surface compaction. Markovich *et al.* (1995) [19] reported beneficial effects of zeolite on soil physical conditions, while Butorac *et al.* (2002) [7] demonstrated its potential for use in cereal, forage, vegetable, fruit and vine production because of its high ion-exchange capacity. He *et al.* (2002) [12] reported improved N-use efficiency, N uptake and dry matter production, together with reduced ammonia volatilization, following zeolite application. Ayan *et al.* (2005) [5] also observed improvements in EC, water retention and plant nutrient availability following zeolite application.

Andronikashvili *et al.* (2008) [4] suggested that the beneficial effects of zeolites on crop productivity are largely associated with soil conditioning, improvement of soil physical and chemical properties, creation of favourable air and water regimes in the rhizosphere, enhancement of cation-exchange capacity and improved nutrient supply to plants. These mechanisms provide a plausible explanation for the improved soil physical properties observed under the integrated treatment in the present study.

The increase in available nitrogen under T₈ may be attributed to the combined contribution of organic matter decomposition and the nutrient-retention capacity of nano-zeolite. Organic matter provides a source of N that is gradually mineralized and converted into plant-available forms. At the same time, zeolite can retain ammonium ions through cation exchange, thereby reducing N losses and maintaining a more sustained nutrient supply. Allen *et al.* (1996) [3] demonstrated that mixtures of rock phosphate and NH₄⁺- and K⁺-saturated clinoptilolite have potential for slow-release fertilization through dissolution and ion-exchange reactions. Malhi *et al.* (2002) [18] further reported that zeolite saturated with monovalent nutrient cations such as NH₄⁺ and K⁺ can enhance the solubility of phosphate rock and improve nutrient availability.

Phosphorus availability was also substantially improved under the integrated treatment. Organic amendments can contribute to the soil phosphorus pool and promote its gradual mineralization, while nano-zeolite can retain nutrient ions and regulate their release. Rahale (2011) [23] reported that surface-modified nano-clays and zeolites were capable of releasing phosphate over an extended period of 40-50 days, compared with only 10-12 days for conventional fertilizer. Such controlled nutrient release can potentially improve phosphorus-use efficiency and reduce fixation or loss of applied P.

The higher available potassium under T₈ may similarly be attributed to the nutrient-retention and ion-exchange properties of zeolite combined with the contribution of organic matter. Zeolites can retain K⁺ and release it gradually according to the concentration gradient and ion-exchange equilibrium. Rezaei and Naeini (2009) [24] reported increased K sorption by zeolite with increasing equilibrium K concentration, while Butorac *et al.* (2002) [7] suggested that K-dominated zeolites may be particularly suitable for plant-growth applications. Li and Zhang (2010) [15] demonstrated the potential of K-loaded zeolite as a slow-release K fertilizer, whereas Rahale (2011) [23] reported improved efficiency of

slow-release K formulations. Zhou and Huang (2007) ^[29] attributed the gradual release of K from nano-zeolite to the ion-exchange properties of zeolite, highlighting its potential as a nutrient reservoir. Guo *et al.* (2008) ^[11] further suggested that zeolite can be recharged by the addition of dissolved nutrients, thereby extending its nutrient-retention function.

The increased availability of micronutrients, including Zn, Fe, Cu and Mn, under T₈ may also be associated with improved nutrient retention, enhanced organic matter decomposition and favourable changes in the soil chemical environment. Zinc is involved in numerous enzymatic reactions and plays an important role in growth-regulating processes. Iron is essential for chlorophyll synthesis and photosynthetic activity, while copper functions as a cofactor for several enzymes and is involved in electron transport. Manganese is required for enzyme activation and contributes to photosynthesis, respiration and nitrogen metabolism. Therefore, improved availability of these micronutrients under the integrated treatment could contribute to better plant nutritional status and physiological performance.

The present findings are consistent with Ahmed *et al.* (2010) ^[2], who reported that the combined application of inorganic fertilizers and zeolite improved N, P and K uptake and nutrient-use efficiency in different plant parts. The authors attributed these effects to the capacity of zeolite to retain nutrients in the soil and subsequently release them for plant uptake. Overall, the results indicate that the combined application of neem cake, nano-zeolite and nano-fertilizers produced complementary effects on soil physical and chemical properties.

The improvement in bulk density, porosity and infiltration rate indicates better soil structural conditions, whereas the changes in pH, EC and organic carbon reflect improved soil chemical status. The enhanced availability of macro- and micronutrients further demonstrates the potential of the integrated nutrient-management approach to improve nutrient retention and supply. Thus, the application of neem cake in combination with nano-zeolite and nano-fertilizers may provide a promising strategy for improving soil quality, nutrient-use efficiency and the overall soil environment for sustainable crop production.

5. Conclusion

The present study demonstrated that the integrated application of soil amendments and nano fertilizers significantly improved the physical, chemical, and nutrient status of soil under temperate conditions of Kashmir. Among the treatments, T₈, comprising neem cake, nano zeolite, and nano fertilizers, consistently performed superior to the recommended dose of fertilizers and untreated control. It improved soil porosity, infiltration rate, pH, electrical conductivity, organic carbon, and the availability of major nutrients and micronutrients, while reducing soil bulk density and particle density. The improvement in soil properties under T₈ may be attributed to enhanced soil aggregation, greater pore space, improved nutrient retention, and efficient nutrient availability resulting from the combined use of organic and nano-based inputs. Therefore, the integrated application of neem cake, nano zeolite, and nano fertilizers appears to be a promising approach for improving soil quality and nutrient availability in temperate agroecosystems of Kashmir. However, further multi-season and field-scale studies are recommended to validate the long-term effects,

optimum application rates, and economic feasibility of this integrated nutrient management strategy.

6. Conflict of Interest

Author has no conflict of interest at all.

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