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Effect of Various Combination of Organic and Inorganic Nutrient Sources on Soil Health and Yield of Maize

Nancy [a++], Amritpal Singh [a++*], Babli [a#] and Abhishek Grover [b#]

[a] Department of Agronomy, Guru Kashi University, Talwandi Sabo, Bathinda, Punjab, India.
[b] School of Agriculture Sciences and Engineering, Maharaja Ranjit Singh Punjab Technical University, Bathinda, Punjab, India.

Authors' contributions

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

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Abstract

A field experiment was conducted during the 2023 kharif season at the Research Farm of Agronomy, Guru Kashi University, Talwandi Sabo, Punjab, to evaluate the effects of organic and inorganic nutrient combinations on maize (*Zea mays* L.) yield and post-harvest soil properties. The experiment followed a randomised block design with nine treatments and three replications. Treatments comprised nitrogen supplied through urea, vermicompost, poultry manure and farmyard manure, either separately or in specified combinations. The highest grain and stover yields (62.45 and 116.19 q ha^{-1}, respectively) were recorded under T5, comprising 75% of the recommended nitrogen dose (RDN) through urea and 25% through vermicompost. Grain yield under T5 exceeded that of the unfertilised control (28.71 q ha^{-1}) and was statistically comparable to that under 100% RDN through urea (56.10 q ha^{-1}). Among fully organic treatments, T6 (50% RDN from poultry manure and 50% from farmyard manure) produced a grain yield of 56.81 q ha^{-1}. T6 also recorded the lowest post-harvest soil bulk density (1.49 Mg m^{-3}) and highest porosity (41.80%).

[++] Master of Science in Agriculture; [#] Assistant Professor;
**Corresponding Email(s): amritbuttar0938@gmail.com;*

Contact Email(s): amritbuttar0938@gmail.com;

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The highest available nitrogen and phosphorus values (77.4 and 11.8 kg ha^{-1}, respectively) occurred under T8. These results indicate treatment-specific differences between yield response and residual soil properties and provide a basis for further evaluation of integrated nutrient management across seasons and locations.

Keywords: Maize; integrated nutrient management; vermicompost; poultry manure; farm yard manure; soil health.

1. Introduction

Maize, also known as *Zea mays* L., is a widely grown cereal found in many developing countries, particularly in highland areas (Kaushal *et al.*, 2023). It is called the "Queen of cereals" because of its impressive yield potential, making it a crucial staple food crop (Unjia *et al.*, 2021). Ranking third among food-grain crops, following wheat and rice, maize serves multiple purposes as a cereal, vegetable and fodder crop. Originating in America, maize has been domesticated for nearly 7,000 years, providing essential nutrients for both humans and animals (Solaimalai *et al.*, 2020). Beyond its role as a staple food, maize serves as a valuable raw material for diverse products, including oil, protein, starch, food sweeteners, alcoholic beverages and even fuel (Unjia *et al.*, 2021). Maize serves multiple purposes because it is cultivated for fodder, feed and food. Additionally, it functions as a raw material for the production of pharmaceutical and industrial goods. While wheat, rice and maize hold significance as major cereal crops globally, maize stands out as the most favoured due to its high yield, ease of processing, digestibility and cost-effectiveness compared with other cereals (Reddy, 2023). The composition of maize grain includes 70% carbohydrates, 10% protein, 4% oil, 10.4% albumin, 2.3% crude fibre and 1.4% ash (Kaushal *et al.*, 2023). Furthermore, it contains essential nutrients such as 90 mg carotene, 1.8 mg niacin, 0.8 mg thiamin and 0.1 mg riboflavin per 100 g of grain (Bojtor *et al.*, 2022). Notably, maize oil is recognised for its high quality and is commonly used as an edible oil.

Fertiliser management stands out as a crucial factor among agronomic factors influencing growth and yield. The application of fertilisers is essential to replenish nutrients depleted from the soil by harvested crops and to enhance yield by supplying additional nutrients (Ghosh *et al.*, 2020). While chemical fertilisers play a significant role in achieving higher crop productivity, an excessive dependence on them is linked to the deterioration of certain soil properties and declining crop yields over time (Shyam *et al.*, 2021). Proper fertiliser usage contributes to increased crop yields and efficient recovery of applied nutrients. Some elements, such as nitrates and phosphates, may pose environmental hazards in various forms (Lu *et al.*, 2021). Therefore, effective fertilisation is crucial for ensuring crops reach maturity within specific growing seasons.

Long-term research in maize has shown that combining organic manures with mineral fertilisers can improve grain yield and soil-quality indicators under the field conditions studied (Abrol *et al.*, 2024). Evidence from maize–wheat systems likewise links integrated organic–inorganic fertilisation with improvements in soil fertility and yield sustainability (J. Wang *et al.*, 2025). In a semi-arid sandy soil, integrated fertilisation was associated with improved maize yield and soil quality relative to chemical fertilisation alone (N. Wang *et al.*, 2025; Zhang et al., 2026).

More specifically, a field comparison of nutrient-management treatments in maize reported favourable yield responses when a reduced mineral fertiliser rate was combined with vermicompost-derived nitrogen (Yadav *et al.*, 2024). Another field study found differences in soil physical properties and maize grain yield among nutrient-management combinations that included poultry manure and inorganic fertiliser; tillage was also varied in that study (Nenge *et al.*, 2025).

As agriculture faces evolving challenges, optimising nutrient management strategies becomes increasingly important. The available data indicate that managing nutrients and biofertilizers is crucial for increasing maize yield. The use of organic and inorganic nutrient sources presents a promising avenue for enhancing crop performance and ensuring the long-term vitality of the soil.

However, the comparative responses of the specific urea–vermicompost and poultry manure–farmyard manure combinations examined in this experiment in terms of maize yield and post-harvest soil properties remain to be established for the study site. A comparison of these nutrient sources under the same field conditions is therefore needed to assess their relative effects on productivity and soil characteristics.

1.1 Objective of the Study

This study seeks to investigate how various combinations of organic and inorganic nutrients affect soil health under maize cultivation, examining parameters such as nutrient uptake, soil structure and overall fertility. Specifically, the study compares grain and stover yields, harvest index, and post-harvest soil physical and chemical properties across the nutrient-source treatments.

2. Materials and Methods

The present investigation was carried out during the 2023 *Kharif* season at the Research Farm of Agronomy, Guru Kashi University, Talwandi Sabo (Bathinda), with soil analysis conducted at the university's Soil Science laboratory. The experiment was laid out in a randomised block design (RBD) with three replications and nine treatments comprising various combinations of organic manures (vermicompost, poultry manure and farmyard manure, FYM) and inorganic fertilisers (urea, diammonium phosphate and muriate of potash) as sources of nitrogen, phosphorus and potassium: T1 – Control; T2 – 100% recommended dose of nitrogen (RDN) through urea; T3 – 100% RDN through vermicompost; T4 – 50% RDN through urea + 50% RDN through vermicompost; T5 – 75% RDN through urea + 25% RDN through vermicompost; T6 – 50% RDN through poultry manure + 50% FYM; T7 – 25% RDN through poultry manure + 75% FYM; T8 – 75% RDN through poultry manure + 25% FYM; and T9 – 100% RDN through poultry manure. The recommended fertiliser dose for maize in the region was 120 kg N, 60 kg P_2O_5 and 40 kg K_2O ha^{-1}, with phosphorus and potassium applied basally through DAP and MOP, nitrogen through urea applied in two doses (basal and knee-high stage) and organic manures incorporated as a single basal dose before sowing about two weeks before sowing.

Maize hybrid Rasi 3033 was sown on 20 May 2023 at a depth of 3–5 cm with a spacing of 60 cm × 15 cm using a seed rate of 25 kg ha^{-1}, following standard field preparation, seed treatment, thinning, interculture and irrigation practices recommended for the region. Vermicompost, poultry manure and FYM were characterised for their nutrient content prior to application and each was incorporated into the topsoil (0–15 cm) ahead of sowing to allow initial decomposition and nutrient release. The initial experimental soil was a sandy loam with a pH of 7.9, EC of 0.22 dS m^{-1}, organic carbon of 0.42% and available N, P and K of 218, 82 and 118 kg ha^{-1}, respectively. Soil samples were collected from each plot at a depth of 0–15 cm before the start of the experiment and again after crop harvest, air-dried, pulverised and sieved for physical and chemical analyses.

Soil pH and electrical conductivity were determined in a 1:2 soil–water suspension (Rhoades, 1996; Thomas, 1996), while bulk density, particle density and porosity were determined by the core sampler method (Kannan *et al.*, 2013), the pycnometer method (Soil and Plant Analysis Council, 2000) and the method of Foth (1990), respectively. Available soil nitrogen was estimated by the alkaline potassium permanganate method (Subbiah & Asija, 1956), available phosphorus by the 0.5 M sodium bicarbonate method of Olsen *et al.* (1954), available potassium by ammonium acetate extraction (Jackson, 1973), available sulphur by the turbidimetric method (Chesnin & Yien, 1951) and soil organic carbon by the Walkley and Black (1934) wet oxidation method.

At physiological maturity (about 110 days after sowing), the crop from the net plot area of each treatment replication was harvested to record grain yield, stover yield and harvest index, with the latter calculated as the percentage ratio of grain yield to total biological yield. All data were subjected to analysis of variance (ANOVA) for a randomised block design as described by Gomez and Gomez (1984), and treatment means were compared using the critical difference (CD) at the 5% level of significance.

3. Results

The results of the field experiment were obtained from experiments conducted in the soil science laboratory at Guru Kashi University, Talwandi Sabo, during the *2023 Kharif* season. The data on soil physicochemical properties and yield attributes are presented in Tables 1, 2 and 3.

Table 1. Effect of organic and inorganic nutrient combinations on yield and yield attributes of maize

Treatments	Grain yield (q/ha)	Stover yield (q/ha)	Harvest index (%)
T1 (Control)	28.71^{e}	81.29^{e}	29.40^{e}
T2 (100% Recommended dose of nitrogen through urea)	56.10^{abc}	110.36^{ab}	30.42^{d}
T3 (100% Recommended dose of nitrogen through vermicompost)	54.79^{bc}	105.65^{bc}	31.13^{cd}
T4 (50% Recommended dose of nitrogen through urea + 50% Recommended dose of nitrogen through vermicompost)	60.89^{ab}	114.08^{a}	33.18^{a}
T5 (75% Recommended dose of nitrogen through urea + 25% Recommended dose of nitrogen through vermicompost)	62.45^{a}	116.19^{a}	32.92^{ab}
T6 (50% Recommended dose of nitrogen through poultry manure + 50% farm yard manure)	56.81^{abc}	106.36^{bc}	32.20^{b}
T7 (25% Recommended dose of nitrogen through poultry manure + 75% farm yard manure)	51.59^{c}	101.23^{cd}	30.59^{cd}
T8 (75% Recommended dose of nitrogen through poultry manure + 25% farm yard manure)	52.90^{c}	102.55^{c}	30.46^{d}
T9 (100% Recommended dose of nitrogen through poultry manure)	44.38^{d}	95.29^{d}	31.32^{c}
Mean	52.07	103.67	31.29
S.E m (±)	3.41	3.53	0.42
CD @ 5%	6.82	7.07	0.84

Note: Values are means of three replications. Same letter within each column indicates no significant differences among the treatments

Table 2. Effect of organic and inorganic nutrient combinations on soil reaction and physical properties of soil after maize harvest

Treatments	pH (1:2)	EC (dSm^{-1})	Bulk density ($Mg\ m^{-3}$)	Particle density ($Mg\ m^{-3}$)	Porosity (%)
T1 (Control)	7.8^{ab}	0.19^{a}	1.59^{a}	2.56	36.19
T2 (100% Recommended dose of nitrogen through urea)	7.7^{b}	0.20^{a}	1.58^{ab}	2.54	37.79
T3 (100% Recommended dose of nitrogen through vermicompost)	7.5^{c}	0.17^{a}	1.53^{f}	2.56	40.23
T4 (50% Recommended dose of nitrogen through urea + 50% Recommended dose of nitrogen through vermicompost)	7.3^{d}	0.16^{a}	1.54^{ef}	2.56	39.85
T5 (75% Recommended dose of nitrogen through urea + 25% Recommended dose of nitrogen through vermicompost)	7.5^{c}	0.18^{a}	1.55^{de}	2.54	38.97
T6 (50% Recommended dose of nitrogen through poultry manure + 50% farm yard manure)	7.7^{b}	0.20^{a}	1.49^{g}	2.56	41.80
T7 (25% Recommended dose of nitrogen through poultry manure + 75% farm yard manure)	7.8^{ab}	0.21^{a}	1.56^{cd}	2.53	38.34
T8 (75% Recommended dose of nitrogen through poultry manure + 25% farm yard manure)	7.9^{a}	0.18^{a}	1.56^{cd}	2.57	39.30
T9 (100% Recommended dose of nitrogen through poultry manure)	7.4^{cd}	0.18^{a}	1.57^{bc}	2.54	38.19
CD (p=0.05)	0.161	0.458	0.012	–	–

Note: Same letter within each column indicates no significant differences among the treatments

Table 3. Effect of organic and inorganic nutrient combinations on soil nutrient availability after maize harvest

Treatments	Available N (kg/ha)	Available P (kg/ha)	Available K (kg/ha)	Available S (kg/ha)
T1 (Control)	22.1^{f}	3.3^{f}	37.6^{d}	11.6^{f}
T2 (100% Recommended dose of nitrogen through urea)	40.5^{e}	4.67^{e}	49.4^{c}	10.6^{f}
T3 (100% Recommended dose of nitrogen through vermicompost)	66.0^{abcd}	7.8^{d}	71.9^{a}	20.0^{e}
T4 (50% Recommended dose of nitrogen through urea + 50% Recommended dose of nitrogen through vermicompost)	56.5^{d}	9.9^{c}	54.5^{bc}	21.6^{d}
T5 (75% Recommended dose of nitrogen through urea + 25% Recommended dose of nitrogen through vermicompost)	58.2^{cd}	10.2^{bc}	58.1^{b}	20.8^{de}
T6 (50% Recommended dose of nitrogen through poultry manure + 50% farm yard manure)	70.2^{abc}	11.2^{ab}	65.7^{a}	36.0^{a}
T7 (25% Recommended dose of nitrogen through poultry manure + 75% farm yard manure)	63.2^{bcd}	10.1^{c}	53.5^{bc}	28.3^{c}
T8 (75% Recommended dose of nitrogen through poultry manure + 25% farm yard manure)	77.4^{a}	11.8^{a}	70.8^{a}	32.8^{b}
T9 (100% Recommended dose of nitrogen through poultry manure)	73.1^{ab}	11.4^{a}	68.6^{a}	31.5^{b}
CD (p=0.05)	12.60	1.07	7.15	1.58

Note: Same letter within each column indicates no significant differences among the treatments

4. Discussion

4.1 Effect of Organic and Inorganic Nutrient Combinations on Yield Attributes of Maize

The results presented in Table 1 clearly demonstrate that the integrated application of organic and inorganic nutrient sources significantly influenced grain yield, stover yield and harvest index of maize compared to the unfertilised control (T1). The highest grain yield of 62.45 q ha^{-1} was recorded under T5 (75% RDN through urea + 25% RDN through vermicompost), significantly surpassing T1 (Control, 28.71 q ha^{-1}) and also exceeding T2 (100% RDN through urea alone, 56.10 q ha^{-1}). T5 achieved numerically the highest yield while remaining statistically comparable to sole inorganic fertilisation (T2), indicating that up to 25% of the recommended nitrogen can be substituted with vermicompost without a yield penalty. This observation is in agreement with the recent findings of Chauhan *et al.* (2023), who reported that the integration of organic and inorganic nutrient sources in maize-based cropping systems in Gujarat significantly improved grain yield over sole inorganic fertilisation, attributing the gains to synergistic improvements in soil biological activity and nitrogen use efficiency.

The numerically higher yield under T5 than under sole inorganic fertilisation (T2) may be explained by the complementary action of urea, which provides immediately available nitrogen for rapid early-season crop uptake and vermicompost, which improves soil biological activity, enhances nitrogen mineralisation and supplies biologically active growth-promoting substances including humic acids, cytokinin, gibberellins and microbial inoculants (Khadtare *et al.*, 2006). Vermicompost has also been shown to enhance the population of nitrogen-fixing and phosphate-solubilising bacteria in the rhizosphere, thereby improving the overall nutrient availability environment for the crop (Bojtor *et al.*, 2022). Similar results were reported by Verma *et al.* (2006), who demonstrated that integrated nutrient management combining 75% inorganic nitrogen with 25% organic nitrogen through FYM resulted in better nitrogen use efficiency (NUE) and grain yield in the maize–wheat system and by Abid *et al.* (2020), who confirmed that integrated nutrient management significantly enhanced both soil quality indices and crop productivity in a maize-based cropping system in Pakistan.

Stover yield followed a trend similar to that of grain yield, with the highest value of 116.19 q ha^{-1} recorded under T5, followed by T4 (50% urea + 50% vermicompost) at 114.08 q ha^{-1}. The enhanced stover yield under integrated treatments reflects greater vegetative dry matter accumulation, which is attributed to improved leaf area development and prolonged photosynthetic efficiency resulting from the sustained release of nutrients from organic sources (Brar *et al.*, 2006). Harvest index (HI) values ranged from 29.40% (T1) to 33.18% (T4), indicating that balanced integrated nutrition not only increases total biomass but also improves the efficiency of assimilate partitioning to the economic product (grain). These HI values are consistent with values reported for high-yielding maize hybrids under integrated nutrient management in the Indo-Gangetic Plains (Verma *et al.*, 2020).

Among wholly organic treatments, T6 (50% poultry manure + 50% FYM) recorded a grain yield of 56.81 q ha^{-1}, substantially exceeding T9 (100% poultry manure, 44.38 q ha^{-1}) and the control. This suggests that combining poultry manure with FYM was more effective than poultry manure alone under the study conditions, likely due to their complementary nutrient profiles and differential decomposition rates that sustain nutrient supply throughout crop growth (Zerihun *et al.*, 2013). Poultry manure provides a relatively concentrated and rapidly mineralising nitrogen source, while FYM contributes to soil structural improvement and sustained slow-release nutrition. This finding is consistent with Zhao *et al.* (2021), who demonstrated that diverse organic amendment combinations produced synergistic improvements in soil fertility parameters and crop yield in cereal crops.

4.2 Effect on Physical Properties of Soil After Maize Harvest

The physical properties of the post-harvest soil are presented in Table 2. Soil pH ranged from 7.3 to 7.9 across all treatments, confirming the slightly alkaline nature of the experimental soil, consistent with the characterization of typical Punjab soils. The lowest pH (7.3) was recorded under T4 (50% urea + 50% vermicompost), while the highest (7.9) was under T8 (75% poultry

manure + 25% FYM). The mild acidification observed under vermicompost-containing treatments is a well-established consequence of organic acid production during microbial decomposition of organic matter, which partially neutralizes soil alkalinity and improves the chemical environment for micronutrient availability (Chang *et al.*, 2007). A moderate reduction in pH under organic treatments is agronomically beneficial in alkaline soils of the Indo-Gangetic Plains, where high pH limits the availability of micronutrients such as zinc, iron and manganese (Abid *et al.*, 2020). The higher pH values under poultry manure treatments are attributable to the alkaline residue left after decomposition of poultry excreta, a phenomenon commonly documented in tropical cereal systems (Zerihun *et al.*, 2013).

Electrical conductivity (EC) remained within safe limits across all treatments (0.16 to 0.21 dS m^{-1}), confirming no salinity hazard to crops. The slightly elevated EC under poultry manure treatments (T6: 0.20a; T7: 0.21a) relative to the control reflects the higher soluble salt content of poultry manure, but these values are well below the threshold of 1.7 dS m^{-1} considered critical for maize cultivation (Keskin *et al.*, 2005). These EC values are consistent with those reported under comparable integrated nutrient management studies in northwest India (Brar *et al.*, 2001).

Bulk density was significantly reduced under organic manure treatments relative to the unfertilised control (1.59 Mg m^{-3}), with the lowest value of 1.49 Mg m^{-3} recorded under T6 (50% poultry manure + 50% FYM). This reduction corresponds directly to the highest porosity observed in the same treatment (41.80%), consistent with the established positive effect of organic matter additions on soil pore architecture. Increases in soil organic matter content improve macro-aggregate stability, reduce inter-particle compaction and enhance the proportion of biopores formed by earthworm activity and root channels (Abid *et al.*, 2020). These improvements in soil physical structure are particularly important for maize, where root penetration depth and soil aeration at the rooting zone have been directly linked to grain yield potential (Bojtor *et al.*, 2022). The findings are consistent with Brar *et al.* (2001), who documented significant reductions in bulk density and improvements in total porosity following the combined application of FYM and inorganic fertilisers in a long-term maize experiment in Punjab. Particle density showed little variation across treatments (2.53 – 2.57 Mg m^{-3}), as expected given that this property reflects soil mineral composition, which is not substantially altered within a single growing season by fertiliser management.

4.3 Effect on Chemical Properties of Soil After Maize Harvest

Post-harvest soil chemical properties (Table 3) revealed marked differences among treatments. Available soil nitrogen was significantly higher in all organic and integrated treatments than in T1 (Control, 22.1 kg ha^{-1}) and T2 (100% urea, 40.5 kg ha^{-1}). The highest available N (77.4 kg ha^{-1}) was recorded under T8 (75% poultry manure + 25% FYM), followed by T9 (73.1 kg ha^{-1}, 100% poultry manure) and T6 (70.2 kg ha^{-1}, 50% poultry manure + 50% farm yard manure), all statistically comparable with T3 (100% vermicompost, 66.0 kg ha^{-1}) and T7 (63.2 kg ha^{-1}). The superior residual nitrogen status under poultry manure and FYM-based treatments is attributable to the slow and sustained release of nitrogen through microbial mineralisation of organic matter, which continuously replenishes the inorganic N pool over the cropping season and beyond (Yaduvanshi, 2003). Notably, the wholly organic treatment T3 maintained a higher residual N status than the urea + vermicompost combinations T4 (56.5 kg ha^{-1}) and T5 (58.2 kg ha^{-1}), suggesting that although the readily available nitrogen from urea supports greater early-season crop uptake and higher grain yield, it leaves behind a smaller unmineralized organic nitrogen reserve at harvest than a fully organic input does. In contrast, the low residual N under urea-only treatment (T2) reflects the susceptibility of inorganic nitrogen to losses via leaching, volatilization and denitrification, consistent with the extensive literature on nitrogen use efficiency in rice-wheat and maize-based systems of the Indo-Gangetic Plains (Kaushal *et al.*, 2023). Recent research by Zhao *et al.* (2021) similarly demonstrated that carbon-based organic amendments significantly improved soil nitrogen retention over inorganic fertiliser application alone, with implications for reducing nitrogen losses and groundwater contamination.

Available soil phosphorus was highest under T8 (11.8 kg ha^{-1}, 75% poultry manure + 25% FYM), statistically comparable with T9 (11.4 kg ha^{-1}, 100% poultry manure) and T6 (11.2 kg ha^{-1}, 50% poultry manure + 50% FYM). Poultry manure is notably rich in both inorganic and organic phosphorus fractions and its decomposition is known to stimulate phosphate-solubilising bacterial populations in the rhizosphere, thereby enhancing plant-available phosphorus beyond what direct nutrient additions alone would explain (Yazdani *et al.*, 2009). This biological mechanism of phosphorus mobilization under organic manure treatments is increasingly recognised as a key advantage of organic and integrated nutrient management over sole inorganic fertilisation, particularly in calcareous alkaline soils where phosphorus fixation by calcium limits its availability (Abid *et al.*, 2020). Among the urea + vermicompost combinations, T5 recorded the highest available P (10.2 kg ha^{-1}), closely followed by T7 (10.1 kg ha^{-1}) and T4 (9.9 kg ha^{-1}), reflecting a synergistic effect of vermicompost on microbial phosphorus cycling, consistent with the findings of Khadtare *et al.* (2006) on the role of vermicompost in improving phosphorus dynamics in cereal crops. Sole vermicompost (T3, 7.8 kg ha^{-1}), although markedly superior to the control and to urea alone, had less available phosphorus than the poultry manure-based treatments, indicating that under the present soil conditions the phosphorus content and mineralisation rate of poultry manure exceeded those of vermicompost.

Available soil potassium followed a somewhat different pattern from that of nitrogen and phosphorus. The highest K availability (71.9 kg ha^{-1}) was observed under T3 (100% vermicompost), statistically comparable with T8 (70.8 kg ha^{-1}, 75% poultry manure + 25% FYM) and T9 (68.6 kg ha^{-1}, 100% poultry manure) and closely followed by T6 (65.7 kg ha^{-1}, 50% poultry manure + 50% FYM). The high potassium availability under sole vermicompost is consistent with the passage of organic residues through the earthworm gut during vermicomposting, a process that converts a substantial fraction of the substrate potassium into readily exchangeable and water-soluble forms, thereby concentrating available K relative to the parent feedstock (Khadtare *et al.*, 2006). Poultry manure and FYM likewise contain substantial potassium in readily exchangeable and slowly soluble forms, released progressively through organic matter decomposition (Vanlauwe *et al.*, 2002). The markedly low available K in the T2 treatment (49.4 kg ha^{-1}) relative to the organic treatments highlights the failure of nitrogen-only inorganic fertilisation to replenish potassium,

which is critical for stover strength, drought tolerance and grain filling in maize (Bojtor *et al.*, 2022). The data reinforce the importance of potassium budgeting in maize production, particularly in the context of declining soil K levels observed across intensively farmed Punjab soils (Brar *et al.*, 2006).

Available sulphur was highest under T6 (36.0 kg ha^{-1}), with all organic and integrated treatments recording substantially higher S levels than T1 (11.6 kg ha^{-1}) and T2 (10.6 kg ha^{-1}). Organic manures, particularly poultry manure, contain appreciable quantities of organic sulphur in the form of sulphur-containing amino acids (cysteine and methionine), which are mineralised by soil microorganisms to release plant-available inorganic sulphate (Ma *et al.*, 2021). Sulphur is increasingly recognised as a critical secondary macronutrient whose deficiency constrains cereal yield in intensively farmed soils of India, where sulphur additions from atmospheric deposition have declined with improved air quality regulations and where conventional fertiliser programmes do not routinely include sulphur supplementation (Kaushal *et al.*, 2023). The substantially higher sulphur availability under organic treatments in this study highlights their additional value as sulphur sources beyond their primary NPK contributions.

4.4 Integrated Interpretation: Agronomic and Environmental Implications of Combined Nutrient Management

Taken together, the results of this study provide strong and consistent evidence that integrated plant nutrient management (IPNM) — combining reduced doses of inorganic fertilisers with appropriate organic manures — is superior to sole application of either source for enhancing both crop productivity and soil health under maize cultivation. The integrated treatments improved nitrogen use efficiency, enhanced phosphorus solubilisation and uptake, promoted potassium and sulphur availability, reduced soil bulk density and improved soil porosity, all of which collectively contributed to better crop growth, yield and post-harvest soil fertility. These multidimensional benefits are fully consistent with the expanding body of evidence from recent research across South Asia and Sub-Saharan Africa demonstrating that IPNM represents the optimal strategy for sustainable intensification of cereal production systems (Abid *et al.*, 2020; Chauhan *et al.*, 2023).

From an agronomic perspective, the present findings suggest that substitution of 25% of the recommended inorganic nitrogen dose with vermicompost (T5) is the most agronomically efficient treatment, achieving the highest grain yield while also showing improvements in selected post-harvest soil nutrient and physical properties. This approach reduces dependence on synthetic urea, with associated reductions in greenhouse gas emissions from fertiliser production and in nitrous oxide (N_2O) emissions from the soil — a climate co-benefit increasingly recognised in the context of agricultural sustainability targets (Abid *et al.*, 2020). Furthermore, the organic manure-based treatments (particularly T6: 50% poultry manure + 50% FYM) demonstrated the greatest improvements in soil physical structure and chemical fertility, making them valuable for long-term soil health maintenance even where their short-term grain yield was not the highest. These results highlight the complementary roles of different treatment strategies: T5 is recommended where maximizing grain yield is the primary objective, while T6 is recommended where long-term soil health improvement is the priority, particularly in degraded or compacted soils.

These findings align with the conclusions of Zerihun *et al.* (2013) in Ethiopia, who reported significant maize yield gains from combined organic and inorganic fertilisation, and with Vanlauwe *et al.* (2002), who demonstrated through ^{15}N-labelled fertiliser studies that organic matter enhances the efficiency of inorganic nitrogen through reduced gaseous losses and improved synchrony of nitrogen supply with crop demand. The present study extends these principles to the semi-arid, alkaline soils of the Punjab region, confirming their applicability across diverse agro-ecological contexts. Collectively, the evidence supports the adoption of IPNM as a policy-endorsed strategy for sustainable maize production in the Indo-Gangetic Plains, consistent with national soil health and food security objectives.

5. Conclusion

This study shows that integrated use of organic and inorganic nutrient sources improves both maize yield and post-harvest soil health more effectively than either source alone. The highest grain yield (62.45 q ha^{-1}) was recorded under 75% RDN through urea combined with 25% RDN through vermicompost (T5), significantly outperforming the unfertilised control and remaining on par with sole inorganic fertilisation. Among wholly organic treatments, combining poultry manure with farm yard manure (T6) produced a higher yield than poultry manure alone (T9), showing that combining organic sources can be more effective than using poultry manure alone under the conditions studied.

Beyond yield, integrated and organic treatments consistently improved post-harvest soil properties relative to sole inorganic fertilisation: bulk density was reduced, porosity increased and available nitrogen, phosphorus, potassium and sulphur were all higher, particularly under T6. This indicates that partial substitution of inorganic nitrogen with organic manures sustains productivity while building longer-term soil fertility.

Overall, substituting 25% of the recommended nitrogen with vermicompost (T5) offers the best balance of yield and soil improvement, while poultry manure–FYM combinations (T6) are preferable where long-term soil health is the priority. Integrated nutrient management thus offers a practical, sustainable strategy for maize production under semi-arid conditions, warranting confirmation across additional seasons.

6. Limitations

The experiment was conducted at one location during a single growing season, and treatment responses may differ under other soil, weather and management conditions. Post-harvest soil measurements describe short-term responses and do not establish long-term trends in soil health. The findings therefore support comparisons among the tested nutrient combinations under the study conditions

but do not establish their performance over successive seasons. Multi-season trials would help assess the consistency of the observed yield and soil-property responses.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. ChatGPT, Claude and Perplexity were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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