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Exploring the potential of enhanced organic formulations for boosting crop productivity, nutrient utilization efficiency, and profitability in baby corn-kabuli gram-vegetable cowpea cropping system

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The preparation of enriched formulation by integrating of agricultural wastes such as paddy husk ash (PHA) and potato peel with organic fertilizer such as farmyard manure (FYM), compost can enrich the soil with essential plant nutrients, leading to higher yields in subsequent crops and potentially reducing the dependence on farmyard manure/compost alone. However, there is lack of adequate research findings regarding the impact of different formulations generated from agricultural waste on productivity, nutrient utilization efficiency and profitability of baby corn-kabuli gram-vegetable cowpea cropping system. Therefore, a two-year field experiment (2020–2022) was conducted ICAR-IARI, New Delhi with baby corn-kabuli gram-vegetable cowpea cropping system. Seven nutrient sources were tested in Randomized Block Design and replicate thrice.The results showed that treatment T_4 (100% recommended dose of nitrogen (RDN) through PHA based formulation) had significant effect on crop yield grown in rotation, followed by treatment T_6 (100% RDN through potato peel compost (PPC) based formulation) and T_2 (100% RDN through FYM). The increase in yield was 75.0, 44.3 and 33.1% during first year and 72.6, 45.9 and 31.0% during second year, respectively, over control. Treatment T_4 also significantly enhanced system uptake of N, P and K as well as system gross returns and net returns, resulting in 65.6, 84.9, 69.5, 50.7 and 55.2% higher returns during first year and 68.6, 80.5, 73.9, 50.0 and 54.2% higher returns during second year, respectively, over control. Furthermore, treatment T_4 significantly improved agronomic nitrogen use efficiency and apparent recovery by 151.6 and 2.0% in baby corn, 74.2 and 1.5% in kabuli gram, 55.7 and 13.9% in veg cowpea over T_7, respectively, averaged across two years of study. Based on these results, it is recommended to adopt (T_4) 100% RDN through PHA based formulation, and (T_6) 100% RDN through PPC based formulation in the area with a shortage of FYM but with the availability of rice husk ash or pototo peels for sustainable utilization of the agricultural wastes and improving the agricultural sustainability.

KEYWORDS

economics, farmyard manure, nitrogen use efficiency, paddy husk ash, potato peel compost, yield

Introduction

Farmers worldwide encounter challenges in achieving sustainability in crop production, attributed to imbalanced and traditional farming practices (Kumar et al., 2022). The increasing global population underscores the importance ensuring sustainability, safety, and security in food production, while minimizing the impact on the economy, earth and the environment (Ramankutty et al., 2018). Traditional farming, which heavily relies on inputs, guarantees food safety but has enduring adverse effects on food quality, biodiversity, environmental sustainability, greenhouse gas emissions (GHG), and human health (Mbow et al., 2020). Over the past two decades, various efforts have been undertaken to explore sustainable approaches to future food security that reduce reliance on chemicals and align with the United Nations Sustainable Development Goals (Castor et al., 2020).

Organic farming emerges as a natural method of crop production, employing ecologically sound fertilization and pest management methods like farmyard manure (FYM), green manure, compost, biological control like bio-pesticides or botanicals like limonoids, nimbecidine etc. (Behera et al., 2012). Further, organic fertilizers produced through composting of farm waste play a substantial role in enhancing soil carbon levels, maintaining nutrient equilibrium, and fostering overall plant growth and yield (Ye et al., 2020; Sharma et al., 2021). Organic farming heavily relies on FYM/compost for nutritional supplementation for crop growth and development but the availability is limited throughout the year in many countries.

A large quantities of crop residues are wasted annually, either through field burning after harvest or in industrial processes during refining, such as with husks and bran (Abbas et al., 2012; Cardoen et al., 2015). Numerous organic sources of nutrients can be generated but utilizing agricultural waste such as rice residues, paddy husk ash and potato peel. By employing suitable methods, agricultural wastes can be recycled to generate important sources of energy and natural fertilizer for crops (Sharma et al., 2019; Koul et al., 2022).

Paddy husk ash (PHA) is a renewable agricultural byproduct derived from rice milling, and it is abundantly available in countries where rice is cultivated (Ginni et al., 2021; Kandagatla et al., 2023). Rice husk is a byproduct of rice milling, with approximately 0.20 tons of rice husk generated from each ton of paddy (Tayeh et al., 2021). Upon incinerated, each ton of paddy husk produces around 20–25% paddy husk ash (PHA), which can vary depending on the rice variety and prevailing climatic conditions (Akram et al., 2009; Khan et al., 2012). Ash obtained from paddy husk at different locations contains potassium oxide (K_2O) within the range of 0.72 to 3.84% and magnesium oxide (MgO) ranging from 0.23 to 1.59% (Muthadhi et al., 2007). The presence of silicon in rice husk ash contributes to the plant's defence mechanism against salinity stress (Ijaz et al., 2023). The ash raises soil pH, leading to an increase in available phosphorus(Schiemenz and Eichler-Löbermann, 2010). It enhances aeration within the crop root zone and elevates water-holding capacity, along with the levels of exchangeable potassium and magnesium (Priyadharshini and Seran, 2009). The utilization of biomass ashes in agriculture offers a potential solution for their disposal while also reducing the need for commercial fertilizer applications (Bougnom and Insam, 2009). Potato peel waste is another product of the food processing industry, containing substantial amounts of starch and nutrients that can be enriched with soil microorganism for composting purposes. Consequently, making use of this by-product has the potential to significantly alleviate the disposal challenges faced by potato industries.

The aim of the study aimed to fill a significant research gap by investigating the potential of enriched organic formulations derived from various agricultural wastes, such as paddy husk ash and potato peel waste in varying proportons, as effective fertilizers. The objective was to reduce the dependence solely on FYM to meet nutritional requirements under organic farming. The hypothesis is grounded in the belief that these formulations, rich in readily available inorganic nitrogen for plants and organic nitrogen forms that will later mineralize in the soil, will demonstrate superior nutrient use efficiency compared to other organic nutrient sources.

Consequently, the primary objective of our study is to investigate the influence of enriched organic formulations on productivity, nitrogen use efficiency, and profitability of baby corn-kabuli gram-vegetable cowpea cropping system.

Materials and methods

Site description

The two-year (2020–21 and 2021–22) field experiment was executed at a fixed location within the IARI, New Delhi at the Agronomy experimental block, situated in northwestern India (28.38° N, 77.09° E) at an elevation of 228.6 m above mean sea level. The climate at the site is characterized as semi-arid to sub-tropical. The soil

TABLE 1 Chemical and nutrient contents of organic manures/formulations used in the experiment.

Parameters	Nutrient sources											
	FYM		RRC		PHA		PPC		PHA-based formulation		PPC-based formulation	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
pH	8.1	8.0	7.7	7.6	7.8	7.7	7.8	7.9	7.9	7.8	8.0	8.0
EC (ds m^{-1})	3.75	3.76	3.82	3.84	3.87	3.85	3.84	3.86	3.76	3.77	3.77	3.78
W&BC (%)	15.42	15.84	13.24	13.96	4.66	4.72	11.56	11.42	14.34	14.73	14.65	14.96
Total N (%)	0.72	0.70	0.55	0.58	0	0	0.61	0.59	0.65	0.63	0.70	0.68
Total P (%)	0.25	0.27	0.22	0.21	0.20	0.17	0.28	0.32	0.25	0.26	0.26	0.28
Total K (%)	0.52	0.49	1.27	1.34	1.66	1.75	0.85	0.90	0.63	0.62	0.59	0.57
Fe (mg kg^{-1})	708.6	778.8	501.2	562.6	1252.4	1298.4	902.8	908.2	1663.0	1730.8	1838.6	1872.7
Mn (mg kg^{-1})	341.7	328.6	232.5	254.3	298.4	312.5	284.0	265.4	327.4	317.0	330.2	316.0
Cu (mg kg^{-1})	36.2	40.5	25.6	30.5	38.4	43.8	55.8	47.5	34.4	38.8	40.7	41.9
Zn (mg kg^{-1})	127.5	115.4	81.7	93.4	98.5	105.5	90.4	102.8	120.8	111.1	122.1	114.9

TABLE 2 Amount of organic formulations applied in different crops during both years of study.

Crop	Year	Input applied (kg ha^{-1})						
		Control	FYM	RRC	PHA-F (100% RDN)	PHA-F (75% RDN)	PPC-F (100% RDN)	PPC-F (75% RDN)
Baby corn	2020–21	–	20,833	27,273	23,148	17,361	21,585	16,189
	2021–22	–	21,429	25,862	23,810	17,857	22,228	16,671
Kabuli gram	2020–21	–	2,778	3,636	3,086	2,315	2,878	2,158
	2021–22	–	2,857	3,448	3,175	2,381	2,964	2,223
Veg. cowpea	2020–21	–	2,778	3,636	3,086	2,315	2,878	2,158
	2021–22	–	2,857	3,448	3,175	2,381	2,964	2,223

at the experimental site exhibits a sandy clay loam in texture (sand 63.8%, silt 12.2%, clay 24.0%) with a pH of 8.1 and an electrical conductivity (EC) of 0.36 dSm^{-1} in the top 15 cm layer. Initial soil analysis revealed low levels of available nitrogen (N) (206.2 kgh a^{-1}) and organic carbon (0.37%), while phosphorus (P) and potassium (K) were present at medium levels (13.6 kg ha^{-1} and 236.0 kg ha^{-1}, respectively). The experimental period experienced higher and evenly distributed rainfall in 2021–22 compared to 2020–21, with total rainfall recorded at 913.6 mm and 1682.9 mm during the respective periods from July to May.

Experimentation design and crop management

The experiment consisted of seven nutrient sources with three replications that were tested using a completely randomized block design in each crop season. These treatments were: (T_1) control, (T_2) 100% RDN through FYM, (T_3) 100% RDN through improved RRC (rice residue compost), (T_4) 100% RDN through PHA-based formulation, (T_5) 75% RDN through PHA based formulation, (T_6) 100% RDN through PPC based formulation and (T_7) 75% RDN through PPC based formulation. The nutrient contents of these used organic formulations are presented in Table 1. The cultivars employed in the experiment were "G-5414" for baby corn, 'Pusa–3022' for kabuli gram, and "Pusa Komal" for vegetable cowpea. Before the application of organic formulations, a sample was collected from each source of organic nutrients and subjected to nutrient composition analysis. The amounts of organic formulations were then determined by multiplying their content by the quantity of the respective material, and these organic nutrient sources were applied before sowing or planting the crops (Table 2). This application was carried out on a nitrogen-equivalent basis, taking into account the nutrient requirements of each crop in the respective treatment. In the year 2020–21, the farmyard manure, rice residue compost, and potato peel compost had nitrogen content levels of 0.72, 0.55, and 0.61%, respectively. In 2021–22, these same materials were analyzed, revealing nitrogen content levels of 0.70, 0.58, and 0.59% (on an oven-dry weight basis) respectively. Following the harvest, which included threshing, cleaning, and drying, the seed yield of crops were examined. Likewise, stover yield was determined by deducting the seed yield from the total biological yield and quantified in tons per hectare (t ha^{-1}). N, P and K content in various plant parts were determined by using the modified Kjeldahl method (Subbiah and Asija, 1956), Vanadomolybdo-phosphoric acid yellow colour method (Olsen, 1954) and flame photometer (Jackson, 1973), respectively and expressed in percentage. To determine total nutrient uptake, the nutrient concentrations were multiplied by the dry weight of the respective plant parts and presented as the combined uptake of three crops in a cropping cycle.

Estimation of nitrogen use efficiency

The various nitrogen use efficiencies such as agronomic nitrogen use efficiency (ANUE), apparent recovery (AR) of applied nitrogen and physiological nitrogen use efficiency (PNUE) were determined using the following equations given by Cassman et al. (1998).

Agronomic nitrogen use efficiency (ANUE), which is a measure of economic yield produced per unit N supplied from each treatment, was calculated using grain yield from each treatment (Eq. 1).

$$\text{ANUE}\left(\text{kg kg}^{-1}\text{N}\right)=\frac{\begin{array}{c}\text{Grain yield in fertilized plot}\left(\text{kg ha}^{-1}\right)\\ -\text{Grain yield in control}\left(\text{kg ha}^{-1}\right)\end{array}}{\text{Quantity of } N \text{ applied}\left(\text{kg N ha}^{-1}\right)} \quad (1)$$

The apparent recovery of applied N (AR) was calculated to determine the ability of the plant to acquire the N supplied from different treatments (Eq. 2).

$$\text{AR}\left(\text{kg kg}^{-1}\text{N}\right)=\frac{\begin{bmatrix}\text{Total } N \text{ uptake}\left(\text{grain and stover}\right)\\ \text{in the fertilizer plot}\left(\text{kg N ha}^{-1}\right)\\ -\text{Total } N \text{ uptake}\left(\text{grain and stover}\right)\\ \text{in control}\left(\text{kg N ha}^{-1}\right)\end{bmatrix}}{\text{Quantity of } N \text{ applied}\left(\text{kg N ha}^{-1}\right)} \quad (2)$$

Physiological N use efficiency (PNUE) was calculated to determine the economic yield per unit N accumulated from each fertilizer treatment (Eq. 3).

$$PNUE\left(kg\,kg^{-1}N\right)=\frac{\begin{bmatrix}Yield\ in\ fertilized\ plot\ \left(kg\,ha^{-1}\right)\\ -Yield\ in\ control\ \left(kg\,ha^{-1}\right)\end{bmatrix}}{\begin{bmatrix}Total\ N\ uptake\ \left(grain\ and\ stover\right)\\ in\ the\ fertilizer\ plot\ \left(kg\,N\,ha^{-1}\right)\\ -Total\ N\ uptake\ \left(grain\ and\ stover\right)\\ in\ control\ \left(kg\,N\,ha^{-1}\right)\end{bmatrix}} \quad (3)$$

Preparation of organic formulations

FYM was meticulously prepared through the aerobic windrow method within the Biomass Utilization Unit, IARI New Delhi. On average, well-decomposed FYM was found to contain approximately 5 to 6 kg N, 1.2 to 2.0 kg P, and 5 to 6 kg K per tonne. Rice residue compost, fashioned through the windrow composting method, involved the thorough chopping of rice residue, which was then placed in windrows to expedite decomposition. Periodic turning of these windrows facilitated enhanced aeration and mixing of compost constituents. The turning process, accompanied by the moistening of chopped residue with water and cow dung slurry, expedited the composting process, requiring approximately 6 to 8 weeks for uniform completion. The application of rice residue compost on a dry weight basis preceded the sowing of all crops in the respective treatment plots. PHA, a renewable agricultural byproduct of rice milling, was abundantly available in rice-growing countries. Produced during rice milling, 0.20 tonnes of rice husk yielded approximately 0.25 tonnes of ash post-burning, contingent upon variety and climatic conditions. The incorporation of paddy husk ash in agriculture offered a potential solution for disposal challenges while concurrently reducing the need for commercial fertilizer application. Consequently, PHA-based formulations were devised by blending paddy husk ash with locally available nutrient sources in varying proportions. Potato peel waste, a byproduct of the food processing industry, featured a substantial starch and nutrient content, rendering it amenable to supplementation with soil microorganism for nitrogen enrichment. Serving as an alternative source of manure for crops, potato peel waste offered a means to mitigate environmental pollution. Therefore, formulations incorporating potato peel were devised based on product availability, employing different proportions alongside other organic nutrient sources. The nutrient composition and detailed descriptions of these organic formulations, applied uniformly across all crops in both experimental years, are comprehensively presented in Tables 1, 2.

Soil sampling and analysis

Composite soil samples were collected from each plot in the experimental field with a soil auger at 0–15 cm soil profile at the beginning and end of each cropping cycle. After removing all stubbles, residue, and root biomass, a composite soil sample weighing approximately 500 grams was obtained. These samples were subsequently air-dried, ground, passed through a 2 mm mesh sieve, and stored in airtight polythene containers for subsequent analysis. The available N was determined by the alkaline potassium permanganate ($KMnO_4$) method proposed by Subbiah and Asija (1956). The available P content in soil was estimated by Olsen's method (Olsen, 1954). Available K was estimated by using the neutral ammonium acetate extraction method as described by Jackson (1973) and further expressed in kg ha^{-1}.

Economic analysis

To find out the most profitable treatment, economics of different treatments were worked out in terms of net returns (₹ ha^{-1}) on the basis of the prevailing market rate and benefit cost ratio for each treatment was calculated to ascertain economic viability of the treatment. System economics were calculated by considering system gross returns, net returns, and Benefit:Cost ratio.

Statistical analysis

The data acquired over a span of two years underwent statistical analysis through the F-test, following the methodology described by Gomez and Gomez (1984). Significance testing of differences between treatment means was conducted using the standard error of means (SEM±) and the least significant difference (LSD) values or Duncan's multiple range test (DMRT) at a significance level of $p \leq 0.05$. The results depicting the significance of differences between treatment means are graphically represented through error bars. The graphical representations were prepared using Graphpad prism version 8.0.1.and correlation analysis was performed through JASP software version 0.18.1.0.

Results

Yield

Baby corn

A comprehensive examination of the data presented in Figures 1A–C indicates that treatment T_4 demonstrated the highest yields for baby corn (1.61 and 1.64 t ha^{-1}), cob (8.7 and 8.8 t ha^{-1}), and green fodder (25.6 and 26.4 t ha^{-1}) during both the year of study. Treatment T_4 exhibited statistical parity with treatments T_6 and T_2, while also asserting statistically significant ($p \leq 0.05$) superiority over the remaining treatments during both the year of study. Notably, treatment T_4, T_6, and T_2 showed a percentage increases of 75.4, 78.1, and 50.7% and 73.6, 76.6, and 50.1% over the control during the first and second year of the experiment. Furthermore, treatment T_3, performed equivalently to T_5 and T_7, demonstrated a substantial enhancement in baby corn yield (both with and without husk) and green fodder, indicating percentage increases of 41.3, 47.4, and 24.7% and 45.1, 45.5, and 28.4% over the control in the 2020–21 and 2021–22, respectively. These results underscore the efficacy of specific treatments in positively influencing crop yield and fodder production over the studied period.

Kabuli gram

Analysis of the data presented in Figures 1D,E indicates that treatment T_4 demonstrated the highest kabuli gram seed yield (2.80 and 2.86 t ha^{-1}) and stover yield (4.41 and 4.54 t ha^{-1}) during both the year of study. Treatment T_4 exhibited statistical parity with treatments T_6 and T_2, while also asserting statistically significant ($p \leq 0.05$) superiority over the remaining treatments. Remarkably, the application of treatment T_4 resulted in a notable augmentation of the seed yield of kabuli gram by 44.3% in 2020–21 and 45.7% in 2021–22, respectively, compared to the control. Furthermore, treatment T_5, at parity with treatment T_7, exhibited a noteworthy increase of 20.6 and 22.4% in seed yield, as well as 19.8 and 20.9% in stover yield over the control during both the year of study, respectively. The observed outcomes emphasize the positive impact of specific treatments on crop yield and fodder production throughout the studied duration.

Vegetable cowpea

The results indicate a statistically significant increase ($p \leq 0.05$) in both green pod (10.9 and 11.0 t ha^{-1}) and stover yield (24.4 and 24.9 t ha^{-1}) when subject to treatment T_4 in comparison to the control as illustrated in Figures 1F,G. Treatment T_4 exhibited comparable performance with both treatment T_6 (green pod yield of 10.6 and 10.8 t ha^{-1}, and stover yields at 23.5 and 23.8 t ha^{-1}) and T_2 (green pod yield of 10.6 and 10.7 t ha^{-1}, and stover yields at 23.2 and 23.5 t ha^{-1}) during the assessment, demonstrating similar productivity levels in terms of both green pod and stover yields. Notably, a noteworthy enhancement of 17.2 and 16.2% in green pod yield over the control was discerned with the application of treatment T_3. This increase was found to be comparable to the yields achieved with treatments T_5 and T_7 throughout the study period. Over the analyzed timeframe, these

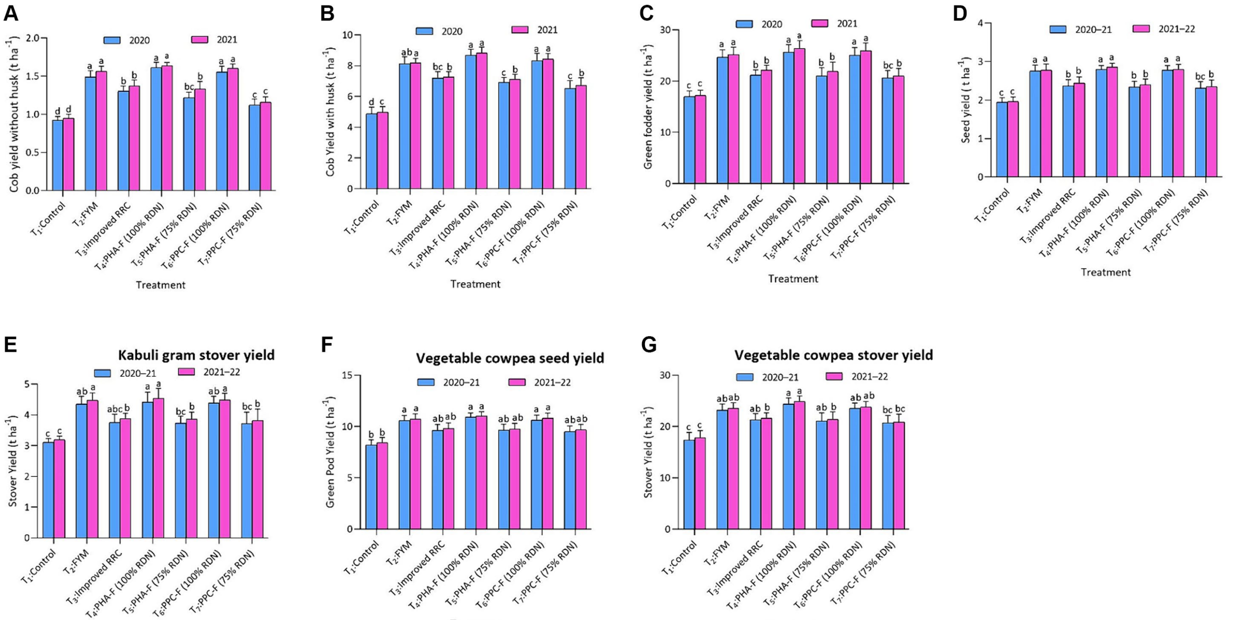

FIGURE 1
Effect of enriched organic formulations on yield of **(A)** babycorn cob yield without husk, **(B)** babycorn cob yield with husk, **(C)** baby corn green fodder yield, **(D)** Kabuli gram seed yield, **(E)** Kabuli gram stover yield, **(F)** vegetable cowpea green pod yield, and **(G)** vegetable cowpea stover yield.

results highlight the effectiveness of particular treatments in enhancing both crop yield and fodder production.

Nutrient concentration among different crops

Baby corn

Significant variations were observed in the concentrations of N, P, and K in both baby corn and green fodder, while examining the impact of enriched organic formulations as depicted in Figures 2A,B to Figures 4A,B. The highest N concentrations in baby corn cob (1.86 and 1.90%) and green fodder (1.07 and 1.13%) were observed in treatment T_6, surpassing the control, and demonstrating statistical parity with the other treatments. Notably, treatment T_4, comparable to T_6 and T_2, exhibited significantly higher concentrations of P in baby corn cob (0.44 and 0.45%) and fodder (0.25 and 0.26%) compared to the other treatments ($p \leq 0.05$). Similarly, K content in baby corn cob (1.43 and 1.43%) and fodder (1.05 and 1.12%) was notably higher under treatment T_3 compared to the control. The percentage increase during the first year was 18.2% for baby corn cob and 24.4% for fodder, while during the second year, it was 20.7% for baby corn cob and 17.2% for fodder. Treatment T_3 exhibited statistical similarity with the remaining treatments. In contrast, the control group recorded the lowest concentrations of N, P, and K.

Kabuli gram

Treatment T_6 demonstrated a significantly elevated concentration of N in both seed (3.51 and 3.53%) and stover (1.07 and 1.08%) of kabuli gram, surpassing the control group throughout the study period ($p \leq 0.05$). Moreover, all alternative organic nutrient sources, excluding the control, exhibited comparable N concentrations in both seed and stover as illustrated in Figures 2C,D. Treatment T_4, comparable to T_6 and T_2, exhibited a noteworthy increase in P concentration in seed (0.47 and 0.48%) and stover (0.25 and 0.25%) compared to other treatments (T_5, T_7, T_3, and control) across both study years as depicted in Figures 3C,D. Similarly, treatment T_3 displayed a heightened K content in seed (1.27 and 1.31%) over the control, while the same treatment also yielded increased K content in stover (1.62 and 1.66%) compared to treatment T_6 (1.48 and 1.50%) and the control (1.37 and 1.38%) as illustrated in Figures 4C,D. Notably, treatment T_3 remained statistically equivalent to the remaining treatments throughout both study years.

Vegetable cowpea

Significant variations in the concentrations of N, P, and K in both green pods and stover of vegetable cowpea were observed, as depicted in Figures 2E,F to Figures 4E,F. The treatment T_6 exhibited the highest concentration of N in green pods (1.19 and 1.27%) and stover (0.56 and 0.65%) in vegetable cowpea, with statistical significance ($p \leq 0.05$) compared to the control and remaining treatments during both study years. Treatment T_4 demonstrated a significantly higher phosphorus content in green pods (0.32 and 0.33%) and stover (0.16 and 0.18%). This resulted in a notable increase of 14.2 and 13.8% in green pods and 6.7 and 3.1% in stover over treatment T_7 and the control, respectively. Consequently, treatment T_4 was comparable to the other treatments during both study years. Likewise, K content in green pods (0.61 and 0.69%) and stover (0.82 and 0.88%) reached its maximum under treatment T_3 compared to the control, exhibiting a substantial increase of 22.0 and 20.6% during the first year and 25.4 and 22.2% during the second year. These values were statistically similar to those of all other treatments, except the control. This suggests that treatment T_3 significantly influenced the potassium content in both green pods and stover of vegetable cowpea, highlighting its potential impact on nutrient concentrations in the crop.

Total nutrient uptake in the system

The enriched organic formulations exerted a significant influence on nutrient uptake within the baby corn-kabuli gram-vegetable cowpea cropping system throughout both cultivation years, as depicted in Figures 5A–C. Among these formulations, treatment T_4 demonstrated a significantly higher ($p \leq 0.05$) total N uptake of 410.6 and 444.6 kg ha^{-1} at the end of the first and second years of the crop cycle, respectively, representing an augmentation of 21.6, 25.4, 25.7, and 65.6% over treatments T_3, T_5, T_7, and the control in the first year, and 20.9, 25.0, 26.6, and 68.6% in the second year. Additionally, treatment T_4, involving 100% RDN through PHA-based formulation, exhibited the highest total P at 94.7 and 101.6 kg ha^{-1}, as well as K at 361.4 and 393.5 kg ha^{-1} during the first and second years, respectively. This observation was significantly superior ($p \leq 0.05$) to other treatments, with treatment T_6 being comparable. Specifically, treatment T_4 demonstrated a significantly higher total P uptake compared to T_3, T_5, T_7, and the control by 26.4, 30.3, 40.7, and 85.0% in the first year, and 23.3, 28.3, 39.9, and 80.5% in the second year, respectively. Additionally, the utilization of treatment T_3, on par with treatment T_2, resulted in elevated K uptake compared to T_5, T_7, and the control by 8.0, 11.6, 48.1% in the first year, and 8.5, 14.6, 53.1% in the second year, respectively.

Nitrogen use efficiency

The nitrogen use efficiency (NUE) data for the enriched organic formulations assessed in both years. Application of treatment T_4 resulted in a significant ($p \leq 0.05$) improvement in ANUE by 53.1 and 151.6%, and AR by 104.1 and 122.2% in baby corn compared to T_5 and T_7, respectively, averaged across the two study years (Table 3). Moreover, treatment T_4 exhibited higher AR by 86.5 and 77.9% in kabuli gram, and 64.2 and 71.8% in vegetable cowpea during both years of the field study (Tables 4, 5). However, no significant difference in ANUE was observed in kabuli gram and vegetable cowpea over the study period. Similarly, treatment T_6 increased ANUE and AR by 7.6 and 14.0% in baby corn (Table 3), 2.7 and 8.7% in kabuli gram, and 3.3 and 8.9% in vegetable cowpea (Tables 4, 5) compared to treatment T_2, respectively. Additionally, treatment T_5 exhibited higher PNUE in baby corn (134.9 and 125.4 kg kg^{-1}), kabuli gram (59.7 and 59.7 kg kg^{-1}), and vegetable cowpea (178.5 and 155.6 kg kg^{-1}), remaining statistically similar to the other treatments (Tables 3–5). However, the lowest PNUE was observed under treatment T_7 for baby corn and kabuli gram, and T_6 for vegetable cowpea during both study years. Furthermore, treatments T_5, T_7, and T_3 demonstrated superior nitrogen use efficiency (ANUE, AR, and PNUE) compared to the control.

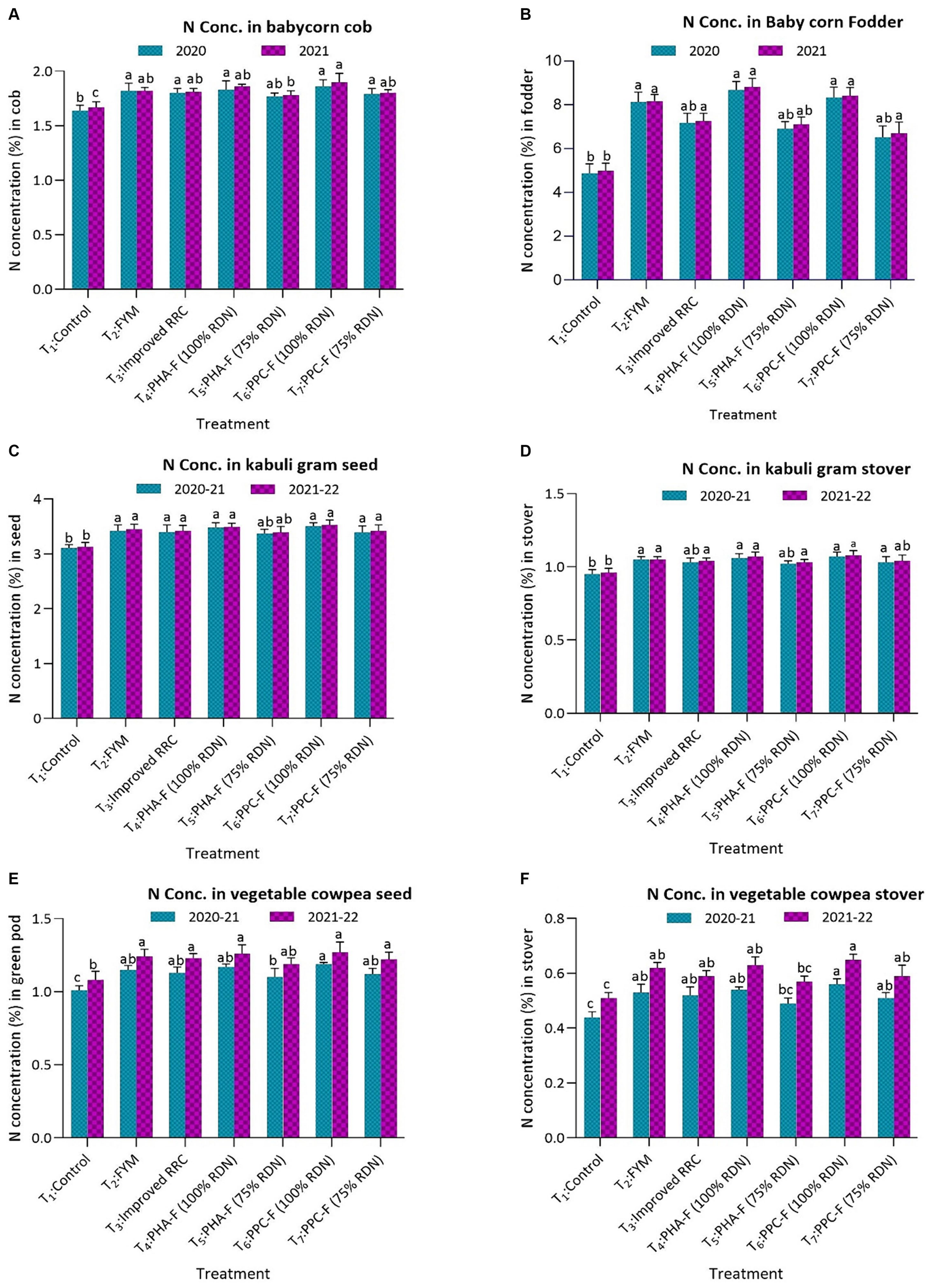

FIGURE 2
Effect of enriched organic formulations on nitrogen concentration in **(A)** baby corn cob, **(B)** baby corn fodder, **(C)** kabuli gram seed, **(D)** kabuli gram stover, **(E)** vegetable cowpea seed, and **(F)** vegetable cowpea stover.

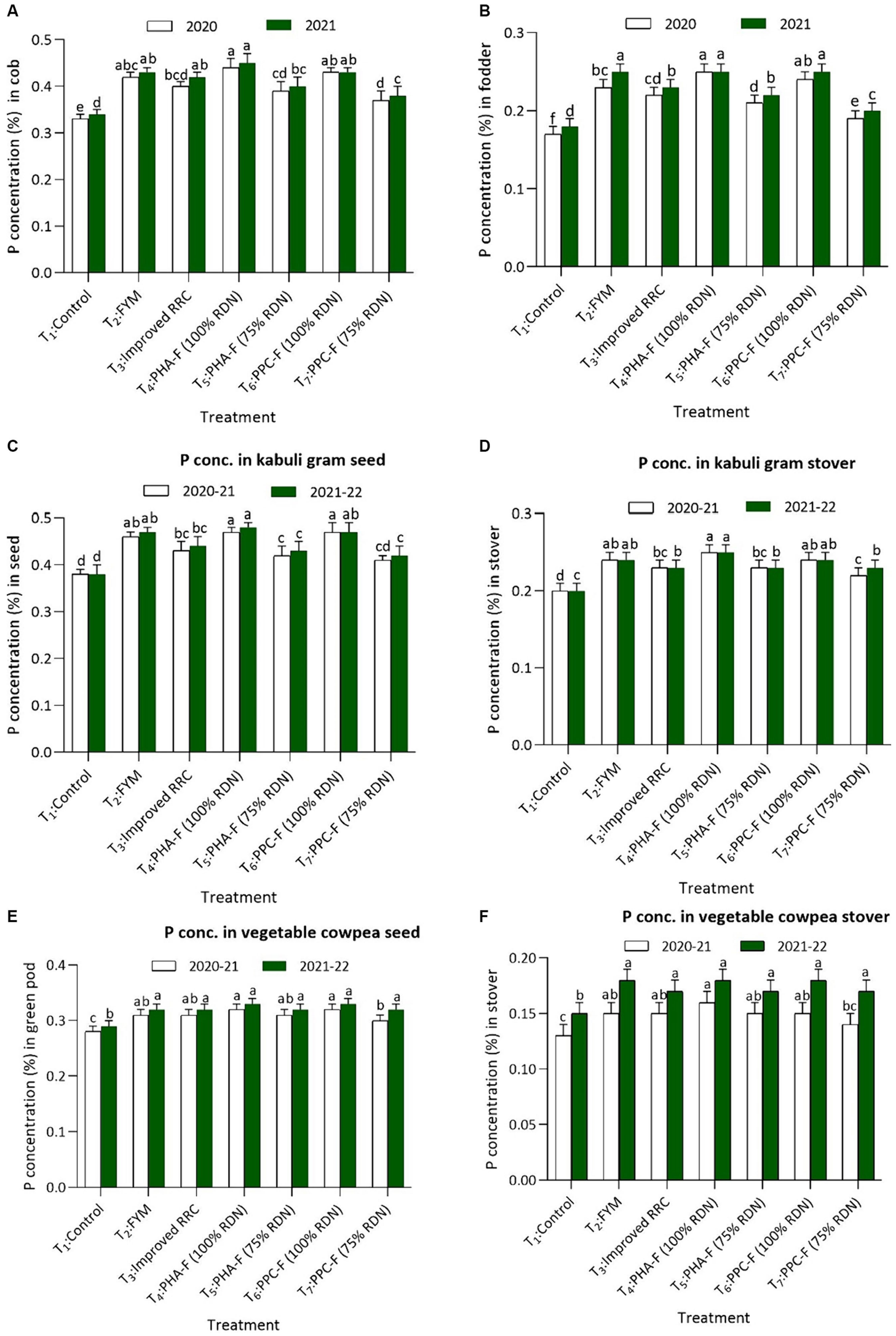

FIGURE 3
Effect of enriched organic formulations on phosphorus concentration in **(A)** P conc. in baby corn cob, **(B)** P conc. in baby fodder, **(C)** kabuli gram seed, **(D)** kabuli gram stover, **(E)** vegetable cowpea seed, and **(F)** vegetable cowpea stover.

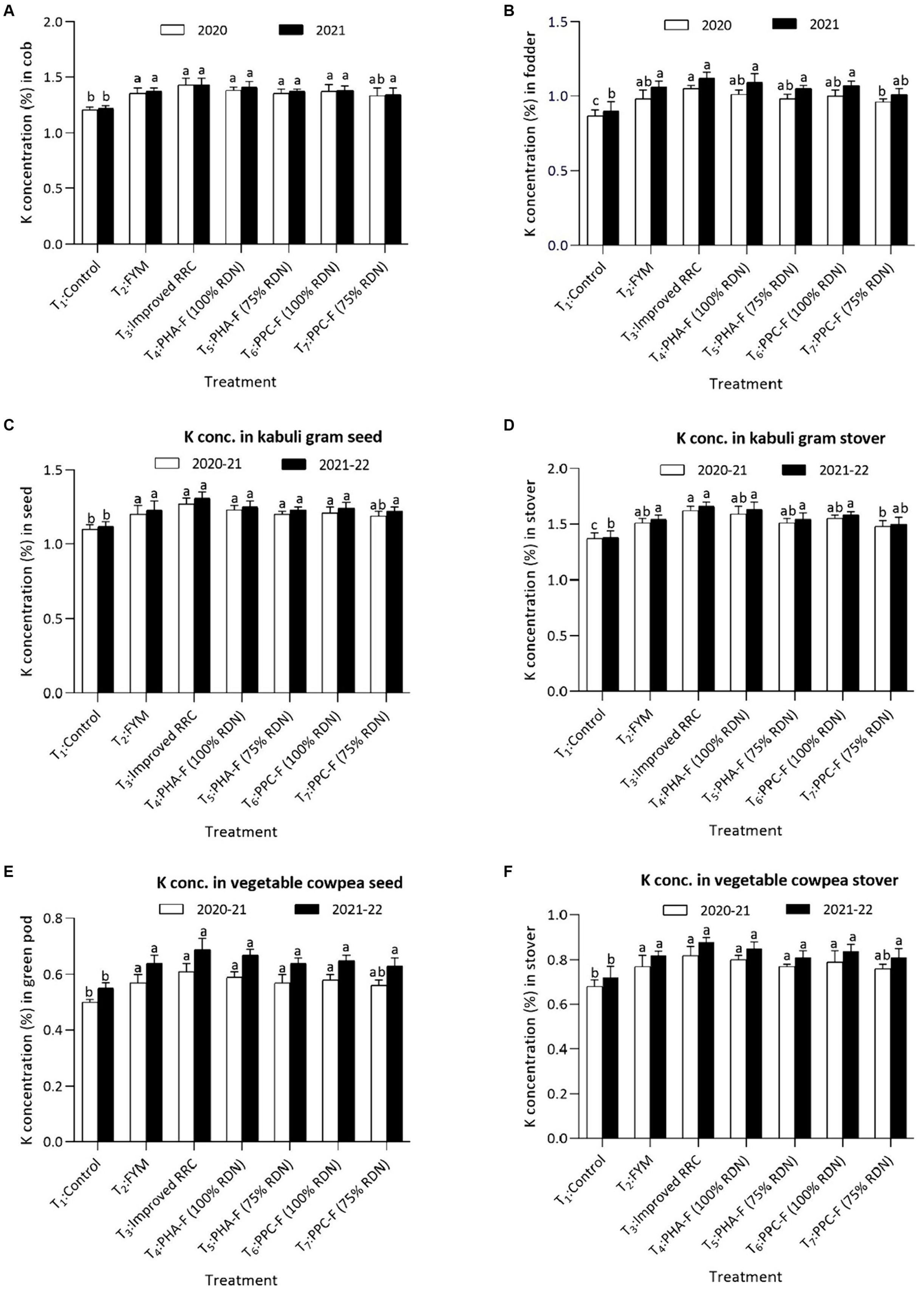

FIGURE 4
Effect of enriched organic formulations on potassium concentration in **(A)** K conc. in baby corn cob, **(B)** K conc. in baby fodder, **(C)** kabuli gram seed, **(D)** kabuli gram stover, **(E)** vegetable cowpea seed, and **(F)** vegetable cowpea stover.

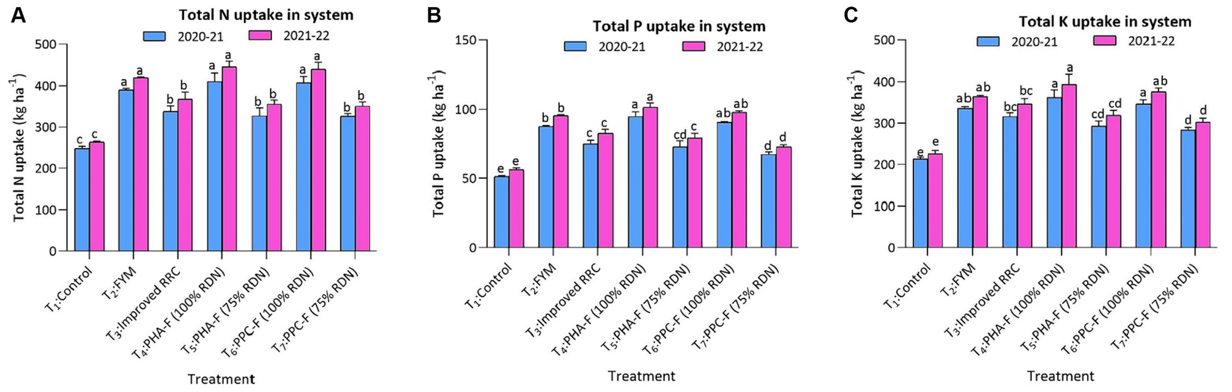

FIGURE 5
Effect of enriched organic formulations on **(A)** total N uptake, **(B)** total P uptake, and **(C)** total K uptake after completion of each cropping cycle during 2020–21 and 2021–22.

TABLE 3 Effect of enriched organic formulations on nitrogen use efficiency of babycorn under baby corn–kabuli gram–vegetable cowpea cropping system.

Treatment	Baby corn					
	ANUE (kg kg^{-1})		AR (kg kg^{-1})		PNUE (kg kg^{-1})	
	2020–21	2021–22	2020–21	2021–22	2020–21	2021–22
T_1:Control	–	–	–	–	–	–
T_2:FYM	3.82 ± 0.79ab	4.09 ± 0.85ab	0.41 ± 0.05ab	0.45 ± 0.04ab	134.9 ± 13.3a	125.4 ± 15.7a
T_3:Improved RRC	2.53 ± 0.50bc	2.84 ± 0.55bc	0.24 ± 0.04bc	0.30 ± 0.03bc	126.3 ± 33.9a	116.0 ± 22.9a
T_4:PHA-F (100% RDN)	4.62 ± 0.64a	4.64 ± 0.63a	0.47 ± 0.09a	0.53 ± 0.09a	132.1 ± 3.7a	123.2 ± 3.6a
T_5:PHA-F (75% RDN)	2.67 ± 0.25bc	3.38 ± 0.44ab	0.22 ± 0.09c	0.27 ± 0.02bc	135.2 ± 16.5a	125.3 ± 21.8a
T_6:PPC-F (100% RDN)	4.18 ± 0.74a	4.33 ± 0.66a	0.46 ± 0.12a	0.52 ± 0.11a	125.6 ± 4.6a	118.9 ± 7.3a
T_7:PPC-F (75% RDN)	1.78 ± 1.02c	1.90 ± 0.90c	0.21 ± 0.11c	0.24 ± 0.10c	116.0 ± 9.0a	107. ± 14.0a

ANUE, Agronomic nitrogen use efficiency; AR, Apparent recovery of applied N; PNUE, Physiological nitrogen use efficiency. The data were represented as mean ± SD value and alphabetic coding showed significance among the treatments at level $p \leq 0.05$.

TABLE 4 Effect of enriched organic formulations on nitrogen use efficiency of kabuli gram under baby corn–kabuli gram–vegetable cowpea cropping system.

Treatment	Kabuli gram					
	ANUE (kg kg^{-1})		AR (kg kg^{-1})		PNUE (kg kg^{-1})	
	2020–21	2020–21	2020–21	2020–21	2020–21	2020–21
T_1:Control	–	–	–	–	–	–
T_2:FYM	40.46 ± 11.64a	41.00 ± 11.67a	1.77 ± 0.27a	1.81 ± 0.25a	59.7 ± 13.8a	59.7 ± 12.6a
T_3:Improved RRC	21.46 ± 14.31ab	23.83 ± 13.91a	1.04 ± 0.34b	1.13 ± 0.28b	49.3 ± 8.6a	50.8 ± 4.5a
T_4:PHA-F (100% RDN)	42.96 ± 0.46a	44.83 ± 1.25a	1.94 ± 0.11a	2.01 ± 0.10a	55.7 ± 5.7a	55.8 ± 5.5a
T_5:PHA-F (75% RDN)	26.61 ± 9.24a	29.33 ± 9.16a	1.27 ± 0.08b	1.37 ± 0.05b	53.4 ± 7.4a	53.8 ± 6.2a
T_6:PPC-F (100% RDN)	41.62 ± 6.49a	42.00 ± 5.72a	1.92 ± 0.16a	1.97 ± 0.13a	54.5 ± 2.2a	54.24 ± 1.5a
T_7:PPC-F (75% RDN)	24.61 ± 18.37a	25.78 ± 17.30a	1.25 ± 0.43b	1.33 ± 0.38b	46.2 ± 28.0a	46.8 ± 23.9a

ANUE, Agronomic nitrogen use efficiency; AR, Apparent recovery of applied N; PNUE, Physiological nitrogen use efficiency. The data were represented as mean ± SD value and alphabetic coding showed significance among the treatments at level $p \leq 0.05$.

Nutrient availability

A comprehensive assessment of soil nutrient dynamics after harvest of each cropping cycle revealed significant variations in N, P, and K concentrations among different enriched organic nutrient sources, as illustrated in Figures 6A–C. Notably, the application of treatment T_6 led to a substantial increase in available N content in the soil post-vegetable cowpea harvest (232.2 and 241.1 kg ha^{-1}) compared to the control (206.3 and 205.3 kg ha^{-1}), with a notable enhancement of 12.6% in the first year and 17.4% in the second year. Treatment T_4,

TABLE 5 Effect of enriched organic formulations on nitrogen use efficiency of vegetable cowpea under baby corn–kabuli gram–vegetable cowpea cropping system.

Treatment	Vegetable cowpea					
	ANUE (kg kg^{-1})		AR (kg kg^{-1})		PNUE (kg kg^{-1})	
	2020–21	2020–21	2020–21	2020–21	2020–21	2020–21
T_1:Control	–	–	–	–	–	–
T_2:FYM	118.00 ± 23.25a	114.50 ± 23.31a	2.26 ± 0.17ab	2.58 ± 0.17abc	178.5 ± 22.3a	155.6 ± 25.9a
T_3:Improved RRC	70.67 ± 44.32ab	68.17 ± 48.56ab	1.62 ± 0.68b	1.77 ± 0.57c	138.7 ± 60.1ab	127.4 ± 64.1a
T_4:PHA-F (100% RDN)	135.17 ± 27.60a	130.83 ± 27.76a	2.66 ± 0.23a	3.04 ± 0.14a	132.3 ± 7.6ab	129.2 ± 16.1a
T_5:PHA-F (75% RDN)	92.00 ± 60.38a	88.22 ± 65.06a	1.79 ± 0.84ab	2.05 ± 0.64bc	127.0 ± 19.0ab	128.8 ± 37.6a
T_6:PPC-F (100% RDN)	121.00 ± 29.20a	119.17 ± 28.85a	2.62 ± 0.14ab	2.95 ± 0.35ab	115.4 ± 8.9b	123.1 ± 12.2a
T_7:PPC-F (75% RDN)	87.56 ± 68.31a	83.33 ± 62.91a	1.90 ± 0.69ab	2.12 ± 0.74abc	117.1 ± 30.3b	129.7 ± 41.9a

ANUE, Agronomic nitrogen use efficiency; AR, Apparent recovery of applied N; PNUE, Physiological nitrogen use efficiency. The data were represented as mean ± SD value and alphabetic coding showed significance among the treatments at level $p \leq 0.05$.

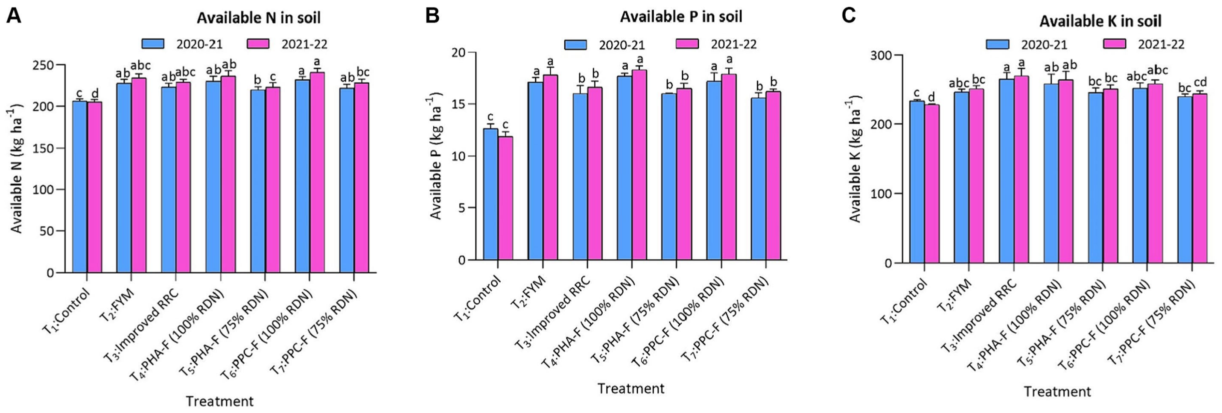

FIGURE 6
Effect of enriched organic formulations on soil **(A)** available N, **(B)** available P, and **(C)** available K after completion of each cropping cycle during 2020–21 and 2021–22.

followed by T_6 and T_2, demonstrated statistically superior levels of available phosphorus in the soil (17.7 and 18.3 kg ha^{-1}), exhibiting superiority over treatment T_3 (16.0 and 16.6 kg ha^{-1}), T_5 (16.0 and 16.5 kg ha^{-1}), T_7 (15.6 and 16.2 kg ha^{-1}), and the control (12.6 and 11.9 kg ha^{-1}), with improvements ranging from 10.6 to 54.3% in the first and second years. Furthermore, treatment T_3 exhibited notable superiority in augmenting available potassium content in the soil (265.4 and 270.1 kg ha^{-1}), surpassing the control by 13.5% in the first year and 18.2% in the second year. This outcome was consistently comparable to the performance of treatments T_4 (258.7 and 264.3 kg ha^{-1}) and T_6 (252.0 and 258.7 kg ha^{-1}) throughout both years of the field study, showcasing the efficacy of these enriched organic formulations in influencing soil nutrient dynamics.

System economics

The economic aspects of the cropping system under various enriched organic formulations are depicted in Figures 7A–C. Rigorous statistical analysis of the data revealed that the application of treatment T_4 yielded significantly higher system gross returns (8.10×10^3 and 8.32×10^3 \$ ha^{-1}), net returns (6.68×10^3 and 6.85×103 \$ ha^{-1}), and net benefit-to-cost (B:C) ratio (5.0 and 4.9). This resulted in a notable increase of 50.8 and 49.9% in gross returns, 55.2 and 54.2% in net returns, and 21.0 and 20.5% in net Benefit:Cost ratio over the control, respectively, and demonstrated statistical equivalence to treatment T_6 and T_2 across both years of the field study. Nevertheless, treatment T_3 exhibited statistical similarity to treatments T_5 and T_7 concerning both gross and net returns in the cropping system during both study years.

Correlation matrix yield, nutrient concentration, and nitrogen use efficiencies

The correlation (r) plot matrices (Supplementary Figures S1, S2) underscored significant positive associations >0.664 and > 0.768 among yield, nutrient concentration, and nitrogen use efficiencies at both the year of study, respectively for baby corn. A positive correlations (r) > 0.604 and > 0.582 were also among yield, nutrient concentration, and nitrogen use efficiencies at both the year of study, respectively (Supplementary Figures S3, S4). Similarly, positive correlations (r) > 0.724 and > 0.724 were also among yield, nutrient concentration, and nitrogen use efficiencies at both the year of study, respectively (Supplementary Figures S5, S6).

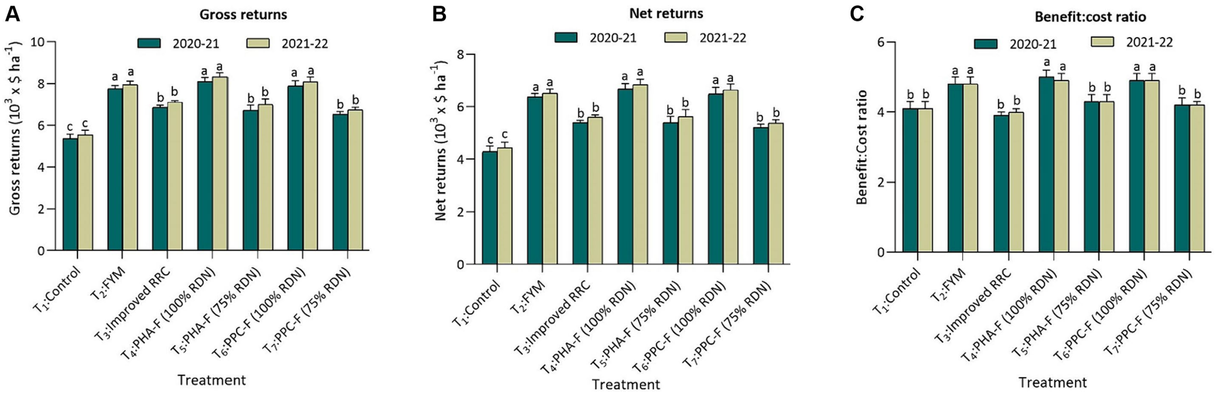

FIGURE 7
Effect of enriched organic formulations on **(A)** gross returns, **(B)** net returns, and **(C)** Benefit:Cost ratio of the cropping system during 2020–21 and 2021–22.

Discussion

Organic manures serve as a nutrient reservoir that gradually releases absorbed ions throughout the entire crop growth period, resulting in enhanced crop yield (Kumar et al., 2005). In present study treatment T_4 resulted in significantly ($p \leq 0.05$) higher yield of babycorn cob with husk (1.6 and 1.6 t ha^{-1}), cob without husk (8.7 and 8.8 t ha^{-1}) and green fodder yield (25.6 and 26.4 t ha^{-1}) over control and at par with treatment T_6 and T_2 during both years of study. Similarly, treatment T_4 recorded higher kabuli gram seed (2.80 and 2.86 t ha^{-1}) and stover yield (4.41 and 4.54 t ha^{-1}) and vegetable cowpea green pod (10.9 and 11.0 t ha^{-1}) and stover yield (24.4 and 24.9 t ha^{-1}) followed by T_6 and T_2 and significantly ($p \leq 0.05$) superior over control. The optimum yield of baby corn, kabuli gram and vegetabl cowpea, notably observed in the treatment T_4 with PHA-based formulation, followed by T_6 with PPC-formulation and T_2-FYM, can be attributed to the comparatively elevated annual carbon and nutrient inputs. This heightened nutritional provision enhanced the fruiting capacity of the baby corn plants, manifesting in increased cob production per plant and ultimately culminating in a higher yield. The superior performance of the PHA-based formulation, particularly in treatment T_4, can be further explained by its composition enriched with organic materials, encompassing essential nutrients and a heightened concentration of nitrogen. This enriched organic formulation played a pivotal role in enhancing soil structure and fertility, thereby fostering an environment conducive to optimal nutrient availability and uptake by baby corn plants. The synergistic effect of these factors is indicative of a comprehensive approach, aligning nutritional input and soil improvement strategies, contributing to the observed superior green fodder yield in baby corn, kabuli gram and vegetable cowpea. PHA contains silicate minerals that encompass carbon and oxygen, along with various micronutrients and its application enhanced that rice yield by 10% and wheat yield by 24% under rice-wheat cropping system (Thind et al., 2012). Potato peel is a valuable source of fiber, carbohydrates, nutrients and bioactive compounds, including phenolics and flavonoids (Ali et al., 2015). Application of Potato peel based biochar improved the yield of Okra (Majee et al., 2021). In contrast, farmyard manures are characterized by a richness in carbonaceous content and provide minimal nutrients (Singh et al., 2020). A combination of PHA/PPC with FYM renders them significant soil ameliorants. Importantly, the application of this combination does not result in any yield reduction when compared to treatment solely involving farmyard manure (Singh et al., 2019). This combination showcases a promising approach to enhance agricultural productivity sustainably.

Organic matter in soil serves as a soil conditioner, a nutrient reservoir, and a substrate for microbial activity (Powlson et al., 2013; Bashir et al., 2021). It not only generates vital plant nutrients but also produces compounds that bind with nutrient elements during the decomposition of organic matter (Murphy, 2015). Plant roots can access complexed elements more readily because the shield formed by complex ions guards against their immobilization in soils (Kumar et al., 2015; Bhatt et al., 2019; Bhakar et al., 2021). In our study we found that treatment T_6 recorded the highest N, P, and K concentrations in baby corn cob, baby corn green fodder, kabuli gram seed, kabuli gram stover, vegetable cowpea green pod and stover, demonstrating statistical parity with treatment T_4, and T_2, surpassing the control (Figures 2–4). The application of FYM and other formulations enhanced the soil's nutrient supply capacity, ensuring a balanced nutrient supply throughout the crop's growth stages. Singh and Chauhan (2021) reported that application of farmyard manure significantly improves the N, P, and K concentration in grain and stover of pearlmillet crop. Chauhan et al. (2020) found that application of nitrogen through urea alone decline the quality, whereas, combined application of fertilizers along with FYM enhances the nutrient concentration in grain and stover of the wheat crop due continuous availability of nutrients through microbial cell autolysis. Furthermore, it improves soil biometric parameters, directly adds nutrients, solubilises native phosphate content in the soil (Das et al., 2002) and augments nutrient use efficiency (Lakpale et al., 1999). RHA and PPC contain substantial amounts of nutrients and utilizing them in FYM/compost preparation encrich the quality and on application release the nutrients for easier uptake by the crop plants (da Silva et al., 2020; Joshi et al., 2020; Hisham and Ramli, 2021; Nepal et al., 2021). These combined effects lead to increased concentrations of N, P, and K in babycorn, kabuli gram and vegetable cowpea crops.

Enriched organic formulations significantly impacted nutrient uptake in the baby corn-kabuli gram-vegetable cowpea cropping system over two cultivation years (Figures 5A–C). In our study, the treatment T_4 displayed a significantly higher ($p \leq 0.05$) total nitrogen, phosphorus and potassium uptake during both the years of study over control. Treatment T_4 found comparable with treatment T_6 and T_2. The enhanced nutrient uptake could be attributed to the higher availability of nutrients particularly N, P, and K in the soil due to application of FYM and improved formulations. This increase in availability of nutrients is likely a result of the mineralization process of organic manure, as well as the natural release of nutrients from the native soil due to favourable relationship between the soil, plants and atmosphere (Rosen and Allan, 2007; Mohanty et al., 2013; Dhaliwal et al., 2019). Further, RHA and PPC for preparing formulation add significant amounts of nutrients and increase the nutrient avaibility for plant uptake and growth (da Silva et al., 2020; Joshi et al., 2020; Hisham and Ramli, 2021; Nepal et al., 2021).

Nitrogen use efficiency (NUE) is a measure of a crop's capacity to absorb and utilize nitrogen to achieve optimal yields. The efficiency of NUE is influenced not only by the plant's effective absorption of nutrients from the soil but also by its internal processes involving the transport, storage, and redistribution of nitrogen. In our study, the treatment T_4 consistently showed the highest ANUE and AR in all the three crops (Tables 3–5). Further, T_4 also recorded comparable results with treatment for PNUE in babyccorn, kabuli gram and vegetable cowpea crop (Tables 3–5). The efficiency of added nitrogen improves when other nutrients are sufficiently available for crop growth. The improved yield and increased N uptake by baby corn based system under the organic treatment might be the main reason for enhanced NUE when compared to control. The higher agronomic efficiency could be attributed to the fact that organic manure alters soil quality following its application, influencing factors such as organic matter content, soil structure, and biological activity (Tisdall and Oades, 1982; Bronick and Lal, 2005). Phillips et al. (2022) reported that addition of organic material in conjuction with inorganic fertilizers increase the nitrogen use efficiency two fold by reducing runoff loses, slow release of nutrients with better synchronization with plant nutrient uptake in rye grass. Organic amendments such as humified sledge and poultry manure signifcnatly affected the N uptake and improves the nitrogen use efficiency in rice crop (Ofori et al., 2005). Further, improved nitrogen use efficiency can be attributed to the positive impact of adequate soil moisture coupled with adequate nutrient supply during crop growth.

In the present study (Figures 6A–C), the application of treatment T_6 led to a substantial increase in available N content in the soil post-vegetable cowpea harvest compared to the control, with a notable enhancement of 12.6% in the first year and 17.4% in the second year. Treatment T_4, followed by T_6 and T_2, demonstrated statistically superior levels of available phosphorus in the soil, exhibiting superiority over treatment T_3, T_5, T_7, and the control, with improvements ranging from 10.6 to 54.3% in the first and second years. Furthermore, treatment T_3 exhibited notable superiority in augmenting available potassium content in the soil, surpassing the control by 13.5% in the first year and 18.2% in the second year. The enhanced available nitrogen content of soil might be due to favourable soil conditions under enriched organic formulations which might have helped in the mineralization of nitrogen leading to higher built up of available N (Mali et al., 2015; Jadhao et al., 2019). The addition of FYM increased Olsen-P due to its P content and perhaps by enhancing P retention in soil through release of different organic acids and CO_2 during the decomposition of organic matter (Rajkhowa et al., 2003), reduced activity of polyvalent cations *viz.,* Al, Fe and Ca through chelation. Since FYM increased soil cation exchange capacity (Blake et al., 1999; Bhattacharyya et al., 2008) and decreased K fixation in soil, the increase in available K under these treatments was attributed to higher release of non-exchangeable K from the soils. The direct addition of N, P, and K through the sole or combined application of organic nutrient sources in an active pool of soil may lead to increased total N and availability of N, P, and K in the soil (Babu et al., 2020; Nima et al., 2020). Our results are corroborated by many previous studies that reported higher N, P, and K contents in organically managed soils under varied agro climatic conditions (Aulakh et al., 2016; Dhaliwal et al., 2019; Jat et al., 2019).

In the current study, the second year stood out with more gross and net returns, mainly due to the higher yields achieved, especially from the all-season crops and also due to higher market price of kabuli gram (₹ 51 kg^{-1}) as compared to first year (2020–21). The increased net returns were observed during both years of the experiment can be attributed to the higher yield and monetary gains obtained from treatment T_4 (100% RDN through PHA-based formulation), along with the relatively lower cost of farmyard manure (FYM) during that period. In an experiment conducted by Kumar (2008) on the maize-wheat system, it was observed that the highest net returns, amounting to ₹ 46,784 per hectare, and the highest benefit-to-cost ratio of 2.17 were achieved when applying 120 kg of nitrogen along with 10 tons of FYM per hectare.

The correlation analysis, as depicted in the supplementary figures (Supplementary Figures S1–S6), provides insights into the relationships among yield, nutrient concentration, and nitrogen use efficiencies in the context of the two study years for baby corn. In Supplementary Figures S1, S2, the correlation (r) plot matrices revealed noteworthy results, emphasizing significant positive associations exceeding 0.664 and 0.768 among yield, nutrient concentration, and nitrogen use efficiencies during both years of the study. These results indicate a robust positive linear relationship between the variables, suggesting that as one variable increases, the others tend to increase as well. Supplementary Figures S3, S4 demonstrated additional positive correlations, with correlation coefficients (r) surpassing 0.604 and 0.582 for yield, nutrient concentration, and nitrogen use efficiencies in both study years. This reinforces the consistent trend of positive associations observed across the variables, further substantiating the interconnected nature of these agricultural factors. Similarly, Supplementary Figures S5, S6 exhibited positive correlations with correlation coefficients (r) exceeding 0.724 in both study years for yield, nutrient concentration, and nitrogen use efficiencies. These results underscore a higher degree of positive correlation, indicating a stronger linear relationship among the variables in the respective years.

Conclusion

In conclusion, our findings underscore the remarkable potential of the 100% RDN through PHA-based formulation and 100% RDN through PPC-based formulation in enhancing crop yield, nutrient uptake, and overall sustainability. The successful application of these formulations not only improves productivity but also represents a pivotal step toward sustainable agriculture by efficiently utilizing agricultural waste resources. This approach not only reduces the reliance on traditional farmyard manure but also improved soil health. For farmers facing FYM shortages and having access to rice husk ash or potato peels, adopting these formulations is not only practical but economically advantageous, as evidenced by higher returns and improved B:C ratios. Moving forward, it is imperative to explore the long-term effects, varying application rates, and performance under diverse climatic conditions, paving the way for a more nuanced understanding and optimized utilization of these formulations in different agricultural contexts. This research provides a foundation for sustainable practices that balance productivity, economic viability, and environmental stewardship in modern agriculture.

Data availability statement

The datasets presented in this article are not readily available because no restrictions applied to data, and will be made available by corresponding author on request. Requests to access the datasets should be directed to bhanusanjeev@gmail.com.

Author contributions

KG: Conceptualization, Data curation, Investigation, Writing – original draft. SD: Conceptualization, Formal analysis, Project administration, Resources, Supervision, Writing – review & editing. EA: Data curation, Formal analysis, Visualization, Writing – original draft. VS: Conceptualization, Data curation, Formal analysis, Supervision, Writing – review & editing. RM: Data curation, Formal analysis, Visualization, Writing – original draft. MH: Data curation, Formal analysis, Visualization, Writing – original draft. MR: Data curation, Formal analysis, Visualization, Writing – original draft. GA: Data curation, Formal analysis, Visualization, Writing – original draft. PH: Data curation, Formal analysis, Writing – original draft. YK: Data curation, Formal analysis, Writing – original draft. SA: Data curation, Formal analysis, Visualization, Writing – original draft. SoK: Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. HO: Data curation, Formal analysis, Writing – review & editing. MT: Data curation, Formal analysis, Visualization, Writing – review & editing. BK: Data curation, Formal analysis, Visualization, Writing – original draft. SaK: Data curation, Formal analysis, Methodology, Visualization, Writing – review & editing.

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Conflict of interest

MR was employed by Dhanuka Agritech Limited.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1380279/full#supplementary-material

References

Abbas, M., Atiq-Ur-Rahman, M., Manzoor, F., and Farooq, A. (2012). 03. A quantitative analysis and comparison of nitrogen, potassium and phosphorus in rice husk and wheat bran samples. *Pure Appl. Biol.* 1, 14–15. doi: 10.19045/bspab.2012.11003

Akram, T., Memon, S. A., and Obaid, H. (2009). Production of low cost self compacting concrete using bagasse ash. *Constr. Build. Mater.* 23, 703–712. doi: 10.1016/j.conbuildmat.2008.02.012

Ali, S. W., Nawaz, A., Irshad, S., and Khan, A. A. (2015). Potato waste management in Pakistan's perspective. *J. Hyg. Eng. Des.* 13, 100–107. Available at: https://www.cabidigitallibrary.org/doi/pdf/10.5555/20163093984

Aulakh, C., Kaur, P., Walia, S., Gill, R., Sharma, S., and Buttar, G. (2016). Productivity and quality of basmati rice (*Oryza sativa*) in relation to nitrogen management. *Indian J. Agron.* 61, 467–473. doi: 10.59797/ija.v61i4.4394

Babu, S., Singh, R., Avasthe, R., Yadav, G. S., Das, A., Singh, V. K., et al. (2020). Impact of land configuration and organic nutrient management on productivity, quality and soil properties under baby corn in eastern Himalayas. *Sci. Rep.* 10, 1–14. doi: 10.1038/s41598-020-73072-6

Bashir, O., Ali, T., Baba, Z. A., Rather, G. H., Bangroo, S. A., Mukhtar, S. D., et al. (2021). "Soil organic matter and its impact on soil properties and nutrient status" in *Microbiota and biofertilizers, Vol 2: Ecofriendly tools for reclamation of degraded soil environs*. eds. G. H. Dar, R. A. Bhat, M. A. Mehmood and K. R. Hakeem (Cham: Springer International Publishing), 129–159.

Behera, K. K., Alam, A., Vats, S., Sharma, H. P., and Sharma, V. (2012). "Organic farming history and techniques" in *Agroecology and strategies for climate change*. ed. E. Lichtfouse (Dordrecht: Springer Netherlands), 287–328.

Bhakar, A., Singh, M., Kumar, S., Kumar, D., Meena, B., Meena, V., et al. (2021). Enhancing root traits and quality of sorghum and guar through mixed cropping and nutrient management. *Indian J. Agric. Sci.* 91, 99–104. doi: 10.56093/ijas.v91i1.110935

Bhatt, M. K., Labanya, R., and Joshi, H. C. (2019). Influence of long-term chemical fertilizers and organic manures on soil fertility-a review. *Univers. J. Agric. Res.* 7, 177–188. doi: 10.13189/ujar.2019.070502

Bhattacharyya, R., Kundu, S., Prakash, V., and Gupta, H. S. (2008). Sustainability under combined application of mineral and organic fertilizers in a rainfed soybean–

wheat system of the Indian Himalayas. *Eur. J. Agron.* 28, 33–46. doi: 10.1016/j.eja.2007.04.006

Blake, L., Mercik, S., Koerschens, M., Goulding, K., Stempen, S., Weigel, A., et al. (1999). Potassium content in soil, uptake in plants and the potassium balance in three European long-term field experiments. *Plant Soil* 216, 1–14. doi: 10.1023/A:1004730023746

Bougnom, B., and Insam, H. (2009). Ash additives to compost affect soil microbial communities and apple seedling growth. *Die Bodenkultur* 60, 5–15. Available at: https://diebodenkultur.boku.ac.at/volltexte/band-60/heft-2/bougnom.pdf

Bronick, C. J., and Lal, R. (2005). Soil structure and management: a review. *Geoderma* 124, 3–22. doi: 10.1016/j.geoderma.2004.03.005

Cardoen, D., Joshi, P., Diels, L., Sarma, P. M., and Pant, D. (2015). Agriculture biomass in India: part 2. Post-harvest losses, cost and environmental impacts. *Resour. Conserv. Recycl.* 101, 143–153. doi: 10.1016/j.resconrec.2015.06.002

Cassman, K. G., Peng, S., Olk, D., Ladha, J., Reichardt, W., Dobermann, A., et al. (1998). Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. *Field Crop Res.* 56, 7–39. doi: 10.1016/S0378-4290(97)00140-8

Castor, J., Bacha, K., and Nerini, F. F. (2020). SDGs in action: a novel framework for assessing energy projects against the sustainable development goals. *Energy Res. Soc. Sci.* 68:101556. doi: 10.1016/j.erss.2020.101556

Chauhan, N., Sankhyan, N., Sharma, R., and Singh, J., and Gourav (2020). Effect of long-term application of inorganic fertilizers, farm yard manure and lime on wheat (*Triticum aestivum* L.) productivity, quality and nutrient content in an acid alfisol. *J. Plant Nutr.* 43, 2569–2578. doi: 10.1080/01904167.2020.1783298

Da Silva, M. T., Martinazzo, R., Silva, S. D. A., Bamberg, A. L., Stumpf, L., Fermino, M. H., et al. (2020). Innovative substrates for sugarcane seedling production: sewage sludges and rice husk ash in a waste-to-product strategy. *Ind. Crops Prod.* 157:112812. doi: 10.1016/j.indcrop.2020.112812

Das, K., Medhi, D., Guha, B., and Baruah, B. (2002). Direct and residual effects of recycling of crop residues along with chemical fertilizers in rice-wheat cropping system. *Ann. Agric. Res. (India)* 23, 415–418. Available at: https://www.cabidigitallibrary.org/doi/full/10.5555/20033156466

Dhaliwal, S., Naresh, R., Mandal, A., Singh, R., and Dhaliwal, M. (2019). Dynamics and transformations of micronutrients in agricultural soils as influenced by organic matter build-up: a review. *Environ. Sustain. Indic.* 1-2:100007. doi: 10.1016/j.indic.2019.100007

Ginni, G., Kavitha, S., Kannah, Y., Bhatia, S. K., Kumar, A., Rajkumar, M., et al. (2021). Valorization of agricultural residues: different biorefinery routes. *J. Environ. Chem. Eng.* 9:105435. doi: 10.1016/j.jece.2021.105435

Gomez, K. A., and Gomez, A. A. (1984). *Statistical procedures for agricultural research*. New York: John Wiley & Sons.

Hisham, N. E. B., and Ramli, N. H. (2021). Incorporation of Rice husk ash with palm oil mill wastes in enhancing physicochemical properties of the compost. *Pertanika J. Trop. Agric. Sci.* 44, 221–236. doi: 10.47836/pjtas.44.1.13

Ijaz, U., Ahmed, T., Rizwan, M., Noman, M., Shah, A. A., Azeem, F., et al. (2023). Rice straw based silicon nanoparticles improve morphological and nutrient profile of rice plants under salinity stress by triggering physiological and genetic repair mechanisms. *Plant Physiol. Biochem.* 201:107788. doi: 10.1016/j.plaphy.2023.107788

Jackson, M. (1973). *Soil chemical analysis*. New Delhi, India: Pentice Hall of India Pvt Ltd

Jadhao, S., Mali, D., Kharche, V., Singh, M., Bhoyar, S., Kadu, P., et al. (2019). Impact of continuous manuring and fertilization on changes in soil quality under sorghum-wheat sequence on a Vertisols. *J. Indian Soc. Soil Sci.* 67, 55–64. doi: 10.5958/0974-0228.2019.00006.9

Jat, H., Datta, A., Choudhary, M., Sharma, P. C., Yadav, A., Choudhary, V., et al. (2019). Climate smart agriculture practices improve soil organic carbon pools, biological properties and crop productivity in cereal-based systems of north-west India. *Catena* 181:104059. doi: 10.1016/j.catena.2019.05.005

Joshi, A., Sethi, S., Arora, B., Azizi, A. F., and Thippeswamy, B. (2020). “Potato peel composition and utilization” in *Potato: Nutrition and food security*. eds. P. Raigond, B. Singh, S. Dutt and S. K. Chakrabarti (Singapore: Springer Singapore), 229–245.

Kandagatla, N., Kunnoth, B., Sridhar, P., Tyagi, V., Rao, P., and Tyagi, R. (2023). Rice mill wastewater management in the era of circular economy. *J. Environ. Manag.* 348:119248. doi: 10.1016/j.jenvman.2023.119248

Khan, R., Jabbar, A., Ahmad, I., Khan, W., Khan, A. N., and Mirza, J. (2012). Reduction in environmental problems using rice-husk ash in concrete. *Constr. Build. Mater.* 30, 360–365. doi: 10.1016/j.conbuildmat.2011.11.028

Koul, B., Yakoob, M., and Shah, M. P. (2022). Agricultural waste management strategies for environmental sustainability. *Environ. Res.* 206:112285. doi: 10.1016/j.envres.2021.112285

Kumar, A. (2008). Direct and residual effect of nutrient management in maize (*Zea mays*)–wheat (*Triticum aestivum*) cropping system. *Indian J. Agron.* 53, 37–41. doi: 10.59797/ija.v53i1.4831

Kumar, S., Dhar, S., Om, H., and Meena, R. L. (2015). Enhanced root traits and productivity of maize (*Zea mays*) and wheat (*Triticum aestivum*) in maize-wheat cropping system through integrated potassium management. *Indian J. Agric. Sci.* 85, 251–255. doi: 10.56093/ijas.v85i2.46530

Kumar, A., Gautam, R., Singh, R., and Rana, K. (2005). Growth, yield and economics of maize (*Zea mays*)-wheat (*Triticum aestivum*) cropping sequence as influenced by integrated nutrient management. *Indian J. Agric. Sci.* 75, 709–711.

Kumar, V., Singh, M. K., Raghuvanshi, N., and Sahoo, M. (2022). Rice (*Oryza sativa* L.)–baby corn (*Zea mays* L.) cropping system response to different summer green manuring and nutrient management. *Agronomy* 12:2105. doi: 10.3390/agronomy12092105

Lakpale, R., Pandey, N., and Tripathi, R. (1999). Effect of levels of nitrogen and forms of pre-conditioned urea on grain yield and N status in plant and soil of rainfed rice (*Oryza sativa*). *Indian J. Agron.* 44, 89–93.

Majee, S., Halder, G., Mandal, D. D., Tiwari, O. N., and Mandal, T. (2021). Transforming wet blue leather and potato peel into an eco-friendly bio-organic NPK fertilizer for intensifying crop productivity and retrieving value-added recyclable chromium salts. *J. Hazard. Mater.* 411:125046. doi: 10.1016/j.jhazmat.2021.125046

Mali, D., Kharche, V., Jadhao, S., Katkar, R., Konde, N., Jadhao, S., et al. (2015). Effect of long term fertilization and manuring on soil quality and productivity under sorghum (*Sorghum bicolor*)-wheat (*Triticum aestivum*) sequence in Inceptisol. *Indian J. Agric. Sci.* 85, 695–700. doi: 10.56093/ijas.v85i5.48510

Mbow, C., Rosenzweig, C. E., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., et al. (2020). "Food security," in *Special report: Special report on climate change and land* IPCC.

Mohanty, M., Sinha, N. K., Sammi Reddy, K., Chaudhary, R., Subba Rao, A., Dalal, R., et al. (2013). How important is the quality of organic amendments in relation to mineral N availability in soils? *Agric. Res.* 2, 99–110. doi: 10.1007/s40003-013-0052-z

Murphy, B. (2015). Impact of soil organic matter on soil properties—a review with emphasis on Australian soils. *Soil Res.* 53, 605–635. doi: 10.1071/SR14246

Muthadhi, A., Anitha, R., and Kothandaraman, S. (2007). Rice husk ash-properties and its uses: a review. *J. Inst. Eng. India* 88, 50–56.

Nepal, T. K., Dorji, U., Nidup, Y., Wangdi, C., Tshering, K., and Wangdi, T. (2021). Comparative analysis of different combinations of composting and testing of soil physical properties, MDPI Soil Science. doi: 10.20944/preprints202102.0446.v1

Nima, D., Aulakh, C., Sharma, S., and Kukal, S. S. (2020). Assessing soil quality under long-term organic Vis-a-Vis chemical farming after twelve years in North-Western India. *J. Plant Nutr.* 44, 1175–1192. doi: 10.1080/01904167.2020.1862195

Ofori, J., Kamidouzono, A., Masunaga, T., and Wakatsuki, T. (2005). Organic amendment and soil type effects on dry matter accumulation, grain yield, and nitrogen use efficiency of rice. *J. Plant Nutr.* 28, 1311–1322. doi: 10.1081/PLN-200067436

Olsen, S. R. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*. US Department of Agriculture. Washington, D.C.

Phillips, I., Paungfoo-Lonhienne, C., Tahmasbian, I., Hunter, B., Smith, B., Mayer, D., et al. (2022). Combination of inorganic nitrogen and organic soil amendment improves nitrogen use efficiency while reducing nitrogen runoff. *Nitrogen* 3, 58–73. doi: 10.3390/nitrogen3010004

Powlson, D., Smith, P., and Nobili, M. D. (2013). “Soil organic matter” in *Soil conditions plant growth*. eds. P. J. Gregory and S. Nortcliff (Oxford, UK: John Wiley & Sons, Ltd), 86–131.

Priyadharshini, J., and Seran, T. (2009). Paddy husk ash as a source of potassium for growth and yield of cowpea (*Vigna unguiculata* L.). *J. Agric. Sci.* 4, 67–76. doi: 10.4038/jas.v4i2.1646

Rajkhowa, D., Saikia, M., and Rajkhowa, K. (2003). Effect of vermicompost and levels of fertilizer on greengram. *Legume Res.* 26, 63–65.

Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M., et al. (2018). Trends in global agricultural land use: implications for environmental health and food security. *Annu. Rev. Plant Biol.* 69, 789–815. doi: 10.1146/annurev-arplant-042817-040256

Rosen, C. J., and Allan, D. L. (2007). Exploring the benefits of organic nutrient sources for crop production and soil quality. *HortTechnology* 17, 422–430. doi: 10.21273/HORTTECH.17.4.422

Schiemenz, K., and Eichler-Löbermann, B. (2010). Biomass ashes and their phosphorus fertilizing effect on different crops. *Nutr. Cycl. Agroecosyst.* 87, 471–482. doi: 10.1007/s10705-010-9353-9

Sharma, S., Singh, P., and Choudhary, O. (2021). Nitrogen and rice straw incorporation impact nitrogen use efficiency, soil nitrogen pools and enzyme activity in rice-wheat system in North-Western India. *Field Crop Res.* 266:108131. doi: 10.1016/j.fcr.2021.108131

Sharma, B., Vaish, B., Monika, , Singh, U. K., Singh, P., and Singh, R. P. (2019). Recycling of organic wastes in agriculture: an environmental perspective. *Int. J. Environ. Res.* 13, 409–429. doi: 10.1007/s41742-019-00175-y

Singh, S., and Chauhan, T. M. (2021). Effect of phosphorus and FYM on yield and uptake of nutrients in pearl millet. *Indian J. Agric. Sci.* 91, 753–756. doi: 10.56093/ijas.v91i5.113096

Singh, R., Srivastava, P., Bhadouria, R., Yadav, A., Singh, H., and Raghubanshi, A. S. (2020). Combined application of biochar and farmyard manure reduces wheat crop eco-physiological performance in a tropical dryland agro-ecosystem. *Energy Ecol. Environ.* 5, 171–183. doi: 10.1007/s40974-020-00159-1

Singh, R., Srivastava, P., Singh, P., Sharma, A. K., Singh, H., and Raghubanshi, A. S. (2019). Impact of rice-husk ash on the soil biophysical and agronomic parameters of wheat crop under a dry tropical ecosystem. *Ecol. Indic.* 105, 505–515. doi: 10.1016/j.ecolind.2018.04.043

Subbiah, B., and Asija, G. (1956). A rapid procedure for the estimation of available nitrogen in soils. *Curr. Sci.* 25, 259–260.

Tayeh, B. A., Alyousef, R., Alabduljabbar, H., and Alaskar, A. (2021). Recycling of rice husk waste for a sustainable concrete: a critical review. *J. Clean. Prod.* 312:127734. doi: 10.1016/j.jclepro.2021.127734

Thind, H. S., Yadvinder, S., Bijay, S., Varinderpal, S., Sharma, S., Vashistha, M., et al. (2012). Land application of rice husk ash, bagasse ash and coal fly ash: effects on crop productivity and nutrient uptake in rice–wheat system on an alkaline loamy sand. *Field Crop Res.* 135, 137–144. doi: 10.1016/j.fcr.2012.07.012

Tisdall, J. M., and Oades, J. M. (1982). Organic matter and water-stable aggregates in soils. *J. Soil Sci.* 33, 141–163. doi: 10.1111/j.1365-2389.1982.tb01755.x

Ye, L., Zhao, X., Bao, E., Li, J., Zou, Z., and Cao, K. (2020). Bio-organic fertilizer with reduced rates of chemical fertilization improves soil fertility and enhances tomato yield and quality. *Sci. Rep.* 10:177. doi: 10.1038/s41598-019-56954-2