



RESEARCH ARTICLE

Synergistic effect of long-term nutrient management and biopolymer composites on soil health and productivity of rice-lentil cropping system under rainfed ecosystem

Chetan Gyawali^{1*}, Ajay Kumar Mishra², Anthony Fulford^{2*} & Nirmal De^{1*}

¹Soil Science and Agricultural Chemistry, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi 221 005, Uttar Pradesh, India

²International Rice Research Institute (IRRI)-South Asia Regional Centre (ISARC), Varanasi 221 006, Uttar Pradesh, India

*Correspondence email - chetan123@bhu.ac.in; nirmalde.soil@bhu.ac.in; a.fulford@cgiar.org

Received: 12 February 2026; Accepted: 27 April 2026; Available online: Version 1.0: 31 May 2026

Cite this article: Chetan G, Ajay KM, Anthony F, Nirmal De. Synergistic effect of long-term nutrient management and biopolymer composites on soil health and productivity of rice-lentil cropping system under rainfed ecosystem. Plant Science Today. 2026; 13(sp2): 1-10. <https://doi.org/10.14719/pst.14086>

Abstract

To intensify rainfed dryland agriculture sustainably, nutrient management practices that improve soil health without compromising productivity are needed. This study evaluated the long-term effects of fertiliser application in conjunction with the short-term application of nutrient-enriched nano-clay biopolymer composites (NCPCs) on soil properties, nutrient dynamics and crop productivity in a rainfed rice-lentil system. The experiment was conducted in a 38-year-old long-term fertiliser trial with the following treatments: control (no applied nutrients), 100 % recommended dose of fertiliser (RDF) (80:40:30 kg N:P₂O₅:K₂O ha⁻¹), 50 % RDF, 50 % RDF+ 50 % nitrogen (N) (foliar spray), 50 % farmyard manure (FYM), 100 % FYM at 5 t ha⁻¹, 50 % RDF + 50 % FYM and farmer practices as a main plot treatments, along with different NCPC treatments as subplot treatments under split plot design during 2023 and 2024. The integrated application of 50 % RDF and 50 % FYM improved soil physicochemical and biological properties and increased the active carbon pool (30 % of the total organic carbon) and the lability index (0.97) compared to the control. The conjunctive use of 50 % RDF and 50 % FYM produced the highest rice yield (2246 kg ha⁻¹), lentil yield (952 kg ha⁻¹) and system equivalent rice yield (5019 kg ha⁻¹). The application of NCPC resulted additive effects, such as molybdenum/*Arthrobotrys oligospora*-loaded composites enhanced lentil productivity, whereas potassium- and zinc-loaded composites improved nutrient uptake. The integration of long-term organic-inorganic fertilisation with nano-enabled nutrient and microbial delivery system improved biological functioning and system productivity of rice under rainfed conditions of the Indo-Gangetic plains.

Keywords: integrated nutrient management; nano-clay biopolymer composite; rainfed ecosystem; rice-lentil cropping; yield

Introduction

To meet the growing demand for food, modern agriculture relies mostly on chemical fertilisers, however, their continuous imbalanced application degrades the physicochemical and biological properties of the soil (1). The long-term use of inorganic fertilisers without organic inputs reduces soil organic carbon (SOC) and disrupts the nutrient cycle, even though they increase short-term yields. Farmyard manure (FYM), on the other hand, enhances soil organic matter, aggregation, moisture retention and nutrient-buffering capacity, thereby maintaining carbon sequestration and productivity (2, 3). Long-term fertiliser trials are crucial for evaluating the sustainability of cropping systems and the evolution of soil quality (4). Large parts of the Indo-Gangetic plains are left as rice fallows during the rabi season due to residual moisture scarcity and nutrient losses in rainfed rice-based systems (5). Under these conditions, lentil cultivation often faces moisture stress and limited nutrient availability.

In rainfed systems, conventional fertilisers often undergo nutrient losses through volatilisation and leaching, leading to low nutrient use efficiency. Superabsorbent nano-clay biopolymer composites (NCPCs) enhance soil moisture retention and enable

controlled nutrient release (6). The application of a biodegradable starch-based polymer to nano-clay further enhances structural stability and fertiliser use efficiency (7). In addition to serving as nutrient carriers, biopolymers can also act as carriers of beneficial microorganisms, which may help enhance crop stress tolerance and disease control (8). However, very few field experiments have been conducted on the short-term impact of biopolymers in rainfed rice-based cropping systems. Therefore, the present experiment was undertaken to study the long-term effects of fertiliser treatments and the short-term impacts of NCPC treatments on nutrient availability, SOC dynamics, nutrient uptake and productivity in a rainfed rice-lentil system under dry conditions.

Materials and Methods

Synthesis and characterisation of the nanocomposites

The starch-grafted nutrient- and fungus-loaded NCPC was synthesised using the methods given in earlier study (9). The synthesised nanocomposites were characterised using an X-ray diffractometer (XRD).

Experimental site

The experiment was conducted in a long-term fertiliser experimental (LTFE) established under the All India Coordinated Research Project for Dryland Agriculture at the Agricultural Research Farm of Banaras Hindu University, Varanasi, Uttar Pradesh, India (25.25517° N, 82.98582° E and 128.93 m above sea level). The experiment was initiated in 1985 under a rainfed rice (NDR-97)-lentil (HUL-57) cropping system. The soil at the study site was an inceptisol belonging to the Typic Ustrochrepts subgroup. The experimental site is characterised by a dry tropical climate with strong seasonal variations in temperature and precipitation. The site received an average of 1018 mm during the two study years (2023–24 and 2024–25), with more than 80 % of the rainfall occurring during the June–September southwest monsoon. The cropping season was marked by a notable water shortage, as reflected by the mean seasonal potential evapotranspiration (PET) of approximately 1219 mm. The minimum temperature was 18.7 °C, while the mean maximum temperature was 31.6 °C. Winter temperatures occasionally declined to about 10 °C, whereas summer temperatures often reached 40 °C. Rice (NDR-97) was grown in the rainy (kharif) season (last week of June each year) after the onset of the first rainfall, followed by lentil (HUL-57) during the winter (rabi) season (last week of October to the first week of November).

Field experiment

The study was conducted within an established long-term fertiliser experiment, where each treatment plot had a gross size of 11 × 10 m. These plots served as main plots, within which four subplots (1 × 1.5 m) were established. Therefore, the long-term fertiliser trial was modified into a split plot design with 8 main plot treatments and 4 subplot treatments. The 38-year-old main plot served as the whole plot factor in a split plot design and the different NCPC formulation are the subplot factor. The experiment was arranged in 3 blocks representing 3 replications. The treatment details are presented in Table 1. Rainfed rice was directly sown after the first rainfall shower during the last week of June to the first week of July, with a row spacing of 20 cm and a seed rate of 35 kg ha⁻¹. The fertiliser treatments were broadcast in the plots after land preparation and layout, whereas NCPC the treatments were broadcasted in plot after seed sowing. Likewise, the succeeding lentil crop was also directly sown during last week of October to first week of November, with a row spacing of 30 cm and seed rate of 45 kg ha⁻¹.

Soil and plant sampling and analysis

Soil and plant samples (grain and straw) were collected randomly from the treated plots. Field moist surface soil samples (0–15 cm) were collected after the rice harvest between 2023 and 2024. A portion of the soil sample was kept at 4 °C for examination of its biological parameters while chemical analyses were performed on air-dried samples. The soil samples were air dried, gently ground and sieved through a 0.5 mm sieve before laboratory analysis for the determination various carbon pools. Soil pH and electrical conductivity (EC) were measured via a 1:2.5 soil-to-water suspension (10). To assess the chemical parameters of the soil, available nitrogen (N) was determined by the alkaline potassium permanganate (KMnO₄) method (11), available phosphorus (P) was extracted via sodium bicarbonate (0.5 M NaHCO₃) and quantified spectrophotometrically (12) and available potassium (K) was determined via neutral N ammonium acetate and quantified using a flame photometer (13). Similarly, diethylene triamine penta acetic acid (DTPA)-extractable micronutrients (iron (Fe), zinc (Zn), copper (Cu) and manganese (Mn)) were determined via atomic absorption spectroscopy (14).

Moreover, SOC was determined by the Walkley and Black (1934) method and the fractions of the very labile pool (VLP), labile pool (LP), less labile pool (LLP) and nonlabile pool (NLP) of organic carbon were examined using the modified Walkley and Black method (15). The active carbon pools, passive carbon pools and lability indices were calculated using the standard protocol (16).

Active pool (AP) = VLP + LP (unstable/labile)

Passive pool (PP) = LLP + NLP (stable/nonlabile)

Lability index (LI) = [(Cfrac1/TOC) × 3 + [(Cfrac2/TOC) × 2 + (Cfrac3/TOC) × 1].

The dehydrogenase activity (17), soil microbial biomass carbon (18), urease activity (19) and soil respiration (20) were measured to assess the biological characteristics of the soil.

The grain and straw samples were dried in an oven for 3 days at 65 °C and grounded. The total N content of the samples was estimated via Kjeldahl's method (21). For estimation of other total P and total K values, wet-acid digestion of dried grain and straw samples was performed with a diacid mixture of HNO₃ and HClO₄ at a ratio of 4:1 (10). The total P concentration was estimated spectrophotometrically via the vanado molybdo phosphoric

Table 1. Treatment details

Experimental design	Split plot design
Cropping system	Rice (NDR-97) as main crop and lentil (HUL-57) as residual crop
Main plot treatments	
T ₁	Control
T ₂	100 % RDF (80:40:30 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹)
T ₃	50 % RDF (40:20:15 30 N:P ₂ O ₅ :K ₂ O kg ha ⁻¹)
T ₄	50 % RDF (soil) and 50 % N (foliar)
T ₅	50 % N (FYM) (40 kg ha ⁻¹ N through FYM)
T ₆	100 % N (FYM) (80 kg ha ⁻¹ N through FYM)
T ₇	50 % RDF and 50 % N (FYM)
T ₈	Farmers practice (20 kg N ha ⁻¹)
Subplot treatments	
KNPCPC	Starch grafted NCPC superabsorbent at 100 kg ha ⁻¹ loaded with potassium at 5 kg ha ⁻¹
ZnNCPC	Starch grafted NCPC superabsorbent at 100 kg ha ⁻¹ loaded with zinc at 5 kg ha ⁻¹
MoNCPC	Starch grafted NCPC superabsorbent at 100 kg ha ⁻¹ loaded with molybdenum 5 kg ha ⁻¹
Arthro NCPC	NCPC loaded with Starch grafted NCPC superabsorbent at 100 kg ha ⁻¹ loaded with <i>Arthrobotrys oligospora</i> at 5 kg ha ⁻¹

RDF: recommended dose of fertiliser; FYM: farmyard manure; KNPCPC: potassium-loaded nano-clay biopolymer composite; ZnNCPC: zinc-loaded nano-clay biopolymer composite; MoNCPC: molybdenum-loaded nano-clay biopolymer composite; *Arthro* NCPC: *Arthrobotrys oligospora*-loaded nano-clay biopolymer composite. N, P and K were applied through urea, diammonium phosphate (DAP) and muriate of potash (MOP), respectively.

yellow colour method (22). The total K concentration was estimated via a flame photometer (23) and the total Zn concentration was estimated via atomic absorption spectroscopy.

The nutrient uptake by the grain and straw samples was calculated via the following formula (24):

Nutrient uptake (kg ha⁻¹) by macronutrients = Nutrient content (%) × Yield (kg ha⁻¹) × 10⁻²

Nutrient uptake (g ha⁻¹) by Zn = Nutrient content (mg kg⁻¹) × Yield (kg ha⁻¹) × 10⁻³

The equivalent rice yield was calculated as follows (25):

Equivalent rice yield = Lentil yield (kg ha⁻¹) × Price of lentil (Rs kg⁻¹) / Price of rice (Rs kg⁻¹) + Rice yield (kg ha⁻¹).

Statistical analysis

The experimental data were subjected to statistical analysis via the RStudio version 4.3.2 (R Foundation for Statistical Computing, Vienna, Austria) package. Analysis of variance (ANOVA) and Duncan's multiple range test were used to compare the least significant difference (LSD) values at $p \leq 0.05$.

Results and Discussion

Characterisation of the synthesised nano-clay biopolymers composites

Clay and synthesised biopolymer nanocomposites were characterised through XRD. The results revealed the typical characteristics peak ($2\theta = 5.81^\circ$ and 9.01°) of montmorillonite clay along with other impurities such as quartz (Fig. 1). Such peak was absent in the starch grafted K-loaded, starch grafted Zn-loaded, starch grafted molybdenum loaded and starch grafted *Arthrobotrys oligospora*-loaded nano-clay biopolymer composite (*Arthro* NCPC) respectively. The absence of the typical montmorillonite clay peak indicated the complete dispersion of clay platelets into the polymer matrixes. Similar results of complete dispersion of clay peak in XRD studies of synthesised nanocomposites were corroborated by previous studies (7, 26).

Effects of long-term fertilisation and nano-clay biopolymers composites on soil physicochemical properties

Fertiliser treatments significantly influenced soil physicochemical properties, whereas NCPC formulations produced selective effects (Table 2). The pH of the soil differed significantly among the fertiliser treatments ($p \leq 0.05$), with the highest pH occurring under 50 % FYM (6.99 ± 0.03) and the lowest occurring under 50 % recommended dose of fertiliser (RDF) + 50 % FYM (6.51 ± 0.18). The effect of NCPC treatments was not significant, whereas the interaction effects on pH were significant. The reduction in soil pH under integrated fertilisation may be attributed to organic acid production during decomposition and nitrification processes reported in long-term studies (27, 28). Fertiliser levels had a significant effect on EC ($p \leq 0.05$), with greater EC at 100 % FYM and the lowest EC was observed in the control treatment due to mineralisation of the organic inputs; nevertheless, the EC was within a non-saline range (29, 30). Nitrogen (N) availability varied dramatically among N rates ($p \leq 0.05$) and the highest value was recorded under 100 % RDF (188 ± 16.2 kg ha⁻¹), which could be attributed to the ease of obtaining N and organic manure being more difficult to mineralise (31). Among the NCPC treatments, the *Arthro* NCPC presented much greater available N ($p \leq 0.05$) because of the regulated release of moisture, which increased the availability of nitrate over time (8) and microbial-mediated N transformation (6, 32). The fertiliser level ($p \leq 0.05$), with the maximum P being less than 50 % RDF + 50 % FYM, had a significant effect because of its lower degree of fixation and greater solubility of organic acid (27). The increased phosphorus availability was explained by the production of organic acids and the solubilisation of phosphorus sources that occur in native soil by microorganisms with biopolymer composites under subplot treatments that had *A. oligospora* loaded (33). Available K differed significantly among fertiliser and NCPC treatments ($p \leq 0.05$). Higher K levels were observed in FYM-based treatments and KNCPC treatments. This response may be related to enhance cation exchange capacity due to addition of organic manures. Likewise, the natural calcium or sodium ions in the montmorillonite interlayer gaps might be replaced by the K⁺ injected into the biopolymer. Instead of dissolving

Table 2. Impact of long-term fertilisation and nano-clay biopolymers on soil physicochemical properties (pooled data from 2023 to 2024)

Treatments	pH	EC ($\mu\text{S m}^{-1}$)	Available nitrogen (kg ha ⁻¹)	Available phosphorus (kg ha ⁻¹)	Available potassium (kg kg ⁻¹)
Fertiliser treatments					
Control	$6.68 \pm 0.04^{\text{cd}}$	$70.7 \pm 12.2^{\text{d}}$	$120 \pm 10.5^{\text{d}}$	$11.2 \pm 4.87^{\text{e}}$	$80.0 \pm 4.07^{\text{c}}$
100 % RDF	$6.6 \pm 0.19^{\text{de}}$	$74.7 \pm 17.3^{\text{cd}}$	$188 \pm 16.2^{\text{a}}$	$49.2 \pm 7.2^{\text{b}}$	$93.2 \pm 3.59^{\text{ab}}$
50 % RDF	$6.79 \pm 0.13^{\text{bc}}$	$87.1 \pm 17.4^{\text{a}}$	$154 \pm 12.7^{\text{b}}$	$24.5 \pm 4.85^{\text{d}}$	$87 \pm 3.8^{\text{bc}}$
50 % soil + 50 % foliar	$6.7 \pm 0.15^{\text{cd}}$	$74.1 \pm 17.4^{\text{cd}}$	$184 \pm 14.9^{\text{a}}$	$36.6 \pm 4.8^{\text{c}}$	$85.4 \pm 4.97^{\text{c}}$
50 % FYM	$6.99 \pm 0.03^{\text{a}}$	$84.8 \pm 17.2^{\text{ab}}$	$144 \pm 8.81^{\text{c}}$	$34.7 \pm 5.88^{\text{c}}$	$93.8 \pm 6^{\text{ab}}$
100 % FYM	$6.89 \pm 0.03^{\text{ab}}$	$91 \pm 19.5^{\text{a}}$	$160 \pm 12.8^{\text{b}}$	$44.8 \pm 7.08^{\text{b}}$	$99.5 \pm 5.23^{\text{a}}$
50 % RDF + 50 % FYM	$6.51 \pm 0.18^{\text{e}}$	$75.8 \pm 19.8^{\text{bcd}}$	$155 \pm 12.2^{\text{b}}$	$55.7 \pm 7.26^{\text{a}}$	$96.8 \pm 4.88^{\text{a}}$
FP	$6.72 \pm 0.03^{\text{c}}$	$82.6 \pm 18^{\text{abc}}$	$122 \pm 11.3^{\text{d}}$	$20 \pm 2.95^{\text{d}}$	$81.3 \pm 4.4^{\text{c}}$
cv (a)	2.84 %	21.33 %	8.64 %	26.48 %	15.57 %
LSD ($p \leq 0.05$)	0.117	13.81	7.33	5.92	7.6
NCPC treatments					
KNCPC	$6.74 \pm 0.24^{\text{a}}$	$77.7 \pm 16.6^{\text{a}}$	$154 \pm 25.7^{\text{ab}}$	$34.5 \pm 16.4^{\text{a}}$	$102.5 \pm 4.08^{\text{a}}$
ZnNCPC	$6.71 \pm 0.23^{\text{a}}$	$79.1 \pm 20.3^{\text{a}}$	$152 \pm 22.4^{\text{b}}$	$33.6 \pm 14.4^{\text{a}}$	$85.9 \pm 4.66^{\text{b}}$
MoNCPC	$6.76 \pm 0.20^{\text{a}}$	$84.8 \pm 17.7^{\text{a}}$	$150 \pm 28.8^{\text{b}}$	$35.2 \pm 15.7^{\text{a}}$	$87.3 \pm 4.59^{\text{b}}$
<i>Arthro</i> NCPC	$6.74 \pm 0.21^{\text{a}}$	$78.8 \pm 18.8^{\text{a}}$	$159 \pm 28.7^{\text{a}}$	$35 \pm 15.5^{\text{a}}$	$82.7 \pm 4.38^{\text{c}}$
cv (b)	1.86 %	17.58 %	7.84 %	11.28 %	8.39 %
LSD ($p \leq 0.05$)	ns	ns	4.86	ns	3.04
Interaction (main*sub)	0.171	ns	ns	7.07	ns

RDF: recommended dose of fertiliser; FYM: farmyard manure; FP: farmers practices; KNCPC: potassium-loaded nano-clay biopolymer composite; ZnNCPC: zinc-loaded nano-clay biopolymer composite; MoNCPC: molybdenum-loaded nano-clay biopolymer composite; *Arthro* NCPC: *Arthrobotrys oligospora*-loaded nano-clay biopolymer composite; cv: coefficient of variation; LSD: least significant difference.

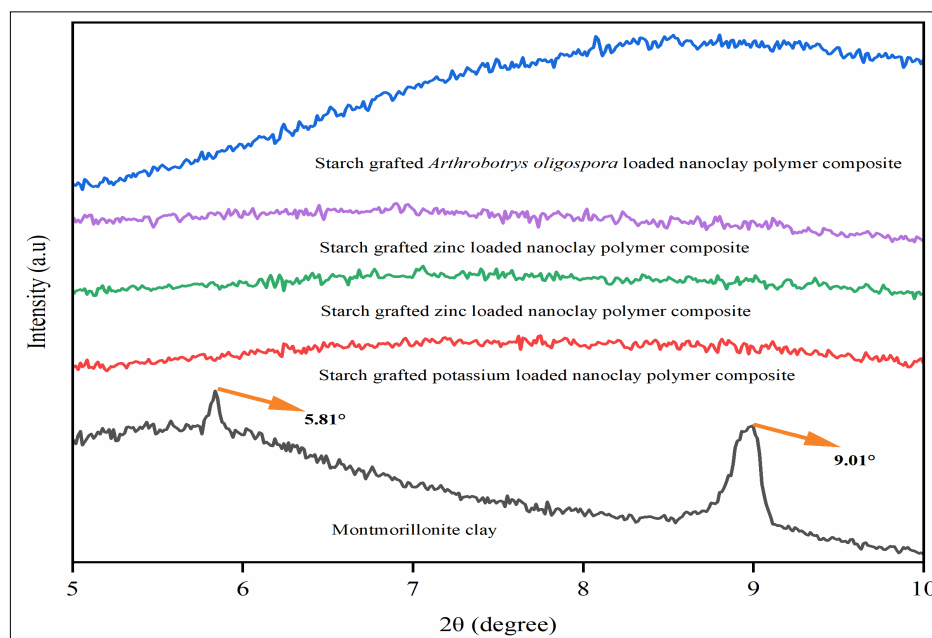


Fig. 1. X-ray diffractometer (XRD) spectra of clay and nano-clay biopolymer composite (NCPC) formulations.

instantly like commercial fertiliser, the nutrient release would be gradual through ion-exchange with the soil solution after it has intercalated or exfoliated (29, 34).

Effects of long-term fertilisation and nano-clay biopolymers composites on soil micronutrients

Fertiliser treatments significantly affected DTPA-extractable micronutrients, whereas NCPC treatments produced selective effects (Table 3). The concentration of Zn under fertiliser treatments varied significantly ($p \leq 0.05$). The 100 % FYM treatment had significantly higher Zn concentration ($0.372 \pm 0.06 \text{ g ha}^{-1}$) followed by 50 % RDF + 50 % FYM ($0.35 \pm 0.06 \text{ g ha}^{-1}$) whereas lowest was observed under control ($0.234 \pm 0.04 \text{ g ha}^{-1}$). Fertiliser treatments also significantly influenced Cu, Mn and Fe concentrations. Higher values of these micronutrients were generally observed in FYM-based and integrated treatments, likely due to enhanced organic chelation and mineralisation processes (28, 29). Nano-clay biopolymer composites (NCPC) treatments significantly influenced Zn availability ($p \leq 0.05$), with ZnNCPC producing highest DTPA-extractable Zn content. This

could be because Zn-loaded biopolymer nanocomposite served as a regulated nutrient delivery system that shielded Zn from quick soil fixation and leaching (35). However, NCPC treatments did not significantly affect Mn and Fe concentrations. The interaction effect was significant only between Fe and Cu, implying that there is different mobilisation of Fe and Cu when they are managed together. This could possibly be due to controlled release due to NCPC formulations and better chelation offered by organic manures that increased micronutrient availability, which is in line with the characteristics of zincated NCPCs (36).

Effects of long-term fertilisation and nano-clay biopolymers composites on soil biological properties

The long-term fertiliser and short-term NCPC management significantly affected the soil biological properties, as illustrated in Table 4. Urease activity ranged from 78.3 ± 11.5 to $138.7 \pm 15.2 \text{ } \mu\text{g NH}_4^+\text{-N g}^{-1} \text{ soil hr}^{-1}$. The highest activity was recorded under the 50 % RDF + 50 % FYM treatment ($138.7 \pm 15.2 \text{ } \mu\text{g NH}_4^+\text{-N g}^{-1} \text{ soil hr}^{-1}$), followed by the 100 % FYM treatment, whereas the lowest value

Table 3. Impact of long-term fertilisation and nano-clay biopolymers on DTPA-extractable micronutrients (pooled data from 2023 to 2024)

Treatments	Zinc (mg kg^{-1})	Copper (mg kg^{-1})	Manganese (mg kg^{-1})	Iron (mg kg^{-1})
Fertiliser treatments				
Control	0.234 ± 0.04^e	1.02 ± 0.16^e	5.51 ± 1.66^d	49.2 ± 16.3^e
100 % RDF	0.306 ± 0.05^c	1.2 ± 0.21^{abc}	8.27 ± 1.54^{bc}	80.5 ± 14.8^b
50 % RDF	0.269 ± 0.05^d	1.09 ± 0.09^{cde}	7.58 ± 1.84^c	67 ± 18.8^{cd}
50 % soil + 50 % foliar	0.295 ± 0.05^c	1.15 ± 0.16^{bcd}	8.32 ± 1.43^{bc}	79.7 ± 10.1^{bc}
50 % FYM	0.333 ± 0.04^b	1.19 ± 0.19^{abc}	8 ± 1.66^{bc}	82.2 ± 14.1^b
100 % FYM	0.372 ± 0.06^a	1.29 ± 0.17^a	9.77 ± 1.61^a	96.9 ± 12.4^a
50 % RDF + 50 % FYM	0.35 ± 0.06^b	1.2 ± 0.26^{ab}	8.93 ± 1.58^{ab}	83.8 ± 11.9^b
FP	0.252 ± 0.04^{de}	1.06 ± 0.13^{de}	5.81 ± 1.36^d	59.7 ± 13.8^{de}
cv (a)	12.41 %	16.30 %	27.01 %	29.49 %
LSD ($p \leq 0.05$)	0.022	0.11	1.24	12.9
NCPC treatments				
KNPCPC	0.283 ± 0.06^b	1.19 ± 0.21^a	7.87 ± 2.33^a	74.6 ± 22.1^a
ZnNCPC	0.360 ± 0.06^a	1.16 ± 0.18^{ab}	7.57 ± 1.76^a	72.9 ± 20.7^a
MoNCPC	0.277 ± 0.06^b	1.12 ± 0.19^b	7.76 ± 2.03^a	76.7 ± 18.4^a
Arthro NCPC	0.286 ± 0.07^b	1.13 ± 0.18^{ab}	7.9 ± 2.19^a	75.3 ± 19^a
cv (b)	11.71 %	11.22 %	18.19 %	14.81 %
LSD ($p \leq 0.05$)	0.014	0.052	ns	ns
Interaction (main*sub)	ns	0.183	ns	17.18

DTPA: diethylene triamine penta acetic acid; RDF: recommended dose of fertiliser; FYM: farmyard manure; FP: farmers practices; KNPCPC: potassium-loaded nano-clay biopolymer composite; ZnNCPC: zinc-loaded nano-clay biopolymer composite; MoNCPC: molybdenum-loaded nano-clay biopolymer composite; Arthro NCPC: *Arthrobotrys oligospora*-loaded nano-clay biopolymer composite; cv: coefficient of variation; LSD: least significant difference.

Table 4. Impact of long-term fertilisation and nano-clay biopolymers on soil biological properties (pooled data from 2023 to 2024)

Treatments	Urease ($\mu\text{g NH}_4^+\text{-N g}^{-1}\text{ soil hr}^{-1}$)	Soil respiration ($\mu\text{g CO}_2\text{ g}^{-1}\text{ hr}^{-1}$)	MBC ($\mu\text{g g}^{-1}\text{ soil}$)	Dehydrogenase ($\mu\text{g TPF g}^{-1}\text{ hr}^{-1}$)
Fertiliser treatments				
Control	78.3 $\pm$ 11.5 ^d	16.3 $\pm$ 3.59 ^f	107 $\pm$ 12.1 ^g	2.98 $\pm$ 0.48 ^d
100 % RDF	99.9 $\pm$ 11.6 ^c	22.9 $\pm$ 4.15 ^{cd}	300 $\pm$ 16.6 ^d	4.32 $\pm$ 0.77 ^{bc}
50 % RDF	96.5 $\pm$ 20.4 ^{cd}	20.3 $\pm$ 3.69 ^{de}	238 $\pm$ 11.5 ^e	3.61 $\pm$ 0.46 ^{cd}
50 % soil + 50 % foliar	104.2 $\pm$ 14.8 ^{bc}	22.8 $\pm$ 5.16 ^{cd}	291 $\pm$ 14.5 ^d	4.4 $\pm$ 0.66 ^b
50 % FYM	103.1 $\pm$ 21.9 ^c	25.8 $\pm$ 2.89 ^{bc}	419 $\pm$ 23.2 ^b	4.49 $\pm$ 0.66 ^b
100 % FYM	123.1 $\pm$ 13.7 ^{ab}	29.6 $\pm$ 4.08 ^a	505 $\pm$ 33.8 ^a	4.84 $\pm$ 0.71 ^{ab}
50 % RDF + 50 % FYM	138.7 $\pm$ 15.2 ^a	26.8 $\pm$ 3 ^{ab}	362 $\pm$ 24.5 ^c	5.43 $\pm$ 0.66 ^a
FP	90.5 $\pm$ 13.0 ^{cd}	18.3 $\pm$ 3.71 ^{ef}	196 $\pm$ 13.8 ^f	3.37 $\pm$ 0.42 ^d
cv (a)	19.29 %	14.88 %	5.84 %	18.11 %
LSD ($p \leq 0.05$)	11.9	1.93	10.42	0.448
NPCPC treatments				
KNCPC	102.8 $\pm$ 23.1 ^b	21.0 $\pm$ 5.36 ^b	298 $\pm$ 118 ^b	4.16 $\pm$ 0.98 ^a
ZnNCPC	98.9 $\pm$ 25.0 ^b	21.9 $\pm$ 5.33 ^b	299 $\pm$ 121 ^b	4.17 $\pm$ 0.94 ^a
MoNCPC	103.4 $\pm$ 21.7 ^b	21.8 $\pm$ 5.42 ^b	294 $\pm$ 117 ^b	4.17 $\pm$ 1.06 ^a
<i>Arthro</i> NCPC	112.0 $\pm$ 22.6 ^a	26.6 $\pm$ 4.78 ^a	318 $\pm$ 128 ^a	4.22 $\pm$ 0.92 ^a
cv (b)	11.79 %	12.11 %	3.18 %	9.83 %
LSD ($p \leq 0.05$)	4.97	1.12	3.88	ns
Interaction (main*sub)	ns	ns	17.53	ns

RDF: recommended dose of fertiliser; FYM: farmyard manure; FP: farmers practices; KNCPC: potassium-loaded nano-clay biopolymer composite; ZnNCPC: zinc-loaded nano-clay biopolymer composite; MoNCPC: molybdenum-loaded nano-clay biopolymer composite; *Arthro* NCPC: *Arthrobotrys oligospora*-loaded nano-clay biopolymer composite; cv: coefficient of variation; LSD: least significant difference.

occurred in the control ($p \leq 0.05$). Soil respiration ranged from 16.3 to 29.6 $\mu\text{g CO}_2\text{ g}^{-1}\text{ hr}^{-1}$ and was significantly higher in FYM-based and integrated fertiliser treatments ($p \leq 0.05$), reflecting increased microbial metabolic activity and N mineralisation. This response reflects enhanced microbial metabolic activity and accelerated carbon cycling under long-term organic carbon inputs (37). Microbial biomass carbon (MBC), which is a labile pool of organic carbon in the soil, was found to be between 196 $\pm$ 12.1 and 505 $\pm$ 33.8 $\mu\text{g g}^{-1}\text{ soil}$ and differed significantly between the 100 % FYM ($p \leq 0.05$) and control treatments (38). Dehydrogenase activity was significantly higher under the 50 % RDF + 50 % FYM treatment ($p \leq 0.05$), with values comparable to those under 100 % FYM, whereas the lowest activity occurred in the control. This response reflects enhanced oxidative activity of soil microorganisms under balanced nutrient management (27, 39). The high urease activity, soil respiration and MBC observed in the *Arthro* NCPC treatment could be attributed to the prolonged release of N, the increased soil moisture sequestration

and the stimulation of microorganisms within the fungus that are immobilised in the clay polymer matrix (8). The interaction effect of fertiliser and NPCPC level did not significantly affect urease, soil respiration or dehydrogenase activity, however, the interaction effect on the biomass carbon of microbes was found to be significant. The interaction between 100 % FYM and *Arthro* NCPC significantly increased microbial activity in the soil, possibly due to presence of large amount of metabolisable C from FYM and slow release of *A. oligospora* from nanocomposites, thereby increasing microbial activity in the soil (Fig. 2).

Effects of long-term fertilisation and nano-clay biopolymers composites on nutrient uptake

Fertiliser treatments significantly influenced nutrient uptake, whereas NPCPC treatments produced selective effects (Table 5). Compared with the control, nutrient uptake in grain and straw was significantly greater under organic fertiliser applied either alone or in combination with inorganic fertiliser, with the highest uptake

Table 5. Impact of long-term fertilisation and nano-clay biopolymers on nutrient uptake (pooled data from 2023 to 2024)

Fertiliser treatments	Nitrogen uptake (kg ha ⁻¹)		Phosphorus uptake (kg ha ⁻¹)		Potassium uptake (kg ha ⁻¹)		Zinc uptake (g ha ⁻¹)	
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
Control	22.2 $\pm$ 8.35 ^f	31.7 $\pm$ 18 ^f	3.82 $\pm$ 1.49 ^f	6.91 $\pm$ 4.32 ^d	1.87 $\pm$ 0.74 ^f	48.5 $\pm$ 27 ^e	23.2 $\pm$ 14.2 ^g	64.7 $\pm$ 40.4 ^d
100 % RDF	36.6 $\pm$ 10.2 ^c	68.8 $\pm$ 16.3 ^{bc}	7.34 $\pm$ 2.59 ^c	13.01 $\pm$ 4.42 ^b	3.33 $\pm$ 1.16 ^c	106.6 $\pm$ 27.3 ^b	60.8 $\pm$ 14.7 ^c	168.8 $\pm$ 32.9 ^b
50 % RDF	33.1 $\pm$ 10.1 ^d	50.7 $\pm$ 17 ^e	6.08 $\pm$ 2.08 ^d	10.67 $\pm$ 4.15 ^c	2.92 $\pm$ 1.32 ^d	82.2 $\pm$ 30.4 ^{cd}	48.3 $\pm$ 12.5 ^e	115.8 $\pm$ 30.6 ^c
50 % soil + 50 % foliar	35.1 $\pm$ 10.6 ^{cd}	65.6 $\pm$ 16.4 ^{cd}	6.96 $\pm$ 2.50 ^c	11.02 $\pm$ 4.15 ^{bc}	3.13 $\pm$ 1.04 ^{cd}	94.5 $\pm$ 23.1 ^{bc}	57.1 $\pm$ 18.7 ^d	163.8 $\pm$ 47 ^b
50 % FYM	33.9 $\pm$ 11.5 ^d	58.9 $\pm$ 12.6 ^{de}	5.97 $\pm$ 2.04 ^d	10.39 $\pm$ 4.09 ^c	3.23 $\pm$ 1.1 ^c	79.9 $\pm$ 25.8 ^d	46.1 $\pm$ 14.8 ^e	120.2 $\pm$ 33.9 ^c
100 % FYM	40.7 $\pm$ 11 ^b	77.6 $\pm$ 18.2 ^b	8.34 $\pm$ 2.57 ^b	12.86 $\pm$ 4.52 ^b	3.88 $\pm$ 1.21 ^b	121.2 $\pm$ 27.5 ^a	87.7 $\pm$ 25.9 ^a	211.3 $\pm$ 44.5 ^a
50 % RDF + 50 % FYM	45.8 $\pm$ 12 ^a	91.4 $\pm$ 7.73 ^a	8.97 $\pm$ 2.72 ^a	15.31 $\pm$ 3.31 ^a	4.37 $\pm$ 1.16 ^a	131.6 $\pm$ 24 ^a	78.2 $\pm$ 11.3 ^b	215.8 $\pm$ 26.5 ^a
FP	25.2 $\pm$ 9.77 ^e	37.5 $\pm$ 16.6 ^f	5.15 $\pm$ 2.16 ^e	8.04 $\pm$ 4.96 ^d	2.34 $\pm$ 0.97 ^e	58.9 $\pm$ 28.7 ^e	32.4 $\pm$ 10.5 ^f	79.2 $\pm$ 37.4 ^d
cv (a)	11.72 %	27.86 %	12.27 %	29.26 %	14.12 %	23.22 %	9.85 %	22.04 %
LSD ($p \leq 0.05$)	2.23	9.92	0.46	2.02	0.3	12.42	3.15	19.75
NPCPC treatments								
KNCPC	33.9 $\pm$ 13.3	59.8 $\pm$ 22.7	6.57 $\pm$ 2.82	10.4 $\pm$ 4.63 ^b	3.61 $\pm$ 1.54 ^a	94.5 $\pm$ 38.3 ^a	52.1 $\pm$ 24.5 ^b	128 $\pm$ 60 ^c
ZnNCPC	34.2 $\pm$ 10.1	60.6 $\pm$ 23.6	6.61 $\pm$ 2.34	12.2 $\pm$ 4.24 ^a	2.96 $\pm$ 0.96 ^b	93.8 $\pm$ 35.4 ^{ab}	62.4 $\pm$ 26.2 ^a	169 $\pm$ 66.1 ^a
MoNCPC	34 $\pm$ 14	61 $\pm$ 27.9	6.72 $\pm$ 3.09	10.8 $\pm$ 5.47 ^b	3.06 $\pm$ 1.42 ^b	88 $\pm$ 40.8 ^{bc}	50.9 $\pm$ 24 ^b	134 $\pm$ 66.7 ^{bc}
<i>Arthro</i> NCPC	34.2 $\pm$ 12.8	59.7 $\pm$ 23.3	6.41 $\pm$ 2.8	10.8 $\pm$ 5.09 ^b	2.91 $\pm$ 1.16 ^b	85.4 $\pm$ 36.9 ^c	51.5 $\pm$ 26.9 ^b	138 $\pm$ 59 ^b
cv (b)	8.81 %	14.11 %	11.42 %	19.86 %	16.79 %	12.76 %	9.03 %	11.67 %
LSD ($p \leq 0.05$)	ns	ns	ns	0.89	0.21	4.66	1.98	6.72
Interaction (main*sub)	3.66	ns	0.87	ns	0.58	16.32	5.73	25.7

RDF: recommended dose of fertiliser; FYM: farmyard manure; FP: farmers practices; KNCPC: potassium-loaded nano-clay biopolymer composite; ZnNCPC: zinc-loaded nano-clay biopolymer composite; MoNCPC: molybdenum-loaded nano-clay biopolymer composite; *Arthro*

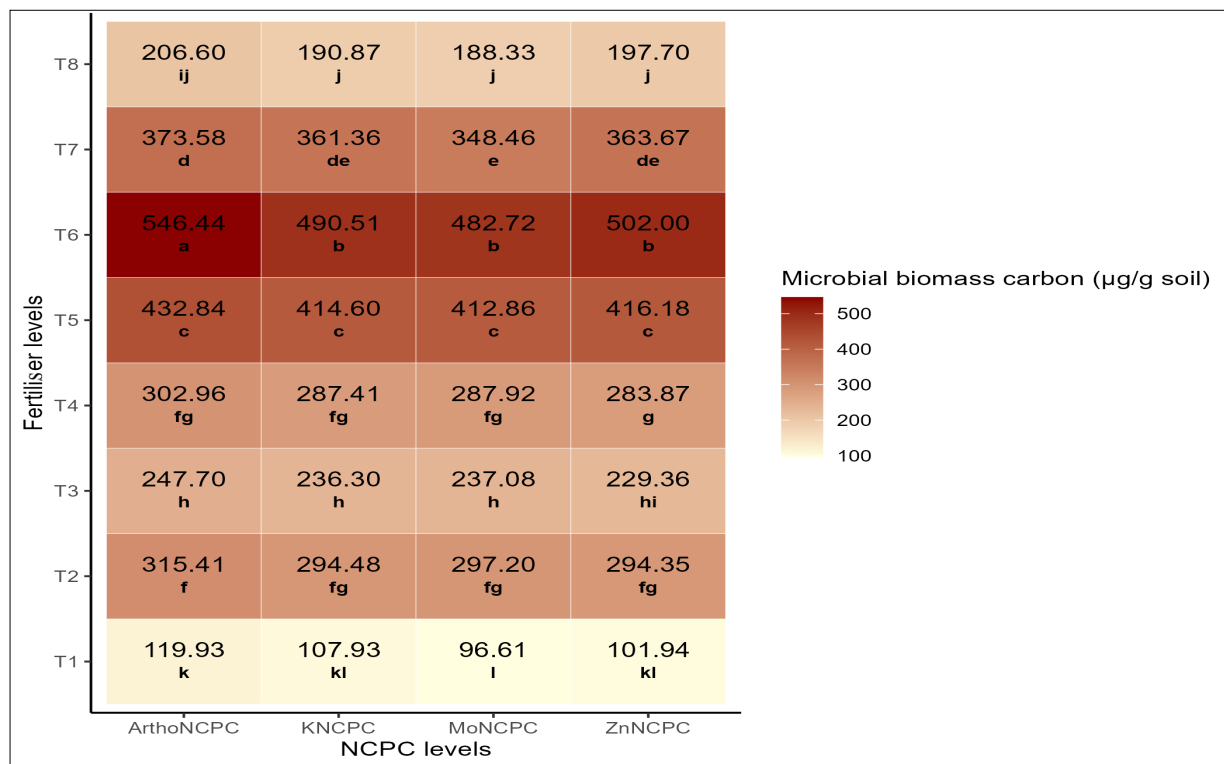


Fig. 2. Interaction between fertiliser treatments and nano-clay biopolymer composite (NCPC) formulations on microbial biomass carbon.

recorded under 50 % RDF + 50 % FYM ($45.8 \pm 12 \text{ kg ha}^{-1}$) ($p \leq 0.05$). Similar patterns were observed for phosphorus and K uptake in both grain and straw. The increased uptake of macronutrients (N, P and K) with or without organic fertiliser was an indication of the increased availability of nutrients and coordinated release of nutrients through integrated nutrient management (40, 41). Similarly, Zn uptake in grain was also much greater in the 100 % FYM treatment ($87.7 \pm 25.9 \text{ g ha}^{-1}$), which was better than that in the other treatments, but Zn uptake by straw was much greater in the FYM-only or integrated treatment than in the control, as the incorporation of FYM increased metal solubility in soil by the formation of ligands that chelate metals, preventing Zn fixation in soil colloids and ultimately increasing the availability of micronutrients to plants (27). Potassium (K)-loaded nano-clay biopolymer composite (KNCPC) and Zn-loaded nano-clay biopolymer composite (ZnNCPC) were some of the NCPCs that were much more effective in stimulating their absorption in grain and straw than the other treatments were, as indicated in Table 5). The grain and straw uptake rates of K were 3.61 ± 1.54 and $94.5 \pm 38.3 \text{ g ha}^{-1}$, respectively, which were much greater than those of the control treatments. Starch-grafted K-loaded NCPC regulates K release in soil, reducing diffusion losses and maintaining K availability in synchrony with crop demand, which supports grain filling (6, 39). Similarly, ZnNCPC markedly increased Zn uptake in grain and straw, which might be explained by the high Zn solubility and the increase in DTPA-Zn content under nano-clay polymer composites (36). The interaction effects were also important for K and Zn uptake, implying greater or complementary advantages of fertiliser level and K- and Zn-loaded biopolymer composites.

Effects of long-term fertilisation and nano-clay biopolymers composites on soil organic carbon (SOC) pools and lability index

The proportion of active carbon pools was higher in the 100 % FYM and 50 % RDF + 50 % FYM treatments, accounting for approximately 30 % of total organic carbon (TOC), whereas the lowest proportion was recorded in the control treatment (about 20 %) (Fig. 3). A high amount of active carbon were present in the FYM-based treatment due to higher availability of easily decomposable substrate that was

readily available (41). A significant proportion of passive carbon was yielded by the carbon pool in all the treatments, but in the control treatment, relatively more passive carbon was found (79 % of TOC) than in the 100 % FYM and 50 % RDF + 50 % FYM treatments (70 % of TOC in each case). This was a proportional growth in active carbon pools as opposed to diminished stabilisation. The highest lability index (LI) was observed at a ratio lower than 50 % RDF + 50 % FYM (0.97), followed by 100 % FYM (0.81), whereas the lowest lability index was obtained in the control treatment. The higher active carbon pool in FYM-based and integrated treatments reflects an increase in labile organic carbon fractions. Compared with the control, organic-based treatment increased the pool and index of lability, increasing microbial biomass and carbon turnover (27, 42).

The increased lability index with integrated treatment also indicated increased turnover of carbon and responsiveness of microbes compared with those of the control. Across NCPC treatments, the active carbon pool ranged from 26 % to 27 % of TOC, whereas the passive carbon pool accounted for approximately 73–74 % (Fig. 4). Differences among NCPC treatments were relatively small; however, KNCPC recorded slightly high active carbon pools, whereas MoNCPC registered showed relatively higher passive carbon fractions. There was a small range of lability indices, from 0.90 to 0.91, within the treatments. This partially enhanced the dynamics of labile carbon with the use of several nutrient-loaded composites of biopolymers without considerably altering SOC partitioning. The application of nutrient- and fungus-loaded nanocomposites demonstrated increased synchronisation of nutrient and microbial stimulation without interference with long-term carbon stabilisation mechanisms (8).

Effects of long-term fertilisation and nano-clay biopolymers composites on crop yield and equivalent rice yield

Soil nutrient status is a good indicator of crop production and system yield. Rice yield increased substantially under integrated and organic nutrient management treatments (Fig. 5). The highest yield was recorded under 50 % RDF + 50 % FYM, followed by 100 % FYM

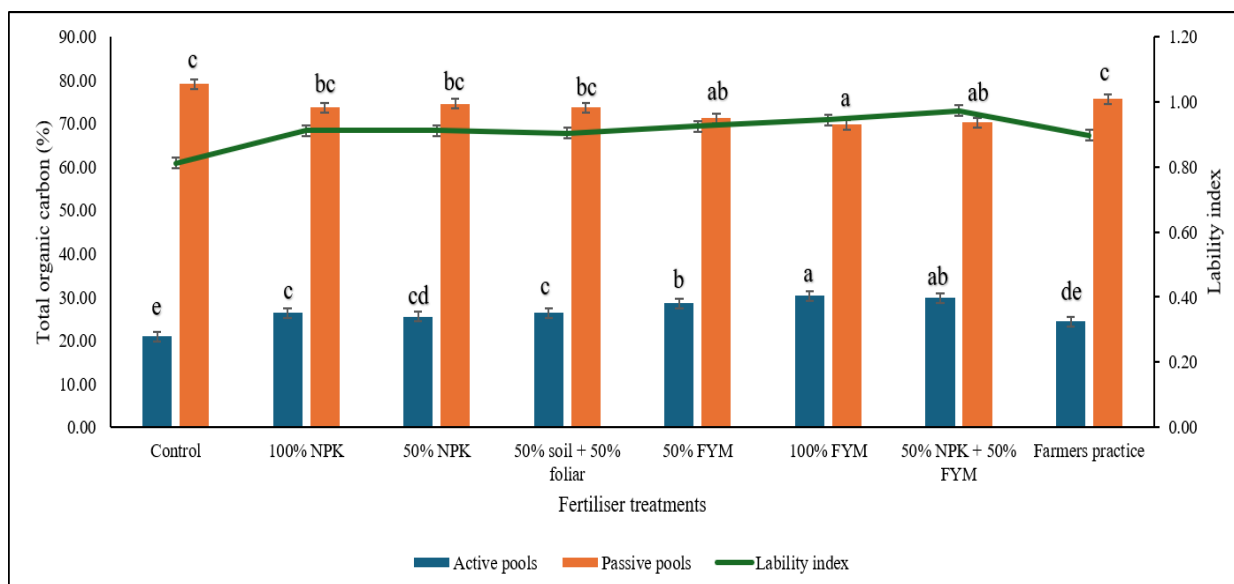


Fig. 3. Impact of fertiliser treatments on the soil organic pools and liability index.

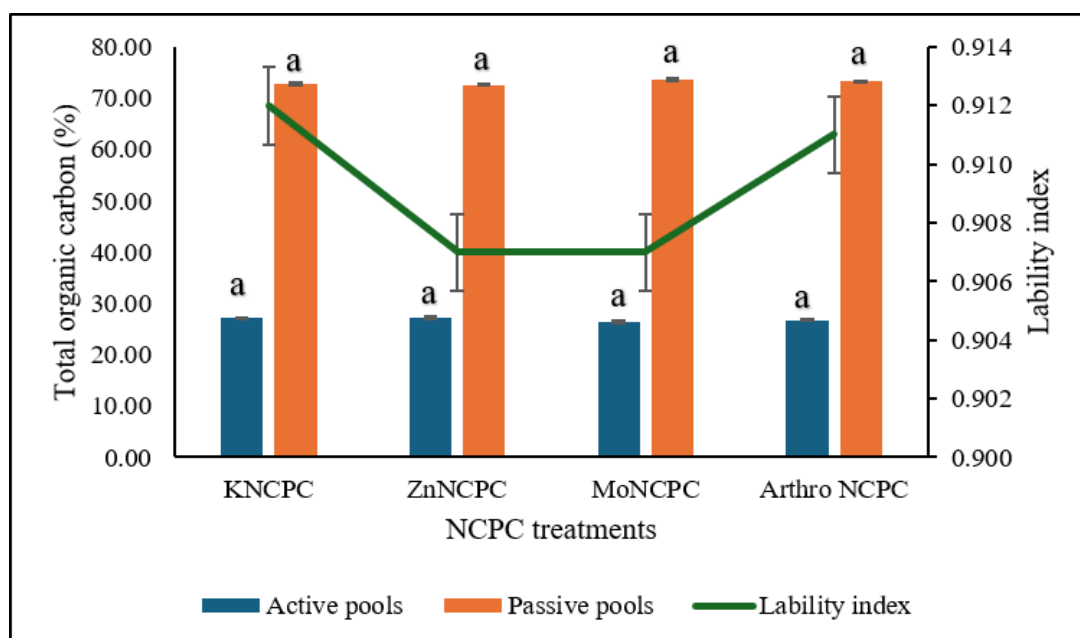


Fig. 4. Impact of nano-clay biopolymer composite (NCPC) treatments on soil organic pools and liability index.

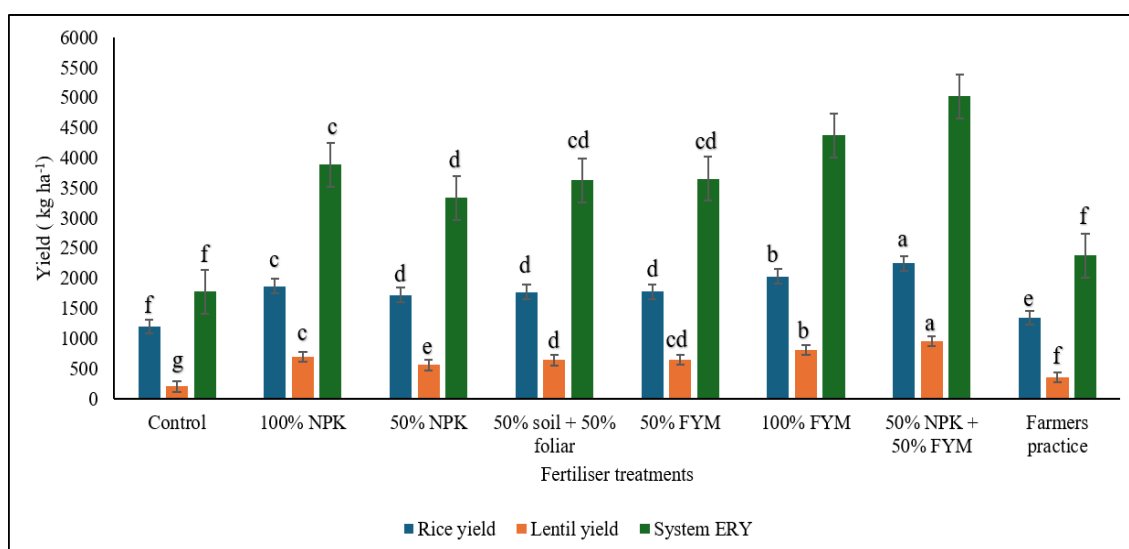


Fig. 5. Impact of fertiliser treatments on yield of rice, lentil and system equivalent rice yield.

and 100 % RDF. The yield of lentils under the control treatment was 199 kg ha⁻¹, whereas under the control treatment, the yield under 50 % RDF + 50 % FYM was 952 kg ha⁻¹; hence, the yield increased significantly. The use of FYM, either alone or in combination with inorganic fertiliser, augmented the amount of SOC and contributed macro- and micronutrients in the soil, facilitating the mineralisation of nutrients, facilitating their timely utilisation by crops and stimulating the growth and activity of microorganisms, which eventually led to improved crop yield (27). Similarly, the highest rice-equivalent yield was reported under the combined application of FYM and inorganic fertiliser (5019 kg ha⁻¹), whereas the lowest equivalent rice yield was recorded under the control treatment (1775 kg ha⁻¹).

Organic inputs may also be used to improve soil aggregation and nutrient retention, thereby increasing crop yield and system productivity (2). The rice yield under different NCPC level, as demonstrated in Fig. 6, ranged from 1727 to 1759 kg ha⁻¹, whereas lentil yield varied greatly, ranging from 477 kg ha⁻¹ under KNCPC to the highest yield under molybdenum-loaded nano-clay biopolymer composite (MoNCPC) (787 kg ha⁻¹). Similarly, the system-equivalent rice yield reached a maximum under the MoNCPC (4022 kg ha⁻¹), followed by the *Arthro* NCPC (3653 kg ha⁻¹) and the lowest yield was under the ZnNCPC (3195 kg ha⁻¹) and KNCPC (3137 kg ha⁻¹). The higher lentil yield under MoNCPC may be attributed to the role of molybdenum as a cofactor in N fixation enzymes, which enhances nodulation and legume productivity (41). The enhanced equivalent rice production under the *Arthro* NCPC was attributed to the prolonged maintenance of the soil moisture and the regulation of the worm population with time, which aided the successful attainment of lentil production under the rainfed rice-lentil system (8). The influence of nano-clay composites was noted to be stronger in lentils than in rice, which suggests the role of legumes in enhancing the productivity of the system.

Conclusion

Long-term nutrient management strategies improved soil health, nutrient availability and productivity in rainfed rice-lentil cropping systems. Integrated nutrient management and farmyard manure

(FYM)-based treatment enhanced the macro- and micronutrient availability, enzymatic activities, carbon dynamics and nutrients uptake, resulting in higher crop yields and system productivity. The short-term application of nutrient and fungi-loaded nano-clay biopolymer composites (NCPC) also improved crop performance, with potassium (K)-loaded nano-clay biopolymer composite (KNCPC) and Zn-loaded nano-clay biopolymer composite (ZnNCPC) increasing nutrient uptake, molybdenum-loaded nano-clay biopolymer composite (MoNCPC) greatly increased the lentil yield and *Arthrobotrys oligospora*-loaded nano-clay biopolymer composite (*Arthro* NCPC), acting as a nano-enabled biofertiliser to improve microbial activity. Combining organic-inorganic fertilisation with nano-enabled biopolymers may enhance nutrient use efficiency and system resilience under rainfed system. Future research should confirm the long-term sustainability of nanocomposites and evaluate the environmental and economic feasibility.

Acknowledgements

The authors would like to acknowledge the technical financial and administrative support of the Institute of Agricultural Sciences, Banaras Hindu University, Project Coordinator of All India Coordinated Research Project on Dryland Agriculture, Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad and International Rice Research Program-South Asia Regional Centre (ISARC), India.

Authors' contributions

CG carried out the field experiment, laboratory analysis and statistical analysis and original manuscript writing. AKM carried out the data visualisation and manuscript editing. AF performed statistical analysis, supervised the experiment and manuscript editing. ND participated in the design of the study, supervised the experiment and edited manuscript. All authors have read and approved the final manuscript.

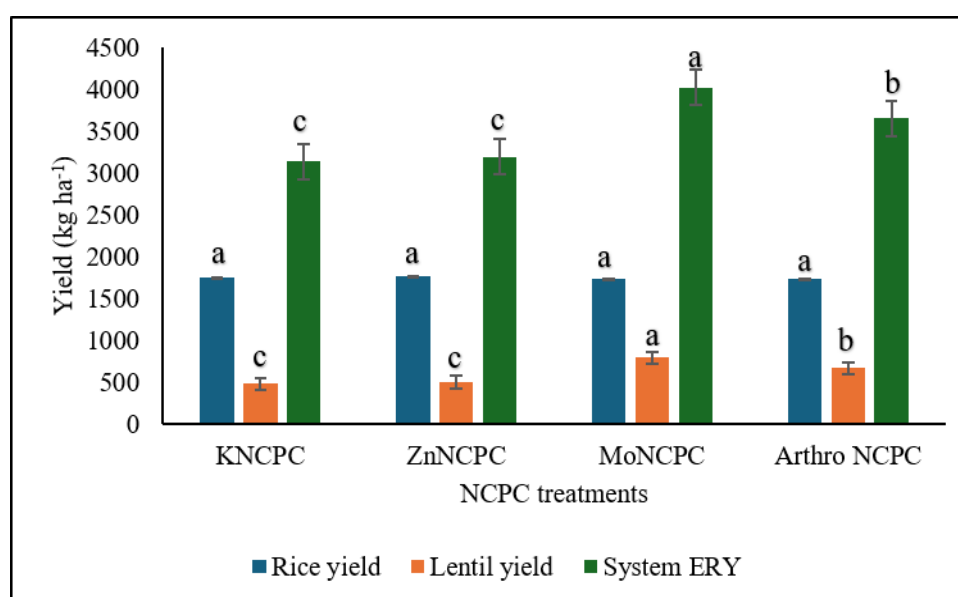


Fig. 6. Impact of nano-clay biopolymer composite (NCPC) treatments rice, lentil and system equivalent rice yield.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

- Bose P, Roy M, Patra PK, Patra PK, Patra PK. Evaluation of long-term different nutrient management practices on crop productivity and soil quality in rice (*Oryza sativa*)-potato (*Solanum tuberosum*)-groundnut (*Arachis hypogaea*) cropping system in new alluvial soil zone of West Bengal, India. *Plant Arch.* 2021;21(Suppl 1):2383–92. <https://doi.org/10.51470/PLANTARCHIVES.2021.v21.S1.390>
- Gupta Choudhury S, Srivastava S, Singh R, Chaudhari SK, Sharma DK, Singh SK, et al. Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice-wheat cropping system under reclaimed sodic soil. *Soil Tillage Res.* 2014;136:76–83. <https://doi.org/10.1016/j.still.2013.10.001>
- Sharma KL, SrinivasaRao Ch, Chandrika DS, Lal M, Indoria AK, Reddy KS, et al. Effect of predominant integrated nutrient management practices on soil quality indicators and soil quality indices under post monsoon (rabi) sorghum (*Sorghum bicolor*) in rainfed black soils (Vertisols) of Western India. *Commun Soil Sci Plant Anal.* 2018;49(13):1629–37. <https://doi.org/10.1080/00103624.2018.1474901>
- Rasmussen PE, Goulding KWT, Brown JR, Grace PR, Janzen HH, Körschens M. Long-term agroecosystem experiments: assessing agricultural sustainability and global change. *Science.* 1998;282(5390):893–6. <https://doi.org/10.1126/science.282.5390.893>
- Singh NP, Praharaaj CS, Sandhu JS. Utilizing untapped potential of rice fallow of East and North-east India through pulse production. *Indian J Genet Plant Breed.* 2016;76(4):388. <https://doi.org/10.5958/0975-6906.2016.00058.4>
- Saini R, Manjaiah KM, Roy D, Kumar R, Gawdiya S, Meena S, et al. Synthesis and evaluation of starch-grafted-poly[(acrylic acid)-co-acrylamide] based nanoclay polymer composite fertilisers for slow release of nitrogen in soil. *Polymers.* 2024;16(21):3013. <https://doi.org/10.3390/polym16213013>
- Mandal N, Datta SC, Manjaiah KM, Dwivedi BS. Synthesis, characterization and biodegradation of novel starch grafted zincated nanoclay polymer biocomposites. *Polym Plast Technol Mater.* 2022;61(5):497–515. <https://doi.org/10.1080/25740881.2021.1995417>
- Mukhopadhyay R, Mukhopadhyay A, Paul S, De N, Singh RK. Urea and *Trichoderma harzianum* loaded clay-polymer composite in conjunction with farmyard manure sustains soil moisture and nitrogen availability to manage Fusarium-Meloidogyne disease complex in lentil (*Lens culinaris*). *Commun Soil Sci Plant Anal.* 2024;55(7):1071–91. <https://doi.org/10.1080/00103624.2023.2295274>
- Liang R, Liu M. Preparation of poly(acrylic acid-co-acrylamide)/kaolin and release kinetics of urea from it. *J Appl Polym Sci.* 2007;106(5):3007–15. <https://doi.org/10.1002/app.26919>
- Piper CS. Soil and plant analysis. Hans Publishers; 1966.
- Subbiah BV, Asija GL. A rapid procedure for the estimation of available nitrogen in soils. *Curr Sci.* 1956;25:259–60.
- Olsen SR, Cole CV, Watanabe FS. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Washington DC: US Government Printing Office; 1954. (USDA Circular No. 939).
- Hanway JJ, Heidal H. Soil analysis methods as used in Iowa State College Soil Testing Laboratory. Iowa State College Agric Bull. 1952; 57:1–31.
- Lindsay WL, Norvell WA. Development of a DTPA soil test for zinc, iron, manganese and copper. *Soil Sci Soc Am J.* 1978;42(3):421–8. <https://doi.org/10.1097/00010694-193401000-00003>
- Walkley AJ, Black IA. Estimation of soil organic carbon by the chromic acid titration method. *Soil Sci.* 1934;37:29–38. <https://doi.org/10.1097/00010694-200101000-00009>
- Blair G, Lefroy R, Lisle L. Soil carbon fractions based on their degree of oxidation and the development of a carbon management index for agricultural systems. *Aust J Agric Res.* 1995;46(7):1459–66. <https://doi.org/10.1071/AR9951459>
- Casida LE, Klein DA, Santoro T. Soil dehydrogenase activity. *Soil Sci.* 1964;98(6):371–6. <https://doi.org/10.1097/00010694-196412000-00004>
- Vance ED, Brookes PC, Jenkinson DS. An extraction method for measuring soil microbial biomass C. *Soil Biol Biochem.* 1987;19(6):703–7. [https://doi.org/10.1016/0038-0717\(87\)90052-6](https://doi.org/10.1016/0038-0717(87)90052-6)
- Tabatabai MA, Bremner JM. Assay of urease activity in soils. *Soil Biol Biochem.* 1972;4(4):479–87. [https://doi.org/10.1016/0038-0717\(72\)90064-8](https://doi.org/10.1016/0038-0717(72)90064-8)
- Waksman SA, Starkey RL. Microbiological analysis of soil as an index of soil fertility: VII. Carbon dioxide evolution. *Soil Sci.* 1924;17(2):141–62. <https://doi.org/10.1097/00010694-192402000-00004>
- Jackson ML. Soil chemical analysis. 2nd ed. Prentice Hall of India Pvt Ltd; 1973.
- Sparks DL, Page AL, Helmke PA, Loeppert RH, Soltanpour PN, Tabatabai MA, et al., editors. Methods of soil analysis: Part 3 chemical methods. Vol. 5. Wiley; 1996. <https://doi.org/10.2136/sssabookser5.3>
- Pratt PF. Potassium chemical and microbiological properties. In: Page AL, editor. Methods of soil analysis: Part 2. Chemical and microbiological properties. Soil Science Society of America, Inc.; 1982. p. 225–46.
- Bhatt R, Singh P, Hossain A, Timsina J. Rice-wheat system in the northwest Indo-Gangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability. *Paddy Water Environ.* 2021;19(3):345–65. <https://doi.org/10.1007/s10333-021-00846-7>
- Ghorai PS, Biswas S, Purakayastha TJ, Ahmed N, Das TK, Prasanna R, et al. Indicators of soil quality and crop productivity assessment at a long-term experiment site in the lower Indo-Gangetic plains. *Soil Use Manag.* 2023;39(1):503–20. <https://doi.org/10.1111/sum.12847>
- Saurabh K, Kanchikeri Math M, Datta SC, Thekkumpurath AS, Kumar R. Nanoclay polymer composites loaded with urea and nitrification inhibitors for controlling nitrification in soil. *Arch Agron Soil Sci.* 2019;65(4):478–91. <https://doi.org/10.1080/03650340.2018.1507023>
- Singh P, Biswas S, Ghoshal N, De N, Singh D. Long-term effect of manuring-fertilization on nutrients availability and yield under rice (*Oryza sativa*)-lentil (*Lens culinaris*) system. *Indian J Agric Sci.* 2023;93(7):790–4. <https://doi.org/10.56093/ijas.v93i7.136245>
- Kumari M, Prakash D, Sheoran S, Yadav PK, Ankit, Yadav HK, et al. Long-term manuring and fertilization influence on soil properties and wheat productivity in semi-arid regions. *Agronomy.* 2024;14(10):2383. <https://doi.org/10.3390/agronomy14102383>
- Bhatt MK, Singh DK, Raverkar KP, Chandra R, Pareek N, Dey P, et al. Effects of varied nutrient regimes on soil health and long-term productivity in a rice-wheat system: insights from a 29-year study in the mollisols of the Himalayan Tarai region. *Front Sustain Food Syst.* 2023;7:1206878. <https://doi.org/10.3389/fsufs.2023.1206878>
- Walia SS, Dhaliwal SS, Gill RS, Kaur T, Kaur K, Randhawa MK, et al. Improvement of soil health and nutrient transformations under balanced fertilization with integrated nutrient management in a rice-wheat system in Indo-Gangetic Plains – a 34-year research outcomes. *Heliyon.* 2024;10(4):e25113. <https://doi.org/10.1016/j.heliyon.2024.e25113>
- Qin W, Wang D, Guo X, Yang T, Oenema O. Productivity and sustainability of rainfed wheat-soybean system in the North China Plain: results from a long-term experiment and crop modelling. *Sci Rep.* 2015;5(1):17514. <https://doi.org/10.1038/srep17514>

32. Nayak BK, Chatterjee D, Paul R, Das SR, Adak T, Mandal N, et al. Review of nano-clay polymer composites for controlled nitrogen release: prospects and limitations. *Agric Res.* 2025;14(4):675–96. <https://doi.org/10.1007/s40003-025-00848-5>
33. Govil S, Van Duc Long N, Escribà-Gelonch M, Hessel V. Controlled-release fertiliser: recent developments and perspectives. *Ind Crops Prod.* 2024;219:119160. <https://doi.org/10.1016/j.indcrop.2024.119160>
34. Teimouri Yanehsari A, Sabahi H, Jahani Y, Mahmoodi MH, Shalileh F. Synthesis of highly intercalated urea–clay nanocomposite via pomegranate peel waste as eco-friendly material. *Agriculture.* 2024;14(12):2097. <https://doi.org/10.3390/agriculture14122097>
35. Martins NCT, Avellan A, Rodrigues S, Salvador D, Rodrigues SM, Trindade T. Composites of biopolymers and ZnO NPs for controlled release of zinc in agricultural soils and timed delivery for maize. *ACS Appl Nano Mater.* 2020;3(3):2134–48. <https://doi.org/10.1021/acsanm.9b01492>
36. Adhikary S, Mandal N, Rakshit R, Das A, Kumar V, Kumari N, et al. Field evaluation of zincated nanoclay polymer composite (ZNCPC): impact on DTPA-extractable Zn, sequential Zn fractions and apparent Zn recovery under rice rhizosphere. *Soil Tillage Res.* 2020;201:104607. <https://doi.org/10.1016/j.still.2020.104607>
37. Paramesh V, Kumar P, Bhagat T, Nath AJ, Manohara KK, Das B, et al. Integrated nutrient management enhances yield, improves soil quality and conserves energy under the lowland rice-rice cropping system. *Agronomy.* 2023;13(6):1557. <https://doi.org/10.3390/agronomy13061557>
38. Biswas S, Singh P, Rahaman R, Patil KV, De N. Soil quality and crop productivity under 34 years old long-term rainfed rice based cropping system in an Inceptisol of sub-tropical India. *Front Soil Sci.* 2023;3:1155712. <https://doi.org/10.3389/fsoil.2023.1155712>
39. Meena A, Rao KS. Assessment of soil microbial and enzyme activity in the rhizosphere zone under different land use/cover of a semiarid region, India. *Ecol Process.* 2021;10(1):16. <https://doi.org/10.1186/s13717-021-00288-3>
40. Singh P, Biswas S, Ghoshal N, De N, Singh D. Impact of thirty-four years of fertilization and manuring on soil nutrients availability, yield and quality of crops in Indo-Gangetic Plains. *J Soil Sci Plant Nutr.* 2024;24(3):6040–52. <https://doi.org/10.1007/s42729-024-01958-9>
41. Moharana PC, Sharma BM, Biswas DR, Dwivedi BS, Singh RV. Long-term effect of nutrient management on soil fertility and soil organic carbon pools under a 6-year-old pearl millet-wheat cropping system in an Inceptisol of subtropical India. *Field Crops Res.* 2012;136:32–41. <https://doi.org/10.1016/j.fcr.2012.07.002>
42. Dutta D, Singh VK, Upadhyay PK, Meena AL, Kumar A, Mishra RP, et al. Long-term impact of organic and inorganic Fertilisers on soil organic carbon dynamics in a rice-wheat system. *Land Degrad Dev.* 2022;33(11):1862–77. <https://doi.org/10.1002/ldr.4267>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.