



RESEARCH ARTICLE

Carbon-positive cropping using vermicompost and recommended dose of fertiliser packages enhances yield and improves farm economics

Kumari Yogita Pandey¹, Meraj Ahmed^{1*}, Princy Thakur¹, Zeeshan T Ahmed², Suraj Varma³, Rajeev Gupta², Anushka Mishra¹, Anurag Malik⁴ & Manish Dev Sharma⁵

¹Department of Soil Science and Agricultural Chemistry, School of Agriculture, Lovely Professional University, Phagwara 144 411, Jalandhar, Punjab, India

²Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara 144 411, Jalandhar, Punjab, India

³Department of Horticulture, Lovely Professional University, Phagwara 144 411, Jalandhar, Punjab, India

⁴Division of Research and Innovation, Uttarakhand University, Dehradun 248 007, Uttarakhand, India

⁵Department of Biotechnology, School of Basic and Applied Sciences, Shri Guru Ram Rai University, Dehradun 248 001, Uttarakhand, India

*Correspondence email - meraj.same@gmail.com

Received: 01 November 2025; Accepted: 22 April 2026; Available online: Version 1.0: 21 May 2026

Cite this article: Kumari YP, Meraj A, Princy T, Zeeshan TA, Suraj V, Rajeev G, Anushka M, Anurag M, Manish DS. Carbon-positive cropping using vermicompost and recommended dose of fertiliser packages enhances yield and improves farm economics. *Plant Science Today*. 2026; 13(sp2): 1-7. <https://doi.org/10.14719/pst.12539>

Abstract

Sustaining soil fertility in the rice-wheat cropping system (RWCS) is increasingly challenging due to continuous fertiliser use, declining soil organic carbon (SOC) and nutrient imbalances. Integrated nutrient management (INM), which combines organic and inorganic sources, offers a viable approach to restoring soil health and maintaining crop yields. This study evaluated the effects of vermicompost (VC) and mineral fertiliser combinations on soil properties, crop performance and profitability under RWCS in Punjab, India. A randomised block field experiment with 12 VC-recommended dose of fertiliser (RDF) combinations was conducted. Vermicompost-fertilisers integration significantly enhanced SOC and available nitrogen (N), phosphorous (P) and potassium (K) and reduced bulk density compared to control or sole fertiliser. The treatment 10 t ha⁻¹ VC + 100 % RDF recorded the highest grain yield (6.88 t ha⁻¹ in rice and 5.41 t ha⁻¹ in wheat) along with the maximum benefit-cost ratio (1.84). Enhanced microbial activity further improved soil quality by accelerating organic matter decomposition and mineralising nutrients, boosting the availability of N, P and micronutrients. A diverse microbial community creates stable aggregates, enhancing soil structure, aeration and water retention. This nutrient synchronisation aligned nutrient release with crop demand, promoting root development, consistent growth and improved soil fertility over time. Overall, partial substitution of mineral fertilisers with VC enhanced nutrient-use efficiency, economic returns and soil resilience, thereby supporting sustainable intensification of RWCS.

Keywords: benefit-cost ratio; integrated nutrient management; rice-wheat system; soil fertility; vermicompost; yield sustainability

Introduction

Sustaining and enhancing productivity in intensive cereal rotations such as the rice-wheat cropping system (RWCS) remains a global priority, as this system underpins the food security of nearly 400 million people across South Asia (1, 2). Over the past five decades, productivity gains in RWCS have largely depended on high-yielding varieties, irrigation and sustained application of chemical fertilisers. However, this fertiliser-driven intensification has accelerated nutrient mining, depletion of soil organic carbon (SOC), deterioration of soil aggregation and the emergence of secondary and micronutrient deficiencies (3, 4). These challenges threaten both yield stability and the long-term ecological sustainability of RWCS, highlighting the need for nutrient management strategies that simultaneously address productivity, soil carbon dynamics and farm profitability (5).

Vermicompost (VC), a biologically stabilised organic amendment produced through earthworm-mediated decomposition, has gained attention for its multifunctional role in restoring soil fertility (6). In addition to supplying macro- and micronutrients, VC contains humic substances and biologically active compounds that enhance microbial activity, enzyme-mediated nutrient cycling and soil structural stability (7, 8). Recent studies suggest that VC preferentially influences labile and particulate SOC pools, which are important indicators of short- to medium-term carbon stabilisation and soil resilience, yet these effects remain underexplored in intensive cereal rotations (9).

Integrated nutrient management (INM), which combines organic amendments with mineral fertilisers, is widely recognised for improving nutrient-use efficiency and sustaining yields in RWCS (10–12). Long-term experiments in the Indo-Gangetic plains have shown that substituting 25–50 % of mineral nitrogen, phosphorous and potassium (NPK) with organic inputs such as VC

can maintain productivity while enhancing soil biological health (3, 13). However, much of the available evidence primarily focuses on SOC or yield responses, providing limited understanding of how INM alters specific SOC fractions, system-level carbon balance and residual effects across rice-wheat rotations.

Moreover, although VC-based INM is often promoted as a climate-smart approach, quantitative assessments linking SOC fractionation with carbon positivity and economic performance remain scarce, particularly under the semi-arid, high-input conditions of Punjab's RWCS (13). Existing economic analyses are frequently crop-specific and short-term, overlooking carry-over benefits, input savings and yield stability at the rotation scale, which ultimately governs farmer adoption decisions (12, 14).

Therefore, the novelty of the present study lies in its integrated, system-level evaluation of VC-based INM under RWCS in Punjab, India. Specifically, this study (i) quantifies the effects of graded vermicompost-recommended dose of fertiliser (VC-RDF) combinations on SOC fractions and soil biological indicators, rather than focusing only on total SOC; (ii) evaluates system productivity and profitability across both rice and wheat seasons, thereby capturing residual and cumulative effects; and (iii) assesses whether VC integration enhances carbon positivity and economic efficiency under region-specific soil and climatic conditions. We hypothesise that partial substitution of mineral fertilisers with VC will not only sustain yields but also improve SOC stabilisation and benefit-cost ratios, thereby offering a scientifically robust and economically viable pathway for sustainable intensification of RWCS.

Materials and Methods

Site-specific agro-climatic context and environmental baseline

The field experiment was conducted during consecutive cropping seasons (kharif and rabi) on a sandy loam soil, at the Soil Science Research Farm of the School of Agriculture, Lovely Professional University, Phagwara, Punjab, India, located at 31°24' N latitude and 75°59' E longitude and situated at 232 m above mean sea level (AMSL). Sandy loam, a dominant soil type of central Punjab and is characterised by low organic carbon content and moderate nutrient-holding capacity, which directly influences nutrient dynamics and crop response under the RWCS.

The region experiences a semi-arid subtropical climate characterised by hot summers and cool winters. The mean annual rainfall is approximately 720 mm, of which nearly 75–80 % is received during the monsoon season (June–September). The mean maximum and minimum temperatures during the rice-growing season were 35.8 °C and 25.2 °C, respectively, whereas during the wheat-growing season they averaged 22.6 °C and 8.4 °C. Meteorological data were recorded daily from the adjacent agrometeorological observatory.

Experimental framework, design protocol and treatment application

Table 1 displays the initial physical and chemical parameters of the study area. The experiment was laid out in a randomised block design (RBD) with 12 treatments and 3 replications. Each plot measured 5 × 4 m with 0.5 m buffer space between plots and 1 m between replications to prevent nutrient contamination. The treatments consisted of varying combinations of VC and RDF, T₁ -

Table 1. Initial soil profile and physico-chemical attributes

Soil properties	Values
Sand (%)	62.67
Silt (%)	5.31
Clay (%)	32.02
Textural class	Sandy loam
Bulk density (g cm ⁻³)	1.51
Water holding capacity (%)	42.96
Porosity (%)	32.37
pH (1:2.5 w/v)	7.91
EC (dS m ⁻¹)	0.28
Organic carbon (%)	0.52
Available N (kg ha ⁻¹)	196.2
Available P (kg ha ⁻¹)	11.01
Available K (kg ha ⁻¹)	168.12
Total organic carbon (%)	1.21

EC: electrical conductivity; N: nitrogen; P: phosphorus; K: potassium.

Control (no fertiliser, no VC), T₂ - 100 % RDF, T₃ - VC alone (VC at 5 t ha⁻¹), T₄ - 5 t ha⁻¹ VC + 50 % RDF, T₅ - 5 t ha⁻¹ VC + 75 % RDF, T₆ - 5 t ha⁻¹ VC + 100 % RDF, T₇ - 10 t ha⁻¹ VC + 50 % RDF, T₈ - 10 t ha⁻¹ VC + 75 % RDF, T₉ - 10 t ha⁻¹ VC + 100 % RDF, T₁₀ - 15 t ha⁻¹ VC + 50 % RDF, T₁₁ - 15 t ha⁻¹ VC + 75 % RDF, T₁₂ - 15 t ha⁻¹ VC + 100 % RDF.

Nitrogen was applied through urea (46 % N), phosphorous (P) through single superphosphate (16 % P₂O₅) and potassium (K) through muriate of potash (60 % K₂O). Vermicompost (VC) was obtained from a certified on-farm unit and prepared using a mixture of crop residues and cow dung decomposed by the earthworm *Eisenia fetida*. It contained approximately 1.5 % N, 0.9 % P, 1.2 % K and 15.3 % organic carbon on a dry weight basis.

Crop management and cultural operations

Rice (*Oryza sativa* L.)

The rice variety “PR-126”, commonly cultivated in the region, was transplanted during the last week of June with a spacing of 20 × 15 cm. Seedlings were raised in a nursery for 25 days prior to transplanting. Half of the N and the full doses of P and K were applied as basal before transplanting, while the remaining N was top-dressed in two equal splits at tillering and panicle initiation stages. Standing water of 5–7 cm depth was maintained until grain filling, followed by field drainage before harvest.

Wheat (*Triticum aestivum* L.)

The succeeding wheat crop (variety PBW 222) was sown after the harvest of rice during the second week of November, with a row spacing of 22.5 cm. Half of the N and the full P and K were applied as basal at sowing, while the remaining N was top-dressed at the crown root initiation and booting stages. Standard agronomic and plant protection practices were followed to maintain uniform crop growth across all treatments. Irrigation management was carefully implemented in the rice-wheat cropping system to achieve optimum crop performance while promoting efficient water use. During the kharif season, rice fields were maintained under shallow submergence (2–5 cm) for the initial one to two weeks after transplanting to ensure proper crop establishment. During the vegetative stage, irrigation was scheduled following the alternate wetting and drying (AWD) approach, in which irrigation was applied after the water level receded to approximately 15 cm below the soil surface and was subsequently restored to about 5 cm. However, during the critical reproductive phases from panicle initiation to flowering, continuous shallow flooding (2–5 cm) was maintained to avoid moisture stress. The fields were drained 7–10 days prior to harvest to facilitate uniform maturity and ease of harvesting.

During the rabi season, wheat was irrigated judiciously with four to six irrigations, providing a total water input of approximately 400–450 mm. Particular emphasis was placed on timely irrigation at critical growth stages, with the first and most crucial irrigation applied at the crown root initiation stage (20–25 DAS), followed by irrigations at tillering (40–45 days), jointing or stem elongation (60–65 days), flowering (85–90 days) and the milk stage (100–105 DAS). This stage-specific irrigation scheduling ensured adequate soil moisture availability throughout the crop growth cycle.

Sampling for soil and plant analysis

Composite soil samples (0–15 cm) were collected before the initiation of the experiment and after each crop harvest. The samples were air-dried, sieved (2 mm) and analysed for soil pH by pH meter (1:2.5 soil-water suspension) (15), electrical conductivity (EC) by EC meter, organic carbon by wet oxidation method (16), available N from alkaline potassium permanganate method (17), available P from Olsen method (18) and available K from ammonium acetate method (15).

Plant growth parameters, including plant height and number of tillers m², were recorded at key phenological stages. At maturity, grain and straw yields were recorded from a net plot area of 4 m², adjusted to 14 % moisture content and expressed in tonnes per hectare.

Economic analysis

The economic viability of the treatments was evaluated using a standard cost-benefit analysis. The total cost of cultivation included expenses on seed, land preparation, irrigation, labour, fertilisers, vermicompost and other inputs. Gross returns were calculated based on the prevailing minimum support prices (MSPs) for rice and wheat grains along with the market rates for straw.

The benefit-cost ratio (BCR) was computed using the following formula:

$$\text{BCR} = \frac{\text{Net returns}}{\text{Cost of cultivation}}$$

Where:

Net return (₹ ha⁻¹) = (Grain yield × Market price) + (Straw yield × Market price)

Total cost of cultivation (₹ ha⁻¹) = All variable costs incurred for each treatment.

Statistical analysis

Data from both rice and wheat seasons were analysed using analysis of variance (ANOVA) appropriate for an RBD. Treatment means were compared using the least significant difference (LSD) test at the 5 % probability level ($p \leq 0.05$). Statistical analysis was performed using the R statistical software (version 4.3).

Results and Discussion

Soil properties and organic carbon dynamics

The analysis of post-harvest soil properties revealed significant variations in soil fertility and physical characteristics in response to different combinations of VC and mineral fertilisers under the rice-wheat cropping system (Table 2). Among all treatments, the highest SOC value (0.68 %) was recorded in (T₁₁ and T₁₂) (15 t ha⁻¹ VC + 75 % RDF, 15 t ha⁻¹ VC + 100 % RDF) while the lowest SOC was observed in the control (T₁; 0.40 %), representing a net improvement of about 70.5 %. This rise in SOC indicates the significant role of organic amendments in supplying labile and recalcitrant carbon pools that promote aggregate stability and carbon sequestration (10, 5). The humic and fulvic fractions in VC enhance microbial proliferation, enzymatic activity and humification processes, leading to better stabilisation of organic carbon within the soil matrix (19).

Similarly, available N ranged from 185 kg ha⁻¹ (T₁) to 245 kg ha⁻¹ (T₁₂: 15 t ha⁻¹ VC + 100 % RDF), with an average increase of approximately 24.5 % over the control. This improvement can be attributed to the slow and sustained mineralisation of VC-derived organic N, which complements the rapid availability from mineral fertilisers and ensures balanced nutrient supply across growth stages (11). The gradual N release from vermicompost also minimises volatilisation losses and enhances N-use efficiency (19). Available P improved from 13.6 kg ha⁻¹ in T₁ to 21.3 kg ha⁻¹ in T₁₂, corresponding to a 57 % increase over the control. This improvement resulted from enhanced phosphate solubilisation through the production of organic acids and microbial metabolites in VC that chelate iron (Fe³⁺) and aluminium (Al³⁺) ions, thereby reducing P fixation in the alkaline soils of Punjab (20, 21).

Available K also increased significantly, ranging from 160 kg ha⁻¹ in T₁ to a maximum of 196 kg ha⁻¹ in T₁₂, reflecting a 22 % improvement over the control. The higher K content under integrated treatments can be attributed to the weathering of K-bearing minerals and the release of exchangeable K facilitated by

Table 2. Synergistic effects of vermicompost and mineral fertilisers on soil properties

Treatments	SOC (%)	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)	Bulk density (Mg m ⁻³)	pH	EC (dS m ⁻¹)
T ₁	0.40	185	13.6	160	1.49	8.12	0.24
T ₂	0.45	200	15.1	168	1.46	8.05	0.26
T ₃	0.49	208	16.0	172	1.44	8.02	0.27
T ₄	0.52	214	17.2	176	1.42	7.98	0.28
T ₅	0.55	220	18.0	180	1.40	7.95	0.29
T ₆	0.58	226	18.8	184	1.39	7.92	0.30
T ₇	0.61	232	19.5	187	1.38	7.89	0.31
T ₈	0.64	237	20.1	190	1.37	7.87	0.32
T ₉	0.66	242	20.7	193	1.36	7.85	0.33
T ₁₀	0.67	243	21.0	194	1.35	7.84	0.33
T ₁₁	0.68	244	21.2	195	1.35	7.83	0.34
T ₁₂	0.68	245	21.3	196	1.35	7.83	0.34
SEM±	0.014	2.90	0.32	2.05	0.007	0.011	0.007
LSD ($p \leq 0.05$)	0.04	8.2	0.9	5.8	0.02	0.03	0.02

SOC: soil organic carbon; EC: electrical conductivity; N: nitrogen; P: phosphorus; K: potassium LSD: least significant difference; SEM: standard error of the mean.

organic acid production and microbial exudates (8, 13). The cumulative improvements in available N, P and K demonstrate the synergistic effect of VC and mineral fertilisers in maintaining a dynamic equilibrium between nutrient mineralisation and immobilisation.

The bulk density (BD) of soil declined significantly from 1.49 Mg m⁻³ in T₁ to 1.35 Mg m⁻³ in T₁₁–T₁₂, indicating improved soil porosity and structural stability. This reduction in BD is associated with increased incorporation of organic matter, microbial polysaccharide activity and formation of macroaggregates that improve aeration and root penetration (22). A corresponding decrease in soil pH from 8.12 (T₁) to 7.83 (T₁₂) under integrated treatments indicates partial neutralisation of alkalinity by weak organic acids formed during VC decomposition, improving micronutrient solubility and overall nutrient buffering capacity (23).

In contrast, EC values showed a slight but non-critical increase from 0.24 dS m⁻¹ (T₁) to 0.34 dS m⁻¹ (T₁₂). The slight increase in EC observed in treatments with higher VC and fertiliser rates likely resulted from greater mineralisation and accumulation of soluble nutrient ions, though all values remained well below the salinity hazard threshold (< 2 dS m⁻¹) (24). Collectively, these findings confirm that integrated VC + RDF treatments enhanced soil chemical fertility while simultaneously improving physical structure and maintaining salinity within permissible limits.

Overall, the integrated application of VC and mineral fertilisers substantially improved soil fertility and physical health by enhancing SOC and nutrient availability while decreasing bulk density and moderating soil pH. The balanced nutrient release from organic and inorganic sources created a synergistic effect that optimised soil quality without inducing salinity or alkalinity problems. These results corroborate findings from long-term integrated nutrient management (INM) studies conducted highlighting that partial substitution of chemical fertilisers with organic manures like VC enhances nutrient-use efficiency, soil carbon sequestration and long-term sustainability of intensive cropping systems (4, 25).

Crop growth and yield attributes

Rice crop

Growth and yield attributes of rice were markedly influenced by different VC and fertiliser combinations under the rice-wheat system (Table 3). The results revealed that integrated nutrient treatments significantly enhanced plant height, tiller production, panicle length and yield components compared to the control

and sole fertiliser applications. Plant height ranged from 88.2 cm in the control (T₁) to a maximum of 109.7 cm in the 10 t ha⁻¹ VC + 100 % RDF treatment (T₉), representing a 24 % increase. The improvement in plant stature may be attributed to balanced nutrient supply and the growth-promoting substances present in VC, such as auxins, gibberellins and humic acids, which stimulate cell elongation and tiller vigour (19, 25).

Tillers hill⁻¹ followed a similar trend, increasing from 9.1 (T₁) to 14.0 (T₉), reflecting improved tiller initiation and survival. This enhancement is likely attributed to sustained N mineralisation and improved soil aeration resulting from higher organic matter inputs, which support continuous nutrient availability and rhizosphere microbial activity (11). Panicle length increased from 21.0 cm in the control to 24.8 cm in T₉, with no significant gains beyond that level. The lengthening of panicles under INM indicates better translocation of assimilates from source to sink organs and improved reproductive development (26).

Grain yield exhibited a pronounced response to combined nutrient application, ranging from 3.48 t ha⁻¹ in T₁ to a maximum of 6.88 t ha⁻¹ in T₉, corresponding to a 97 % increase over the control and a 25.8 % increase over the sole RDF treatment (T₂). The yield enhancement under T₉ resulted from the synergistic effects of organic and inorganic nutrient sources that improved nutrient-use efficiency, soil microbial biomass and root physiological activity (22, 27). The continuous nutrient release from VC maintained plant nutrient supply during grain filling, reducing spikelet sterility and improving sink strength (28).

Straw yield followed a similar trend, increasing from 4.10 t ha⁻¹ in T₁ to 7.41 t ha⁻¹ in T₉, reflecting enhanced biomass accumulation. The significant increase in total dry matter under integrated treatments is consistent with earlier reports from long-term Indo-Gangetic studies, where VC combined with chemical fertilisers improved both yield and carbon assimilation efficiency in rice (10, 24). Beyond 10 t ha⁻¹ VC, no substantial yield gain was observed (T₁₀–T₁₂), indicating a saturation threshold likely due to nutrient immobilisation or suboptimal N:P:K ratios in excessive organic inputs (5).

Overall, the integrated application of 10 t ha⁻¹ VC + 100 % RDF (T₉) proved most effective in enhancing rice growth and yield performance. These results emphasised that VC, when used in combination with mineral fertilisers, provides a synchronised nutrient supply that enhances physiological efficiency, promotes root development and ensures higher grain productivity (23, 25).

Table 3. Growth dynamics and yield performance of rice under integrated nutrient regimes

Treatments	Plant height (cm)	Tillers hill ⁻¹	Panicle length (cm)	Grain yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)
T ₁	88.2	9.1	21.0	3.48	4.10
T ₂	97.5	11.5	22.4	5.10	5.85
T ₃	94.3	10.7	22.1	4.76	5.49
T ₄	100.1	12.0	23.2	5.54	6.15
T ₅	103.0	12.8	23.5	5.91	6.56
T ₆	105.2	13.0	23.8	6.15	6.79
T ₇	104.1	13.2	24.0	6.28	6.87
T ₈	107.8	13.6	24.3	6.58	7.12
T ₉	109.7	14.0	24.8	6.88	7.41
T ₁₀	106.3	13.3	24.2	6.42	6.95
T ₁₁	108.0	13.7	24.5	6.70	7.19
T ₁₂	108.5	13.9	24.6	6.74	7.25
SEM±	0.94	0.21	0.18	0.067	0.099
LSD (<i>p</i> ≤ 0.05)	2.65	0.6	0.5	0.19	0.28

LSD: least significant difference; SEM: standard error of the mean.

Wheat crop

Wheat growth and yield attributes responded significantly to integrated applications of VC and mineral fertilisers under the rice-wheat system (Table 4). Plant height increased from 74.3 cm (T_1) to 92.4 cm (T_9), a 24 % rise, due to the synergistic effect of balanced nutrient supply and improved soil physical properties reflecting improved nutrient availability and hormonal stimulation from VC-derived humic substances (29).

Effective tillers m^{-2} increased from 248 (T_1) to 329 (T_9), a 24.6 % this can be attributed to the steady N release from VC that complements mineral N and reduces losses through leaching or volatilisation, ensuring nutrient availability throughout the vegetative phase (21). A higher tiller count under integrated fertilisation indicates better physiological efficiency and a more robust source-sink balance (30). Spike length increased from 9.3 to 10.9 cm, while grains spike $^{-1}$ improved to 37–48, respectively, due to balanced nutrient uptake and improved floret fertility (14).

Grain yield increased from 3.15 t ha^{-1} (T_1) to 5.41 t ha^{-1} (T_9), representing a 72 % gain, while straw yield rise by 48 % (3.94–5.86 t ha^{-1}). Yield improvement was associated with increased tiller density, nutrient-use efficiency and photosynthetic activity (29). Beyond 10 t ha^{-1} VC, yield plateaued, possibly due to temporary N immobilisation at high organic inputs (31). Overall, the treatment of 10 t ha^{-1} VC + 100 % RDF (T_9) achieved the highest productivity, confirming that VC-fertiliser integration optimises soil fertility, plant growth and yield stability (28).

The yield advantage under integrated treatments is likely due to enhanced synchronisation of nutrient release and plant demand, leading to improved nutrient use efficiency (NUE) and

reduced losses through leaching and volatilisation. The gradual mineralisation of nutrients from VC maintained nutrient availability during the later growth stages, ensuring continuous plant uptake and improved grain filling

Economic analysis and benefit-cost ratio (BCR)

The economic evaluation of the RWCS revealed that INM significantly improved profitability (Table 5). The total cultivation cost increased with higher VC rates, primarily due to the cost of procurement, transportation and labour associated with organic manure handling. However, these costs were offset by substantial gains in productivity and market returns, particularly when VC was applied in combination with chemical fertilisers.

Among all treatments, T_9 (10 t ha^{-1} VC + 100 % RDF) recorded the highest gross return (₹158800 ha^{-1}) and net return (₹72300 ha^{-1}), with a benefit:cost (B:C) ratio of 1.84, demonstrating superior economic efficiency. In contrast, the lowest profitability was observed in the control (T_1), where gross return was only ₹80700 ha^{-1} and B:C = 1.48, due to low crop yield and low resource-use efficiency. Treatments with partial substitution of fertilisers (T_5 – T_8) showed 15–25 % higher net returns than sole RDF (T_2), emphasising that integrating organic and inorganic nutrient sources enhances system productivity and profitability.

Although higher VC levels (15 t ha^{-1}) marginally improved yield, the accompanying rise in input cost reduced the net benefit, lowering the B:C ratio to 1.61–1.72, this aligns with the findings diminishing economic returns beyond 10 t ha^{-1} of organic input in north-western India (29). The greater profitability at moderate VC rates can be attributed to the

Table 4. Growth dynamics and yield performance of wheat under integrated nutrient regimes

Treatments	Plant height (cm)	Effective tillers m^{-2}	Spike length (cm)	Grains spike $^{-1}$	1000-grain weight (g)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})
T_1	74.3	248	9.3	37	39.5	3.15	3.94
T_2	82.1	283	9.8	42	40.8	4.32	5.00
T_3	80.2	272	9.6	40	40.3	4.08	4.83
T_4	84.5	295	10.1	43	41.5	4.56	5.15
T_5	87.2	308	10.4	45	41.9	4.89	5.37
T_6	88.9	314	10.6	46	42.3	5.08	5.52
T_7	89.5	318	10.7	46	42.6	5.15	5.59
T_8	91.1	324	10.8	47	43.0	5.28	5.72
T_9	92.4	329	10.9	48	43.3	5.41	5.86
T_{10}	91.5	321	10.8	47	43.0	5.24	5.74
T_{11}	92.0	325	10.9	48	43.2	5.35	5.80
T_{12}	92.2	327	10.9	48	43.2	5.37	5.82
SEM $\pm$	0.74	3.47	0.11	0.64	0.21	0.060	0.099
LSD ($p \leq 0.05$)	2.10	9.8	0.3	1.8	0.6	0.17	0.28

LSD: least significant difference; SEM: standard error of the mean.

Table 5. Profitability and input-output economics

Treatments	Total cost (₹ ha^{-1})	Gross return (₹ ha^{-1})	Net return (₹ ha^{-1})	Benefit:cost ratio
T_1	54500	80700	26200	1.48
T_2	65800	122600	56800	1.86
T_3	70200	114200	44000	1.63
T_4	72400	128700	56300	1.77
T_5	74600	136800	62200	1.83
T_6	76800	142400	65600	1.85
T_7	80000	145800	65800	1.82
T_8	83300	152900	69600	1.83
T_9	86500	158800	72300	1.84
T_{10}	90900	156400	65500	1.72
T_{11}	94200	157000	62800	1.67
T_{12}	97600	157600	60000	1.61
SEM $\pm$	-	1397	990	0.018
LSD ($p \leq 0.05$)	-	3950	2800	0.05

LSD: least significant difference; SEM: standard error of the mean.

synergistic effects of nutrient availability, improved soil structure and microbial activity that enhance fertiliser-use efficiency (3).

Overall, the integration of 10 t ha⁻¹ VC with 100 % RDF proved most profitable, which confirmed that balanced organic-inorganic nutrient management not only sustains yields but also maximises farm income through reduced dependency on costly chemical fertilisers and improved soil fertility over time (13, 24).

Conclusion

The integration of vermicompost (VC) with mineral fertilisers significantly improved soil fertility, crop performance and profitability in the rice-wheat system. The treatment of 10 t ha⁻¹ VC + 100 % recommended dose of fertiliser (RDF) produced the highest yields and economic returns, performing comparably to higher VC doses but at a lower cost. These outcomes reaffirm the potential of integrated nutrient management (INM) to reduce reliance on synthetic inputs while maintaining productivity and profitability.

This approach aligns with the principles of climate-smart agriculture, offering pathways to improve soil resilience, enhance nutrient cycling and mitigate carbon emissions through organic matter recycling (32, 33). The results are consistent with climate-smart nutrient management principles, as VC additions support soil organic carbon (SOC) buildup and improve soil resilience. These findings suggest that vermicompost-based INM practices can be promoted as a sustainable strategy for enhancing productivity and soil health in intensively cultivated rice-wheat systems.

Acknowledgements

The authors express their sincere gratitude to the Lovely Professional University, Phagwara, Punjab, India, for providing research facilities, field support and technical assistance during the study. Special thanks are extended to the Department of Soil Science and Agronomy for laboratory and analytical support throughout the experimental period. The authors also acknowledge the contributions of field staff and laboratory technicians for their cooperation in sample collection and analysis. Infrastructural support from Lovely Professional University is gratefully acknowledged. The constructive comments and technical inputs provided by senior faculty members greatly improved the quality and interpretation of this work.

Authors' contributions

KYP conceptualised the study, designed the experiment, conducted fieldwork, collected data, performed statistical analyses and prepared the initial draft of the manuscript. MA supervised the research, provided methodological guidance, interpreted results and critically revised the manuscript. PT assisted in field experimentation, soil and plant analysis and preparation of tables. ZTA contributed to literature review and interpretation of nutrient and soil carbon dynamics. SV supported the experimental setup, fertilizer and vermicompost management and agronomic observations. RG assisted in soil physico-chemical analysis, data interpretation and manuscript editing. AM¹

contributed to statistical analysis, data validation and reference formatting. AM² provided technical guidance and offered critical feedback on the manuscript. MDS provided overall supervision and final revision of the manuscript for intellectual content and scientific accuracy. All authors have read and approved the final manuscript [AM¹ - Anushka Mishra and AM² - Anurag Malik].

Compliance with ethical standards

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

Ethical issues: None

References

- Ladha JK, Rao AN, Raman AK, Padre AT, Dobermann A, Gathala M, et al. Agronomic improvements can make future cereal systems in South Asia far more productive and result in a lower environmental footprint. *Global Change Biology*. 2016;22(3):1054–74. <https://doi.org/10.1111/gcb.13143>
- Chauhan BS, Mahajan G, Sardana V, Timsina J, Jat ML. Productivity and sustainability of the rice–wheat cropping system in the Indo-Gangetic Plains of the Indian subcontinent: problems, opportunities and strategies. *Advances in Agronomy*. 2012;117:315–69. <https://doi.org/10.1016/B978-0-12-394278-4.00006-4>
- Kakraliya SK, Jat RD, Kumar S, Choudhary KK, Prakash J, Singh LK. Integrated nutrient management for improving fertilizer-use efficiency, soil biodiversity and productivity of wheat in irrigated rice–wheat cropping system in Indo-Gangetic Plains of India. *International Journal of Current Microbiology and Applied Sciences*. 2017;6(3):152–63. <https://doi.org/10.20546/ijcmas.2017.603.017>
- Ranjan S, Kumar S, Dutta SK, Padhan SR, Dayal P, Sow S, et al. Influence of 36 years of integrated nutrient management on soil carbon sequestration, environmental footprint and agronomic productivity of wheat under rice–wheat cropping system. *Frontiers in Environmental Science*. 2023;11:1222909. <https://doi.org/10.3389/fenvs.2023.1222909>
- Bhardwaj AK, Rajwar D, Mandal UK, Ahmadi S, Kaphaliya B, Minhas PS, et al. Impact of carbon inputs on soil carbon fractionation, sequestration and biological responses under major nutrient management practices for rice–wheat cropping systems. *Scientific Reports*. 2019;9(1):9114. <https://doi.org/10.1038/s41598-019-45534-z>
- Ghadimi M, Sirousmehr A, Ansari MH, Ghanbari A. Organic soil amendments using vermicomposts under inoculation of N₂-fixing bacteria for sustainable rice production. *PeerJ*. 2021;9:e10833. <https://doi.org/10.7717/peerj.10833>
- Aira M, Monroy F, Domínguez J. Microbial biomass governs enzyme activity decay during aging of worm-worked substrates through vermicomposting. *Journal of Environmental Quality*. 2007;36(2):448–52. <https://doi.org/10.2134/jeq2006.0262>
- 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>
- Dutta D, Singh VK, Upadhyay PK, Meena AL, Kumar A, Mishra RP, et al. Long-term impact of organic and inorganic fertilizers on soil organic carbon dynamics in a rice–wheat system. *Land Degradation and Development*. 2022;33(11):1862–77. <https://doi.org/10.1002/ldr.4267>
- Das B, Pooniya V, Shivay YS, Zhiipao RR, Biswakarma N, Kumar D, et al. Twenty-one years' impact of using organic amendments on the productivity of rice–wheat rotation and soil properties. *Field Crops Research*. 2024;309:109311. <https://doi.org/10.1016/>

j.fcr.2024.109311

11. Ranjan S, Kumar S, Dutta SK, Sow S, Ghosh M. Effect of integrated nutrient management in rice on vegetative growth and economic profitability of wheat under long term rice-wheat cropping system. *Journal of Cereal Research*. 2022;14(2):198–203. <https://doi.org/10.25174/2582-2675/2022/125999>
12. Kamdi PJ, Swain DK, Wani SP. Improving grain quality and nitrogen use efficiency of cereal-based cropping systems on vertisols in semi-arid tropics. *Field Crops Research*. 2024;307:109258. <https://doi.org/10.1016/j.fcr.2024.109258>
13. Dhaliwal SS, Sharma S, Sharma V, Shukla AK, Walia SS, Alhomrani M, et al. Long-term integrated nutrient management in the maize-wheat cropping system in alluvial soils of North-Western India: influence on soil organic carbon, microbial activity and nutrient status. *Agronomy*. 2021;11(11):2258. <https://doi.org/10.3390/agronomy11112258>
14. Tripathi SC, Venkatesh K, Kumar N, Meena RP. Unravelling the potential of rice residue-boosting wheat's productivity, profit and soil health with varying N levels. *International Journal of Plant Production*. 2024;18(2):201–15. <https://doi.org/10.1007/s42106-024-00288-1>
15. Jackson ML. Soil chemical analysis. New Delhi: Prentice Hall of India; 1958. p.29.
16. Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science*. 1934;37(1):29–38. <https://doi.org/10.1097/00010694-193401000-00003>
17. Subbiah BV, Asija GL. A rapid procedure for the estimation of available nitrogen in soils. *Current Science*. 1956;25(8):259–60.
18. Olsen SR. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Washington: US Department of Agriculture; 1954.
19. Joshi R, Singh J, Vig AP. Vermicompost as an effective organic fertilizer and biocontrol agent: effect on growth, yield and quality of plants. *Reviews in Environmental Science and Bio/Technology*. 2015;14(1):137–59. <https://doi.org/10.1007/s11157-014-9347-1>
20. Khan KS, Ali MM, Naveed M, Rehmani MI, Shafique MW, Ali HM, et al. Co-application of organic amendments and inorganic P increase maize growth and soil carbon, phosphorus availability in calcareous soil. *Frontiers in Environmental Science*. 2022;10:949371. <https://doi.org/10.3389/fenvs.2022.949371>
21. Kaur P, Saini KS, Sharma S, Kaur J, Bhatt R, Alamri S, et al. Increasing the efficiency of the rice-wheat cropping system through integrated nutrient management. *Sustainability*. 2023;15(17):12694. <https://doi.org/10.3390/su151712694>
22. Sharma S, Paddhushan R, Kumar U. Integrated nutrient management in rice-wheat cropping system: evidence on sustainability in the Indian subcontinent through meta-analysis. *Agronomy*. 2019;9(2):71. <https://doi.org/10.3390/agronomy9020071>
23. Mahanta K, Jha DK, Rajkhowa DJ, Manoj-Kumar. Microbial enrichment of vermicompost prepared from different plant biomasses and their effect on rice (*Oryza sativa* L.) growth and soil fertility. *Biological Agriculture and Horticulture*. 2012;28(4):241–50. <https://doi.org/10.1080/01448765.2012.738556>
24. Nisar S, Benbi DK. Long-term effects of organic and inorganic fertilizers on some soil quality indicators in rice-wheat cropping system. *Agricultural Research Journal*. 2020;57(2):154–9. <https://doi.org/10.5958/2395-146X.2020.00025.3>
25. Walia SS, Gill MS, Bhushan B, Phutela RP, Aulakh CS. Alternate cropping systems to rice (*Oryza sativa*)-wheat (*Triticum aestivum*) for Punjab. *Indian Journal of Agronomy*. 2011;56(1):20–7. <https://doi.org/10.59797/ija.v56i1.4664>
26. Mangaraj S, Paikaray RK, Maitra S, Pradhan SR, Garnayak LM, Satapathy M, et al. Integrated nutrient management improves the growth and yield of rice and greengram in a rice-greengram cropping system under the coastal plain agro-climatic condition. *Plants*. 2022;11(1):142. <https://doi.org/10.3390/plants11010142>
27. El Mazlouzi M, Morel C, Robert T, Chesseron C, Salon C, Cornu JY, et al. The dynamics of phosphorus uptake and remobilization during the grain development period in durum wheat plants. *Plants*. 2022;11(8):1006. <https://doi.org/10.3390/plants11081006>
28. Singh K, Sharma PK, Singh YV, Barnwal PP, Jaiswal S, Goswami S. Synergistic effects of combined organic and inorganic nitrogen on wheat nutrient uptake and soil fertility in Inceptisol of Eastern Uttar Pradesh, India. *International Journal of Plant and Soil Science*. 2024;36(11):441–50. <https://doi.org/10.9734/ijpss/2024/v36i115161>
29. Singh SP. Effect of integrated nutrient management on wheat (*Triticum aestivum*) yield, nutrient uptake and soil fertility status in alluvial soil. *Indian Journal of Agricultural Sciences*. 2019;89(6):929–33. <https://doi.org/10.56093/ijas.v89i6.90761>
30. Mishra S, Yadav S, Kumar P. Source-sink relationships and nutrient uptake efficiency of wheat under combined vermicompost and fertilizer application. *Frontiers in Sustainable Food Systems*. 2023;7:1225348.
31. Kumari M, Sheoran S, Prakash D, Yadav DB, Yadav PK, Jat MK. Long-term application of organic manures and chemical fertilizers improve the organic carbon and microbiological properties of soil under pearl millet-wheat cropping system in North-Western India. *Heliyon*. 2024;10(3):e25333. <https://doi.org/10.1016/j.heliyon.2024.e25333>
32. Urmi TA, Rahman MM, Islam MM, Islam MA, Jahan NA, Mia MA, et al. Integrated nutrient management for rice yield, soil fertility and carbon sequestration. *Plants*. 2022;11(1):138. <https://doi.org/10.3390/plants11010138>
33. Melak E, Molla E, Feyisa T, Sebnie W, Shitaw M, Shiferaw Sida T. Wheat yield and soil physicochemical properties through mineral nitrogen and vermicompost application in Lasta district, North Ethiopia. *Scientific Reports*. 2025;15(1):32906. <https://doi.org/10.1038/s41598-025-16912-7>

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.