



# Integrated organic nutrient management: a sustainable approach for cleaner maize (*Zea mays* L.) production in the Indian Himalayas

Amit Kumar · Raghavendra Singh · Subhash Babu · R. K. Avasthe · Anup Das · Aastika Pandey · B. A. Gudade · Ramgopal Devadas · Saurav Saha · Sanjay Singh Rathore

Received: 19 December 2023 / Accepted: 27 June 2024 / Published online: 1 August 2024  
© The Author(s), under exclusive licence to Springer Nature B.V. 2024

**Abstract** Inadequate availability of quality organic nutrient sources is the major hurdle in adopting organic farming. Hence, a study was conducted during 2019–21 at Sikkim state of the Indian Himalayas to investigate the effect of integrated organic manuring on energy dynamics, profitability, and soil health of maize (*Zea mays* L.) crops grown in acidic soil. Five organic nutrient management practices viz., T2: 100% recommended dose of nitrogen (RDN) through

farmyard manure (FYM); T3: 100% RDN through mixed compost (MC); T4: 100% RDN through vermicompost (VC); T5: 50% RDN through FYM and 50% RDN through MC + biofertilizers (BFs) and T6: 50% RDN through FYM and 50% RDN through VC + BFs were tested in a four-times replicated randomized block design against the farmers' practice (T1: application of 5 Mg ha<sup>-1</sup> FYM). Results indicated that the supply of 50% RDN through FYM and 50% RDN through MC along with the BFs consortium improved the green cob and biological yields, net return, production efficiency, energy net return, and energy output efficiency by 26.3%, 24.8%, 29%, 26.4%, 24%, and 24.7%, respectively over farmers' practices. Likewise, the supply of 50% RDN through FYM + 50% RDN through MC + BFs reduced soil bulk density (*pb*) by 6.87% while increasing total water stable aggregates (TWSA) by 23.1% and mean weight diameter (MWD) by 18.7% over farmers' practice. Similarly, a significant improvement in soil organic carbon, available N, P, K, Zn, Fe, and Mn was observed with 50% RDN through FYM + 50% RDN through MC + BFs over farmers' practice. Furthermore, integrated nitrogen supply with FYM and MC in equal proportion improved soil enzymatic activity considerably over existing practice. Hence, the study inferred that the supply of 50% RDN through FYM + 50% RDN through MC + BFs may be a viable and soil-supportive approach for cleaner maize production in the acidic soils of Indian Himalayas and other similar ecoregions.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s13165-024-00471-8>.

A. Kumar · R. K. Avasthe · R. Devadas · S. Saha  
ICAR Research Complex for NEH Region, Sikkim Centre,  
Tadong, Gangtok, Sikkim 737102, India

R. Singh  
ICAR- Indian Institute of Farming System Research,  
Modipuram, Meerut, Uttar Pradesh 250110, India

S. Babu (✉) · A. Pandey · S. S. Rathore  
Division of Agronomy, ICAR- Indian Agricultural  
Research Institute, New Delhi 110012, India  
e-mail: Subhash.Babu@icar.gov.in

A. Das  
ICAR Research Complex for Eastern Region, Patna,  
Bihar 800014, India

B. A. Gudade  
Spices Park Chhindwara, Spices Board of India,  
Chhindwara, Madhya Pradesh 480107, India

**Keywords** Energy productivity · Ecosystems · Economics · Mixed compost · Soil health

## Introduction

Conventional agricultural production systems coupled with faculty conservation and management practices jeopardize the long-term sustainability of the Himalayan rainfed ecosystem (Babu et al. 2020a). The decline in soil health contributes to a self-reinforcing cycle of inadequate food production (Yadav et al. 2013; Yang et al. 2019; Dhillon and Sahu 2024). Organic carbon is crucial for soil health, environmental quality, and crop yields (Singh et al. 2021a; Nallagatla and Patil 2024). Organic carbon rich soil holds more moisture, improves aggregate stability, and the nutrients supplying capacity to crops (Boone et al. 2019; Manjappa 2023). Consistent soil organic carbon (SOC) depletion in Indian soils, especially in the Himalayan region, has been a serious concern for sustainable agriculture and in achieving sustainable development goals (Babu et al. 2023a; Yadav et al. 2023). Hence, it is essential to replace conventional agricultural production methods with environmentally friendly agricultural systems that reduce environmental impacts while increasing farm productivity to assure food and nutritional security without compromising soil health, and environmental sustainability (Babu et al. 2023b; Yadav et al. 2024). Organic farming represents a sustainable production system that minimizes negative effects on ecosystem services (Willer and Lernoud 2019; Singh et al. 2021b). Furthermore, the global demand for organic food has multiplied several times as compared to inorganic products (Onte et al. 2019). Organic farming holds great promise for producing high-quality food with the ability to command premium prices (Babu et al. 2020b). Similarly, the organic production system has tremendous potential to contribute to long-term ecosystem services through soil microbial diversity and SOC sequestration (Babu et al. 2020d). Despite this, some studies have shown that organic farming produces less crop yield as compared to conventional farming during the transition phase (Kalantri et al. 2011; Avasthe et al. 2020), but the magnitudes of yield variations are primarily governed by the type and number of crops grown, management systems, and environmental factors (Wortman et al. 2011;

Babu et al. 2023a). Under deficit moisture conditions or rainfed situations, the yield gaps from organic farming and conventional production decrease to about 10–15% (Ponisio et al. 2015).

Lack of access to high-quality organic manures that can fulfill the nutritional requirements of crops is one of the main obstacles to organic farming adoption at the field level (Röös et al. 2018; Bhutia et al. 2016). Bulky organic manures relatively contain plant nutrients and are applied in large quantities in organic farming which increases the financial load on the growers (Wortman et al. 2011; Yadav et al. 2013; Singh et al. 2023). These manures are incapable of addressing the essential nutrient demands and also encouraging the proliferation of the soil's helpful macro and microflora (Singh et al. 2018; Babu et al. 2020c). Many brands of organic manures/fertilizers claim to have high amounts of natural supplements and essential elements (Onte et al. 2019; Moasunep et al. 2019). However, most farmers are unaware of the risks associated with using commercially available bio-manure products (Lei et al. 2019). Animal excreta-based manures, bio-solids from agro-industries, residues/biomass of crops/weeds, bio-fertilizers, green manures, and wastes of food processing are excellent sources of nutrients for organic farming (Babu et al. 2020a). Even though there are still alternative uses for animal dung as fuel, it is widely employed as farmyard manure. Optimizing the use of different organic and biological sources to keep soil fertility at an optimal level is a viable strategy to maintain targeted crop production (Adugna 2016). The yield potential of cereals under an organic farming system is frequently hampered by low nutrient content organic resources (Babu et al. 2020c). FYM applied in agricultural fields typically comprises 0.52–0.81% N, 0.22–0.44% P, and 0.83–1.05% K, with no declaration of manure quality or other alternate sources for efficient use of nutrients (Halvorson et al. 2016).

The Himalayas spread over 52.5 Mha and harbor ~50 million people (Yadav et al. 2019). The northeastern hill region (NEHR) of India covers 26.23 Mha of total geographic area that receives high rainfall (>2000 mm annually) (Babu et al. 2020c). Nonetheless, a significant quantity of nutrients in soil is lost through runoff and percolation during the rainy season resulting in widespread deficiency of multiple nutrients (Singh et al. 2021b). The majority

of Himalayan soils are acidic in reaction Soil acidity hinders root development due to aluminum toxicity, damaging root cells, and inhibiting elongation. This leads to poor root growth, limited water and nutrient access, and disrupts enzyme activities and hormonal balances in maize plants, resulting in impaired nutrient uptake and reduced biomass (Singh et al. 2023).

Maize (*Zea mays* L.) is an important crop having high demand in national and international markets. Maize has immense potential for contract organic farming to provide farmers with a stable income in mountainous areas. Hence, the adequate provision of nutrients becomes especially crucial for nutrient-demanding crops like maize cultivated within the framework of organic farming (Babu et al. 2020d). A satisfactory and consistent supply of nutrients to crops from sowing to harvest is required for superior economic output (Babu et al. 2020a). In the realm of organic management, achieving synchronization between nutrient release and crop demand holds paramount importance. Therefore, a comprehensive understanding of the patterns governing nutrient release from organic sources becomes essential to mitigate crop nutritional stress. Thus, the formulation and application of optimal nutrient management strategies are critical for efficient organic crop production (Lei et al. 2019).

The application of diverse organic sources of nutrients instead of a single source in an integrated way offers substantial long-term prospects to reduce the cost of cultivation while increasing yield, profitability, energy use efficiency, and sustaining soil health (Singh et al. 2021b). The application of vermicompost, FYM, rock phosphate, and *Rhizobium* significantly improves crop productivity (Masmoudi et al. 2018). Conjoint application of FYM with vermicompost led to increased crop yields and improved soil health (Kalantri et al. 2011). Likewise, the mixed application of straw compost with biofertilizers consortia enhances rice productivity, profitability, energy output-input relationship, and soil health (Yadav et al. 2013). The use of vermicompost offers advantages in terms of boosting crop productivity and enhancing overall soil quality. The effects are more pronounced with increasing organic manures and inoculation of biofertilizers as an integrated approach (Babu et al. 2020a). The heightened development of roots and shoots, coupled with greater biomass buildup has been ascribed to the invigorating

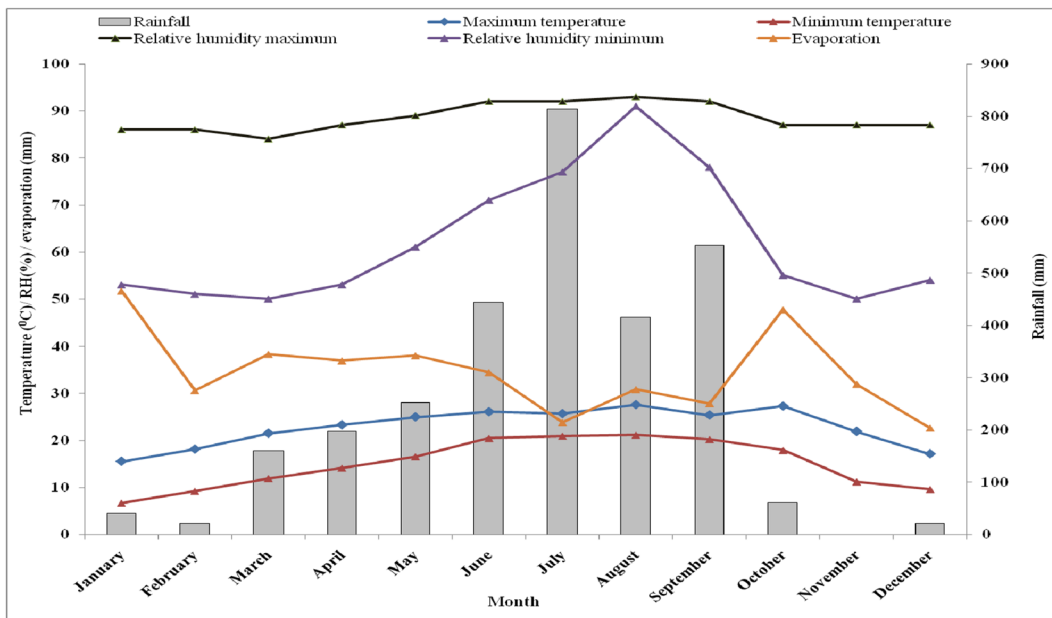
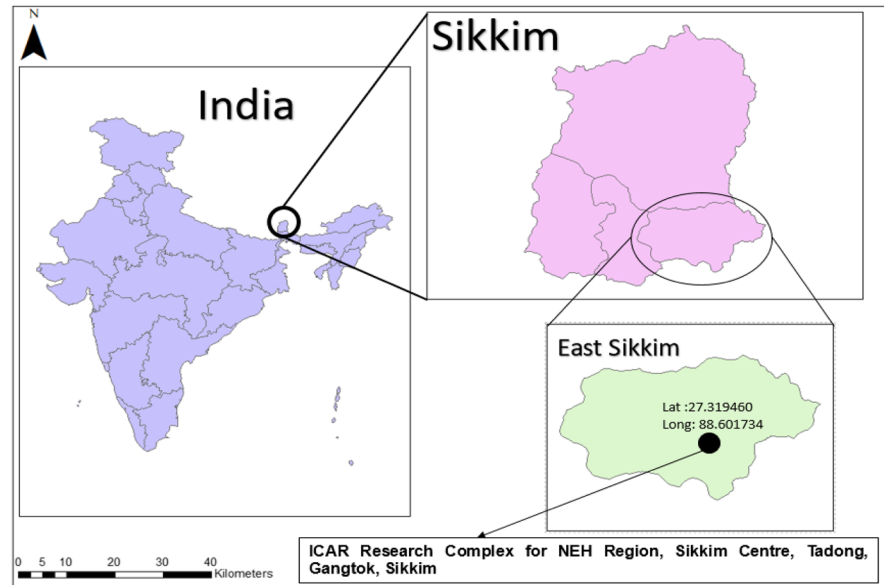
impact of increased microorganism growth and their activities, potentially negating the need for sole focus on elevating SOC content (Li et al. 2015; Onte et al. 2019). Studies indicated that most of the work on organic nutrition either focused on crop productivity (Avasthe et al. 2020; Mulyati et al. 2021), soil health (Babu et al. 2020d; King et al. 2020), or profitability (Singh et al. 2021a). To date, there has been a lack of research in Himalayan ecology that comprehensively examines the comparative effects of substituting organic sources on aspects such as crop productivity, profitability, energy use efficiency, and soil health, particularly in acidic soils. Consequently, a hypothesis was designed that the combined application of different organic sources and BF's may result in long-term improvements in soil health as well as sustained increases in crop production, profitability, and energy use efficiency (EUE) per unit of investment. Against this backdrop, the current study was devised to investigate the effects of microbe-incubated simultaneous use of nutrients derived from organic sources on maize yield, financial returns, EUE, and soil health after completion of three cropping cycles in the Indian Himalayas.

## Materials and methods

### Experimental site

The field experiment was conducted from 2019 to 2021 at the Research Farm of ICAR Research Complex for North Eastern Hill Region, Sikkim Centre Tadong, Gangtok, Sikkim, India. The research field was positioned at 27°32' N latitude, 88°60' E longitude, and an elevation of 1300 m above mean sea level (Fig. 1). Weather parameters during the experimental period are presented in Fig. 2. Physicochemical and biological characteristics of soil were evaluated before the field experiment by taking samples from 0–30 cm depth. The study site's soil was categorized into the Haplumbrept group, sandy clay loam texture, and acidic in reaction (pH 5.18). The experimental soil was high in soil organic carbon; SOC (1.54%), medium in available nitrogen (332 kg ha<sup>-1</sup>), phosphorus (14.3 kg ha<sup>-1</sup>), and potassium (210 kg ha<sup>-1</sup>). Available iron; Fe (59.9 mg kg<sup>-1</sup>), manganese; Mn (15.01 mg kg<sup>-1</sup>), zinc; Zn (0.84 mg kg<sup>-1</sup>), SMBC (511 µg g<sup>-1</sup> soil),

**Fig. 1** Study site in Eastern Himalayan region



**Fig. 2** Average weather data of the experimental site during the experimental period for three consecutive years (2019, 2020 and 2021)

DHA ( $17.1 \mu\text{g TPF g}^{-1} \text{ soil h}^{-1}$ ), acid phosphatase activity ( $250 \mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$ ), FDA ( $31.2 \mu\text{g FDA g}^{-1} \text{ soil h}^{-1}$ ), urease ( $1011 \mu\text{g NH}_3\text{-N g}^{-1} \text{ soil h}^{-1}$ ) and  $\beta$ -glucosidase activities ( $60.3 \mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$ ) were also recorded.

#### Experimental design and crop management

The six specified treatment combinations of different organic nitrogen (N) sources were, T1: Farmers' practice (control); T2: 100% RDN through FYM; T3: 100% RDN through MC; T4: 100% RDN through

VC; T5: 50% RDN through FYM and 50% RDN through MC+BFs and T6: 50% RDN through FYM and 50% RDN through VC+BFs were laid out in randomized block design with four replications. In the experimental field, distinct plots (5.40 m × 4.20 m) were manually made. The manures were manually incorporated into the soil with the help of iron-made spades. The average nutrient composition in various organic manures used in the study is given in Table 1. The composite maize variety 'RCM 1-1' was sown manually with a seed rate of 21 kg per hectare using a spacing of 50 cm between rows and 20 cm between individual plants. The RCM1-1 is a composite variety of maize having yield potential of 5.0–5.5 Mg ha<sup>-1</sup> and matured in 120–125 days. Maize requires a firm and compact seedbed free from stubbles and weeds. Three tillage was done through a power tiller to bring the soil to a fine tilth. The sowing was done in the 2nd fortnight of February, and the green cobs were harvested in the first fortnight of June during each of the study years. The desired plant density was achieved through thinning and gap-filling done 15 days after sowing (DAS). Two manual weeding were done at 20–25 DAS and 40–45 DAS for managing weeds. The maize crop was grown as rainfed and no external irrigation was applied during the course of investigation. As per the treatment, organic manures were applied as basal dose on an 80 kg N equivalent basis. Three weeks before sowing, the dolomite (2 Mg ha<sup>-1</sup>) was applied and mixed in the soil to neutralize the soil pH. To manage stem borers, fall armyworms, and leaf-eating caterpillars, foliar application of Spinosad 45% EC @ 0.25 ml per liter or phytoneem @ 4–5 ml per liter was followed.

#### Preparation of mixed compost

Samples of the dominant weed species available in the study site (*Artemisia absinthium*, *Eupatorium cannabinum*, and leaves of N-fixing tree species, *Alnus*

*nepalensis*, and *Schima wallichii*) were collected from the farm and surrounding areas. Weeds were collected, and cut into small pieces (1–1.5 cm) with an electrically powered chaff cutter, properly mixed, and layered by spreading on the cement floor. Thereafter fresh cow dung was collected from the dairy located on the Research Farm. Subsequently, a structured arrangement was established in a one-meter-deep pit, wherein chopped weed biomass and cow dung were layered in an alternating pattern. A thin layer of soil was placed on top of the layered material. Subsequently, the mixture was covered with a polythene sheet to facilitate decomposition. The material in the pit was left undisturbed for ten days and thereafter, the pit was uncovered to allow for the release of heat and to promote aeration. To ensure that all of the material resorted to consistent temperature and aeration, the decaying material was rotated every week for up to 90 days. The temperature within the pit was observed regularly at 8 a.m., and turning was completed when the recorded temperature exceeded 45 °C. Once the temperature dropped below 45 °C and the moisture content reduced below 25%, the entire mixture was allowed to undergo a curing process for approximately 20–25 days. Following this, fully matured co-composts were collected, processed, and stored to undergo subsequent chemical analysis and eventual application in the field.

#### Yield measurement

A thread and meter scale was employed to determine the length and girth of 10 randomly selected cobs from every plot. Then the average was determined and represented in centimeters per cob. Utilizing a conversion factor, the net plot area taken from each plot was used to compute the yield of green cob and stover weight in kg plot<sup>-1</sup> and finally, it was converted into Mg ha<sup>-1</sup>.

**Table 1** Composition of manures

Name of Manure	Nutrient composition								
	pH	Total C%	C: N ratio	N%	P%	K%	Fe (mg kg <sup>-1</sup> )	Mn (mg kg <sup>-1</sup> )	Zn (mg kg <sup>-1</sup> )
FYM	6.58	31.8	29.8	0.59	0.27	0.51	1670	46	73
Vermicompost	7.43	36.6	26.1	1.55	0.90	1.27	5579	338	382
Mixed compost	7.51	37.2	26.3	1.42	0.78	1.22	5345	97	98.3

## Energy input–output relationships

Both operational (direct) and non-operational (indirect) energy employed in agricultural and related activities were taken into computation (Devasenapathy et al. 2009). The sources of direct energy are those that release energy directly i.e., fuel, human and animal power, etc. Indirect sources of energy are those that do not immediately release energy but instead dissipate energy via different conversion processes, such as seeds, manures, biofertilizers, and biopesticides are all available. Based on energy equivalents, primary data on a variety of inputs and management techniques were utilized to calculate energy consumption (Suppl Table 1). Increasing the corresponding production levels with their corresponding energy equivalents allowed us to compute the energy output from the produce (green cob and green stover of maize) (Suppl. Table 2). The energy-use indices were determined by the input energy and output, production cost, and crop yield utilizing the guidelines provided by Choudhary et al. (2017), and Mittal and Dhawan (1988) as follows:

$$\text{Total energy input (MJha}^{-1}\text{)} = \Sigma i + \dots \dots \dots i^{\text{th}}$$

$$\text{Total energy output (MJha}^{-1}\text{)} = \Sigma i + \dots \dots \dots i^{\text{th}}$$

where:  $\Sigma i \dots \dots \dots i^{\text{th}}$  was the summation of all the energy input used and the amount of total output in terms of energy

$$\text{Total energy returns (MJha}^{-1}\text{)} = \text{TEO (MJ ha}^{-1}\text{)} - \text{TEI (MJ ha}^{-1}\text{)}$$

$$\text{EUE} = \frac{\text{TEO (MJ ha}^{-1}\text{)}}{\text{TEI (MJ ha}^{-1}\text{)}}$$

$$\text{E}_p = \frac{\text{Economic yield (kg ha}^{-1}\text{)}}{\text{TEI (MJ ha}^{-1}\text{)}}$$

$$\text{Energy intensiveness (MJUS\$}^{-1}\text{)} = \frac{\text{TEI (MJ ha}^{-1}\text{)}}{\text{COC (US\$ ha}^{-1}\text{)}}$$

$$\text{EP}_f = \frac{\text{NEO (MJ ha}^{-1}\text{)}}{\text{TEI (MJ ha}^{-1}\text{)}}$$

$$\text{E}_s = \frac{\text{TEI (MJ ha}^{-1}\text{)}}{\text{Green cob yield (kg ha}^{-1}\text{)}}$$

$$\text{Ei}_e \text{ (MJ US\$}^{-1}\text{)} = \frac{\text{TEO (MJ ha}^{-1}\text{)}}{\text{COC (US\$ ha}^{-1}\text{)}}$$

$$\text{Eo}_e \text{ (MJ ha}^{-1}\text{day}^{-1}\text{)} = \frac{\text{TEO (MJ ha}^{-1}\text{)}}{\text{Crop duration (Days)}}$$

where: TEO: Total energy output; TEI: Total energy input; EUE: Energy use efficiency;  $E_p$ : Energy productivity;  $EP_f$ : Energy profitability;  $E_s$ : Specific

energy;  $Ei_e$ : Energy intensity in economic terms;  $Eo_e$ : Energy output efficiency.

## Economic analysis

For economic auditing, the expenditure incurred in crop production (from sowing to harvesting (Suppl. Table 2) and the economic worth of all the products were calculated based on the market price prevailing during the investigation period (2019–21). The economic value of the entire output was expressed as gross returns while net return, benefit: cost (B: C) ratio, profitability, and production efficiency were calculated by the following equations:

$$\text{GR (US\$ ha}^{-1}\text{)} = \text{Return from green cobs (US\$ ha}^{-1}\text{)} - \text{Return from stover (US\$ ha}^{-1}\text{)}$$

$$\text{NR (US\$ ha}^{-1}\text{)} = \text{Gross returns (US\$ ha}^{-1}\text{)} - \text{Cost of cultivation (US\$ ha}^{-1}\text{)}$$

$$\text{B:C ratio} = \frac{\text{Gross returns (US\$ ha}^{-1}\text{)}}{\text{Cost of cultivation (US\$ ha}^{-1}\text{)}}$$

$$\text{Profitability (US\$ ha}^{-1}\text{day}^{-1}\text{)} = \frac{\text{Net returns (US\$ ha}^{-1}\text{)}}{\text{Duration of crop (Days)}}$$

$$\text{Production efficiency (kg ha}^{-1}\text{day}^{-1}\text{)} = \frac{\text{Economic yield (kg ha}^{-1}\text{)}}{\text{Duration of crop (Days)}}$$

## Soil sampling

After a three-year crop cycle, soil samples from each plot were obtained from 0 to 30 cm depth with a screw augur. Three locations within each plot were randomly used to collect samples, which were then combined to create a composite soil sample. A total of 24 sets of soil samples were collected and placed in zip-top plastic bags for transport to the lab. Soil samples were shade-dried, grounded and strained through a 2- mm sieve after the visible fragments of the crop and the roots were removed. A portion of the fresh representative soil samples was stored at 4°C for microbial analysis.

## Analysis of physical properties of soil

The bulk density ( $pb$ ) of the soil was determined using the core sampler method (Piper 1950), with measurements taken from three randomly chosen locations within each plot. For calculating  $pb$ , the protocol provided by Chopra and Kanwar (1991) was followed. The Wet sieving method was used to measure the stability of the aggregate (Haynes 1993). The

outcomes are presented using the mean weight diameter (MWD) technique, which involves multiplying the proportion of soil retained on each sieve after the specified sieving time by the mean weight diameter of the neighboring sieve opening. In this study, the MWD values ranged from 1.15 mm (lower limit) to 6 mm (upper limit).

#### Analysis of chemical properties of soil

A glass electrode pH meter was used to measure the pH in a soil–water (1:2.5) suspension at 25 °C after equilibrating for 30 min (Jackson 1973). Wet oxidation was used to measure the organic carbon in the soil (SOC) (Walkley and Black 1934). The alkaline  $\text{KMnO}_4$  method for available N (Subbiah and Asija 1956), the Bray and Kurtz method P (Bray and Kurtz 1945), and flame photometry for K (Jackson 1973) were employed to assess the impact of treatments on soil fertility and expressed in  $\text{kg ha}^{-1}$ . The chelating agent diethylene triamine penta-acetic acid (DTPA) method was used for the determination of available Fe, Mn, and Zn in soil (Lindsay and Norwell 1978).  $\text{Fe}^{++}$ ,  $\text{Mn}^{++}$ , and  $\text{Zn}^{++}$  from the DTPA extract were identified using their respective hollow cathodes and an Atomic Absorption Spectrophotometer.

#### Analysis of soil biological properties

The fluorescein diacetate hydrolysis (FDA) which serves as an indicator of soil microbial activity was measured by Green et al. (2006). By using the p-nitrophenol release from analog substrate methods, acid phosphor monoesterase activities were assessed (Tabatabai 1994). The activity of  $\beta$ -glucosidase was measured by Eivazim and Tabatabai (1988). The amount of soil microbial biomass carbon (SMBC) was calculated following the chloroform-fumigation extraction procedure (Vance 1987). Klein et al. (1971) procedure was employed to determine the dehydrogenase activity.

#### Statistical analysis

The data obtained from four separate replicates for each treatment were subjected to analysis using the general linear model procedures within the Statistical Analysis System software package. The significance of the 'F' value was determined based on analysis of

variance (ANOVA) for randomized block design. The Least Significant Difference (LSD) test was employed at a significance level of 5% probability for conducting multiple comparisons of treatment means.

$$LSD = S.Ed. \times t \text{ value at error degree of freedom}$$

where S.Ed. = Standard error of difference;  $t$  = value of percentage point of 't' distribution for error degrees of freedom at 5% level of significance.

PCA is one of the methods of factor analysis that involves reducing the number of variables to a smaller number of variables called factors. PCA was performed to determine the impact of various organic sources of nutrients on yield parameters and soil qualities. Principal components (PCs) that were statistically significant were chosen using the Kaiser (1960) described Eigen significant criteria. The PCA was performed using the PAST (3.14) software. In Pearson correlation, two variables are measured in terms of their linear relationship. Depending on its value, it can range from -1 to +1, with -1 meaning a total negative linear correlation, zero meaning no correlation, and +1 meaning a total positive correlation. The Excel-based data analysis Tool Pack was used for the analysis of the Pearson correlation matrix. Using a heat map, hierarchical cluster analysis was demonstrated (Double dendrogram). A heat map (or heatmap) is a graphical representation of data that visualizes hierarchical clustering by showing values by color. The heat maps were created using three software packages: 'Heat+' (Babicki et al. 2016), 'R Color Brewer' (Khomtchouk et al. 2014), and 'g plots' in R (version 3.6.1). Path analysis was used to test and evaluate the cause-outcome model of soil characteristics and nutrient content on maize green cob yield. Simple correlation coefficients between dependent and independent characteristics were divided into direct and indirect effects in route analysis. Path coefficients are standardized partial regression coefficients that symbolize direct influences or effects (Khomtchouk et al. 2014).

## Results

### Soil health

Conjoint application of diverse organic sources had failed to significantly impact soil bulk density

**Table 2** Effects of conjoint application of organic sources of nutrients on chemical properties of soil after completion of three years of cropping cycle

Treatment	Soil pH	Soil organic carbon %	Available N (kg ha <sup>-1</sup> )	Available P (kg ha <sup>-1</sup> )	Available K (kg ha <sup>-1</sup> )	Available Fe (mg kg <sup>-1</sup> )	Available Zn (mg kg <sup>-1</sup> )	Available Mn (mg kg <sup>-1</sup> )
T1	5.22	1.59	338	15.0	214	60.2	0.88	15.04
T2	5.46	1.63	367	17.5	225	67.4	1.01	15.51
T3	6.08	1.68	377	19.9	236	70.4	1.05	15.90
T4	5.33	1.66	363	17.1	219	64.1	0.91	15.35
T5	6.12	1.72	390	20.4	249	72.1	1.07	16.02
T6	5.54	1.69	372	18.7	230	68.7	1.02	15.74
SEm±	0.16	0.02	5.26	0.36	4.15	1.5	0.02	0.15
LSD (P=0.05)	0.50	0.06	15.1	1.05	13.2	4.4	0.06	0.48

T1: Farmers' practice (control); T2: 100% RDN through FYM; T3: 100% RDN through mixed compost (MC); T4: 100% RDN through vermicompost (VC); T5: 50% RDN through FYM and 50% RDN through mixed compost (MC)+ biofertilizers and T6: 50% RDN through FYM and 50% RDN through vermicompost (VC)+ biofertilizers

(*pb*) at 0–30 cm depth after three years of cropping. However, marginally lower *pb* (1.22 Mg m<sup>-3</sup>) was observed under 50% RDN through FYM and 50% RDN through MC+BFs (T5) followed by the supply of 100% RDN through MC; T3 (1.25 Mg m<sup>-3</sup>), while higher *pb* (1.31 Mg m<sup>-3</sup>) was noticed under control plot (Farmers' practice). The treatment T5 resulted in a significantly higher percentage of >0.25-mm soil aggregates (37.5%) at a soil depth of 0–30 cm as compared to that recorded in soil under control. Treatment T5 gave statistically similar results to the percentage observed with the T3. The significantly ( $p < 0.05$ ) higher percentage of <0.25 mm soil aggregates at 0–30 cm soil depth was noticed under T5 (50.2%) followed by T3 (49%) and T6 (47.6%). The T5 exhibited the most substantial enhancements, with a 30% increase in TWSA and a 23% increase in MWD (Fig. 3). These improvements were statistically comparable with those observed under T3, while significantly surpassing the outcomes of other manurial treatments.

Concerning chemical properties, T5 resulted in significantly higher soil pH (6.12) followed by T3 (6.08) as compared to the control; T1. In comparison to the initial SOC at 0–30 cm depth, significantly higher SOC (1.72%) was registered under T5 followed by T6 (1.69) and T3 (1.68). The percent rise in available N by 15.3%, available P by 36%, and available K by 16.3% in the soil was noticed under T5 over T1. Likewise, increased concentrations of Fe (72.1 mg kg<sup>-1</sup>), Zn (1.07 mg kg<sup>-1</sup>), and

Mn (16.02 mg kg<sup>-1</sup>) in soil were noted under treatment T5, which were statistically similar to T3 and T6 (Table 2). Among the diverse organic sources, treatment T5 exhibited higher levels of SMBC (607 µg g<sup>-1</sup> soil), FDA (45 µg kg<sup>-1</sup> soil h<sup>-1</sup>), acid-P (276 µg PNP g<sup>-1</sup> soil h<sup>-1</sup>), DHA (23.4 µg TPF g<sup>-1</sup> soil h<sup>-1</sup>), urease (1266 µg NH<sub>3</sub><sup>-</sup>N g<sup>-1</sup> soil h<sup>-1</sup>), and β-glucosidase (80.3 µg PNP g<sup>-1</sup> soil h<sup>-1</sup>) over others. However, these values were statistically at par with those obtained in soils under T3 and T6, and notably greater compared to the other treatments (Table 3).

#### Energy budgeting

The energy consumption data indicated that 100% RDN through VC (T4) was regarded as the highest energy demand nutrient management practice requiring an input of 7.31 × 10<sup>3</sup> MJ ha<sup>-1</sup> followed by the supply of 50% RDN through FYM and 50% RDN through VC+BFs (T6) with an energy input of 6.99 × 10<sup>3</sup> MJ ha<sup>-1</sup> (Table 4). In contrast, the plots treated with FYM and MC had lower energy requirements compared to those treated with VC, ranging from 3.86 × 10<sup>3</sup> MJ ha<sup>-1</sup> to 6.81 × 10<sup>3</sup> MJ ha<sup>-1</sup>). Among the organic nutrient management practices, the lowest energy requirement (3.86 × 10<sup>3</sup> MJ ha<sup>-1</sup>) was registered under control. The gross energy output, net energy gains, and energy production efficiency resulting from organic nutrient sources ranged from 192.9 × 10<sup>3</sup> MJ ha<sup>-1</sup> to 256.3 × 10<sup>3</sup> MJ ha<sup>-1</sup>, 189 × 10<sup>3</sup> MJ ha<sup>-1</sup> to 249.5 × 10<sup>3</sup> MJ ha<sup>-1</sup>, and



1837 MJ day<sup>-1</sup> to 2440 MJ day<sup>-1</sup>, respectively (Table 3). The data indicated that the supply of 50% RDN through FYM and 50% RDN through MC+BFs (T5) resulted in a substantial increase in gross energy production by 32.8%, net energy return by 32% and energy production efficiency by 32.8%, followed by those obtained under the supply of 100% RDN through MC(T3). The T4 treatment application yielded the lowest energy productivity, energy profitability, and energy use efficiency. The T2 treatment exhibited the most substantial energy intensiveness (8.95 MJ US\$<sup>-1</sup>) followed by T5 (8.88 MJ US\$<sup>-1</sup>) and T6(8.75 MJ US\$<sup>-1</sup>). In comparison to the control, T4 showed a 53% increase in specific energy which was statistically comparable to T6 (0.90) and notably higher than the other treatments. The T5 exhibited a 35.7% higher energy intensity compared to the T4 (248.6 MJ US\$<sup>-1</sup>). The T5 demonstrated a 32.8% greater energy output efficiency which was statistically equivalent to T3 (2346 MJ day<sup>-1</sup>) and particularly superior to the other treatments.

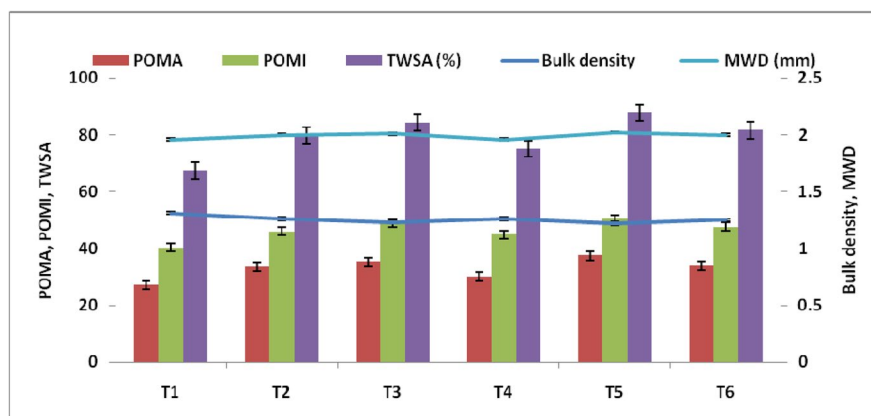
### Economic productivity

The integrated use of organic sources exerted a notable and statistically significant ( $p < 0.05$ ) influence on maize yield (Table 5). The averaged data over three years revealed that the highest green cob yield (8.30 Mg ha<sup>-1</sup>)

and green stover yield (12.2 Mg ha<sup>-1</sup>) was achieved under 50% RDN through FYM and 50% RDN through MC+BFs. These outcomes were found to be comparable with those obtained under T3 (8.21 and 11.5 Mg ha<sup>-1</sup>), and T6 (7.76 and 11.3 Mg ha<sup>-1</sup>) and remained significantly superior to the other treatments. The supply of 50% RDN through FYM and 50% RDN through MC+BFs exhibited a 33% increase in biological yield which was statistically equivalent to that of 100% RDN through MC and markedly higher than the rest of the treatments.

### Profitability

The plot that received 100% RDN through VC registered the highest production cost (907.5 US\$ ha<sup>-1</sup>) in comparison to other plots where organic nutrients were applied through different sources (Table 5). This increase ranged from 8.50% to 29.8% considering the mean values throughout the three-year study. Contrarily, the control plot (Farmers' practice) had the lowest cost of cultivation (636.6 US\$ ha<sup>-1</sup>). The significantly ( $p < 0.05$ ) higher gross return (3537.9 US\$ ha<sup>-1</sup>) and net return (2779.4 US\$ ha<sup>-1</sup>) was registered under 50% RDN through FYM and 50% RDN through MC+BFs followed by 100% RDN through MC. Likewise, the supply of 50% RDN through FYM and 50% RDN through MC+BFs registered the maximum B: C ratio (3.66), profitability (26.5 US\$ day<sup>-1</sup>), and production efficiency (79 kg ha<sup>-1</sup> day<sup>-1</sup>) followed by 100% RDN through MC.



**Fig. 3** Effects of conjoint application of organic sources of nutrients on physical properties of soil after completion of three years of cropping cycle. Where, T1: Farmers' practice (control); T2: 100% RDN through FYM; T3: 100% RDN through mixed compost (MC); T4: 100% RDN through ver-

micompost (VC); T5: 50% RDN through FYM+50% RDN through mixed compost (MC)+biofertilizers and T6: 50% RDN through FYM+50% RDN through vermicompost (VC)+biofertilizer

**Table 3** Effects of conjoint application of organic sources of nutrients on biological properties of soil after completion of three years of cropping cycle

Treatment	SMBC ( $\mu\text{g g}^{-1}$ soil)	FDA ( $\mu\text{g g}^{-1}$ soil $\text{h}^{-1}$ )	DHA ( $\mu\text{g TPF g}^{-1}$ soil $\text{h}^{-1}$ )	Acid-P ( $\mu\text{g PNP g}^{-1}$ soil $\text{h}^{-1}$ )	Urease ( $\mu\text{g NH}_3\text{-N}$ $\text{g}^{-1}$ soil $\text{h}^{-1}$ )	$\beta$ -glucosidase ( $\mu\text{g}$ PNP $\text{g}^{-1}$ soil $\text{h}^{-1}$ )
T1	518	33.9	18.2	253	1053	63.8
T2	553	38.1	21.0	260	1176	71.5
T3	599	42.3	23.0	270	1230	76.8
T4	541	36.4	19.5	258	1163	69.1
T5	607	45.0	23.4	276	1266	80.3
T6	566	40.8	21.7	267	1192	75.0
SEm $\pm$	13.8	0.91	0.48	2.66	14.1	1.74
LSD (P=0.05)	42.3	2.78	1.42	8.12	39.3	5.13

T1: Farmers' practice (control); T2: 100% RDN through FYM; T3: 100% RDN through mixed compost (MC); T4: 100% RDN through vermicompost (VC); T5: 50% RDN through FYM and 50% RDN through mixed compost (MC)+ biofertilizers and T6: 50% RDN through FYM and 50% RDN through vermicompost (VC)+ biofertilizers

### Principal component analysis (PCA)

Principal component analysis (PCA) is a recurrently resorted statistical technique to condense complex data sets into orthogonal and uncorrelated variables called principal components. Redundant variables of less significance ( $p < 0.01$ ) were warded off from the original datasets, retaining the most prominent factors that can be figured out by the PCA technique. The results (Table 6) shown in PCA exercised on the soil parameters extracted two dominant principal components PC1 and PC2 accounting for 78.59% and 18.42% variability which explained up to 97.01% of the total variability. The biplot which depicted both factor loading of soil parameters (blue color) and scores of treatments (red color) showed that TWSA had very high loadings on PC1 which was closely followed by FDA, available-P, SMBC, and POMI wherein they are found to be diligently correlated to each other and scores (plot) whereas T5, T3, T6 were associated with the existing PC1. On the other hand, SOC, MWD, BD (pb), and available Zn had a strong loading on PC2 and were highly correlated to each other with associated scores of T4, T2, and T1 as seen in the biplot.

### Path coefficient analysis

The path analysis results showed that the available K with the highest direct path coefficient (2.01), followed by the available N was the most important

factor affecting the production of maize green cobs. Overall, the degree of contribution of available soil nutrients in augmenting the maize green cob yield followed the order of available K > available N > available P > available Zn > available Mn > available Fe (Fig. 4).

### Correlation study

The relationship between green cob yield and overall soil physical, chemical, and biological characteristics indicated a noteworthy positive correlation ( $p < 0.01$  and  $p < 0.05$ ) in most cases, except for a negative correlation with soil pb as observed (Fig. 5). The utilization of organic nutrient sources reduced soil pb and enhanced various other soil physical, chemical, and biological characteristics leading to an eventual increase in grain yield.

## Discussion

### Soil health

The degradation of soil quality poses a serious challenge in sustaining hill agriculture (Singh et al. 2021a). Organic farming offers a sustainable approach to production that minimizes the negative impacts on soil health, energy usage, and the ecosystem (Babu et al. 2023a). Within organic agriculture, the utilization of effective sources enhances

**Table 4** Energy budgeting of *pre-kharif* maize influenced by organic nutrient management practices (Mean data of three years)

Treatment	Energy gross return ( $\times 10^3$ MJ ha $^{-1}$ )	Energy input ( $\times 10^3$ MJ ha $^{-1}$ )	Energy net return ( $\times 10^3$ MJ ha $^{-1}$ )	Energy productivity (kg MJ $^{-1}$ )	Energy inter-siveness (MJ US\$)	Energy profitability	Specific energy	Energy intensity in economic term (MJ US\$ $^{-1}$ )	Energy output efficiency (MJ day $^{-1}$ )	Energy use efficiency
T1	192.9	3.86	189.0	1.58	6.06	49.0	0.63	303.0	1837	50.0
T2	232.3	6.42	225.8	1.20	8.95	35.2	0.84	323.5	2212	36.2
T3	246.4	6.81	239.6	1.21	8.20	35.2	0.83	296.7	2346	36.2
T4	225.6	7.31	218.3	1.03	8.06	29.9	0.97	248.6	2149	30.9
T5	256.3	6.74	249.5	1.23	8.88	37.0	0.81	337.8	2440	38.0
T6	238.3	6.99	231.3	1.11	8.75	33.1	0.90	298.1	2269	34.1
SEm $\pm$	3.46	–	3.30	0.02	0.16	0.96	0.02	3.61	33.8	1.30
LSD (P=0.05)	10.3	–	9.97	0.07	0.54	2.98	0.07	10.6	97.4	3.92

T1: Farmers' practice (control); T2: 100% RDN through FYM; T3: 100% RDN through mixed compost (MC); T4: 100% RDN through vermicompost (VC); T5: 50% RDN through FYM and 50% RDN through mixed compost (MC)+biofertilizers and T6: 50% RDN through FYM and 50% RDN through vermicompost (VC)+biofertilizers

soil productivity and fosters improvements in the physico-chemical, and biological properties (Lei et al. 2019). The persistent decline in SOC and the disruption of the fragile soil structure in the Himalayan region have raised significant concerns about the viability of agriculture (Bai et al. 2018; Babu et al. 2020b). The implementation of organic nutrient management has been reported to improve soil properties (Lorenz and Lal 2016). Concerning physical characteristics, *pb*, and soil aggregation are of notable significance for soil health, particularly in the vulnerable Himalayan conditions. Soil *pb* assumes a crucial role as the primary physical factor that affects other physical properties, thereby influencing soil fertility and crop growth (Singh et al. 2021b). Crops thrive in soils that are crumbly and well-aggregated with an ideal *pb* that significantly impacts both root growth and nutrient absorption. Long-term adoption of organic nutrient management has been previously reported to favorably alter both *pb* and aggregation characteristics (Li et al. 2015). The primary cause for the reduction in *pb* under organic management arises from the bonding of soil particles through increased organic matter along with enhanced aggregate stability. This, in turn, augments the overall pore space within the soil. In our investigation, the utilization of organic nutrient sources led to a decrease in *pb* within the 0–30 cm soil layer ranging from 3.81% to 6.87% as compared to the control plot. Notably, the application resulted in the most pronounced reduction of *pb* achieving a decrease of 6.87% in the uppermost soil layer. In contrast, the control plot (representing traditional farmers' practice) exhibited a higher *pb* value of 1.31 Mg m $^{-3}$  in the 0–30 cm soil layer. For soil aggregation (SA), the implementation of T5 led to a notable rise in SA (>0.25 mm) by 27.7%, SA (<0.25 mm) by 19.7%, TWSA by 23.1%, and MWD by 18.7% in comparison to the conventional farmers' practices. This could potentially be attributed to the incorporation of appropriate amounts of voluminous MC into the soil which raises soil organic carbon (SOC) levels and enhances aeration. These factors collectively contribute to a decrease in soil *pb* and improved SA (Zhang et al. 2016). Correspondingly, Yu et al. (2015) reported a 4.1% decrease in *pb* at a depth of 0 to 15 cm in a similar agro-ecosystem with a three-year continuous application of organic nutrient sources when compared with control. In alignment with these findings,

**Table 5** Productivity and profitability of *pre-kharif* maize influenced by organic nutrient management practices (Mean data of three years)

Treatment	Green cob yield (Mg ha <sup>-1</sup> )	Green stover yield (Mg ha <sup>-1</sup> )	Biological yield (Mg ha <sup>-1</sup> )	Gross returns (US\$ ha <sup>-1</sup> )	Cost of cultivation (US\$ ha <sup>-1</sup> )	Net returns (US\$ ha <sup>-1</sup> )	B: C ratio	Profitability (US\$ day <sup>-1</sup> )	Production efficiency (kg ha <sup>-1</sup> day <sup>-1</sup> )
T1	6.11	9.32	15.4	2608.7	636.6	1972.1	3.10	18.8	58.2
T2	7.68	10.9	18.6	3268.3	717.9	2550.5	3.55	24.3	73.1
T3	8.21	11.5	19.7	3491.8	830.3	2661.5	3.21	25.3	78.2
T4	7.55	10.5	18.1	3210.1	907.5	2302.6	2.54	21.9	71.9
T5	8.30	12.2	20.5	3537.9	758.5	2779.4	3.66	26.5	79.0
T6	7.76	11.3	19.1	3306.2	799.1	2507.1	3.14	23.9	73.9
SEm±	0.17	0.30	0.42	71.3	–	41.1	0.05	0.40	1.34
LSD (P=0.05)	0.54	0.87	1.23	217.1	–	125.4	0.16	1.21	3.94

T1: Farmers' practice (control); T2: 100% RDN through FYM; T3: 100% RDN through mixed compost (MC); T4: 100% RDN through vermicompost (VC); T5: 50% RDN through FYM and 50% RDN through mixed compost (MC)+ biofertilizers and T6: 50% RDN through FYM and 50% RDN through vermicompost (VC)+ biofertilizers

the present study also affirmed favorable physical properties resulting from organic nutrient management. Organic nutrient sources promote the buildup of soil carbon, enhancing soil porosity and fostering the proliferation of microorganisms and larger organisms thus reducing soil  $\rho_b$  (Saha et al. 2012). Babu et al. (2020b) similarly indicated an inverse relationship between soil organic carbon (SOC) content and soil  $\rho_b$ . Applying organic manures creates conditions that boost earthworm populations, promote the development of a porous network, and encourage root channel activities. These combined effects contribute to the decrease in soil  $\rho_b$  and also positively impact the stability of SA (Singh et al. 2021a).

Soil pH plays a crucial role in determining nutrient availability, and its levels can be influenced by various management approaches (Babu et al. 2023a). Among the chemical attributes of soil, pH, and SOC hold significant importance. Thus, the application of organic nutrients can yield favorable outcomes by promoting the increase of SOC content and facilitating the maintenance of an appropriate pH level. This is particularly beneficial as soil pH directly impacts nutrient availability and overall soil health (Halvorson et al. 2016). In the present study, significant improvement in the soil chemical properties at 0–30 cm depth was obtained due to the application of diverse organic sources of nutrients after the completion of three years of cropping cycles.

Of the various organic nutrient sources, a supply of 50% RDN through FYM and 50% RDN through MC+BFs resulted in a notable enhancement in soil characteristics. Specifically, it led to a substantial improvement in soil pH by 14.7%, SOC by 7.55%, available N by 13.3%, available P by 26.4%, available K by 14.0%, and a ~16.4% increase in micro-nutrient availability over control plot. The organic nutrients' fertilized plots indicated better soil health because organic sources of nutrients help in improving the water regimes, soil structure, and adsorption of nutrients (Jarvan et al. 2014). A similar result was also reported by Adugna et al. (2016). According to Schlegel et al. (2017) plots receiving cattle dung manure on an equivalent nitrogen basis exhibited elevated levels of available soil N, P, and K. In comparison, MC proved to be a more potent supplier of nutrients accessible to plants when compared with other bulky organic manures. Many researchers reported that regions characterized by elevated organic matter content also displayed notably heightened availability of N, P, and K (Tamilselvi et al. 2015; Zhang et al. 2015; Singh et al. 2021b).

The soil's microbiomes and enzymes have a crucial role in maintaining soil equilibrium, facilitating the broader processes of decomposition and mineralization within the soil system (Yadav et al. 2013). These factors contribute to the acceleration of microbial populations and the stabilization

**Table 6** Results depicting the loading of principal component analysis of soil parameters

Principal components		PC 1	PC 2
Initial Eigen values	Total	14.15	3.31
	% of Variance	78.59	18.42
	Cumulative %	78.59	97.01
Rotation Sums of Squared Loadings	Total	78.59	97.01
	% of Variance	13.29	4.17
	Cumulative %	73.84	23.16
Factor loadings			
Eigen vectors <sup>b</sup>		Principal components	
		PC 1	PC 2
BD		-0.329	0.944
POMA		0.975	0.132
POMI		0.978	0.130
TWSA		0.985	0.115
MWD		0.304	0.951
Soil pH		0.851	0.396
SOC		0.221	0.961
Available N		0.972	0.096
Available P		0.981	0.159
Available K		0.960	0.103
Available Fe		0.920	0.372
Available Zn		0.414	0.902
Available Mn		0.905	0.418
SMBC		0.980	0.100
FDA		0.982	0.129
DHA		0.977	0.163
Acid-P		0.975	0.112
Urease		0.973	0.090

Extraction Method: Principal Component Analysis,

Rotation Method: Varimax with Kaiser Normalization

<sup>a</sup>Boldfaced factor loadings are considered highly weighted

<sup>b</sup>Rotation converged in 5 iterations

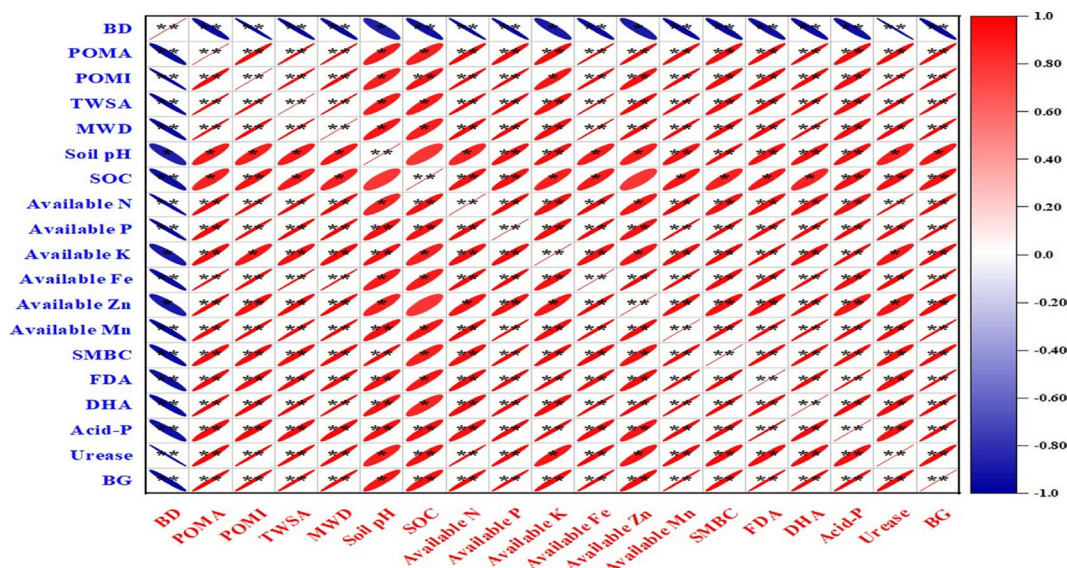
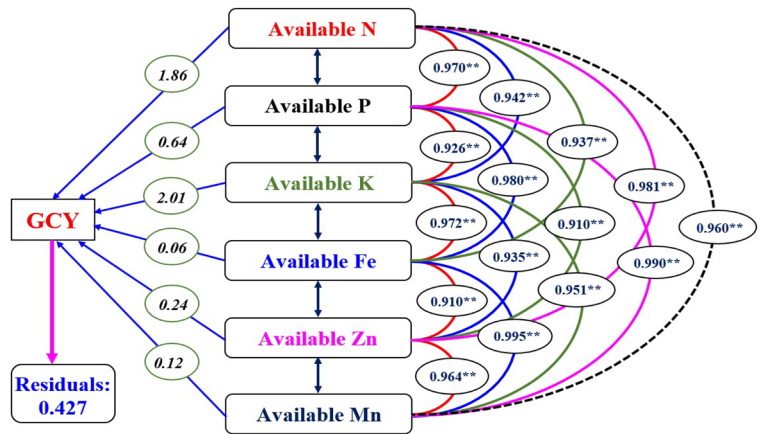
Where, POMA = Percentage of macro aggregates (>0.25 mm); POMI = Percentage of micro aggregates (<0.25 mm); TWSA: Total water stable aggregates; BD = Bulk density ( $\text{Mg m}^{-3}$ ); MWD = Mean weight diameter (mm); SMBC = Soil microbial biomass carbon ( $\mu\text{g g}^{-1}$  soil); FDA: ( $\text{mg kg}^{-1}$  soil  $\text{h}^{-1}$ ); DHA = ( $\mu\text{g TPF g}^{-1}$  soil  $\text{h}^{-1}$ ); Acid-P ( $\mu\text{g PNP g}^{-1}$  soil  $\text{h}^{-1}$ ); Urease ( $\mu\text{g NH}_3\text{-N g}^{-1}$  soil  $\text{h}^{-1}$ );  $\beta$ -glucosidase ( $\mu\text{g PNP g}^{-1}$  soil  $\text{h}^{-1}$ )

of soil structure. Microbial biomass in the soil also functions as an essential agent in transforming vital elements making it a significant biological indicator of soil health (Yang et al. 2019). In contrast to inorganic or chemical inputs, organic farming has

demonstrated its effectiveness in elevating soil enzymic activities (Tal 2018). In the current study, results indicated a notable enhancement in soil biological properties under 50% RDN through FYM and 50% RDN through MC + BFs in comparison to farmers' practices with improvements of 15.81% in SMBC, 24% in FDA, 22.2% in DHA, 8.33% in acid-P, 16.8% in urease, and 20.5% in  $\beta$ -glucosidase. This could be attributed to an increase in SOC content due to the incorporation of organic manures into the soil. SOC serves as a vital food source for soil microbiomes, thereby fostering a larger microbial population and heightened enzymatic activity (Li et al. 2015; Dou et al. 2020; Babu et al. 2020c). Enzymatic processes like soil dehydrogenase and acid phosphatase activity are also closely tied to the abundance of carbon which is generously supplied through organic nutrient inputs (Chen et al. 2015; Babu et al. 2020a; Singh et al. 2021a). Singh et al. (2023) stated that the enhancement of soil biological parameters in organically treated plots could be attributed to the application of substantial organic manure. This accumulation served as an energy source for bacteria contributing to the observed increase in biological activity (Onte et al. 2019). Some other researchers also reported that the introduction of mixed organic manure likely led to heightened microbial biomass carbon and increased enzymatic activity. This combination alongside favorable soil geophysical parameters significantly contributed to the enhancement of soil quality (Paul 2016; Bai et al. 2018).

The PCA exercised on the soil parameters extracted two dominant principal components, PC1 and PC2 accounting for 78.59% and 18.42% variability which explained up to 97.01% of the total variability. The biplot showed that TWSA had very high loadings on PC1 which was closely followed by FDA, available-P, SMBC, and POMI wherein they are found to be diligently correlated to each other and scores (plot) 50% RDN through FYM and 50% RDN through MC + BFs, 100% RDN through MC and 50% RDN through FYM and 50% RDN through VC + BFs were associated with the existing PC1. On the other hand, SOC, MWD, *pb*, and available Zn had a strong loading on PC2 and were highly correlated to each other with associated scores of 100% RDN through VC, 100% RDN through FYM, and control as seen in the biplot. Similar results were also reported by Wang et al. (2022).

**Fig. 4** Path analysis depicting the contribution of soil nutrients to green cob yield of maize. Single-headed arrows and connectors signify the direct effect and mutual association, respectively Where, GCY = Green cob yield



**Fig. 5** Pearson's correlation coefficient (*r*) matrix between soil properties. The correlation coefficient (*r*) values are significantly positive (Red coloured boldfaced italics) and negative (Blue coloured boldfaced italics) at  $p < 0.01$  (2-tailed); the colour assigned to a point in the table grid indicates the strength of a correlation between the soil parameters. The correlation coefficient (*r*) values correspond directly to the color codes from green to yellow and red, respectively. Where,

POMA=Percentage of macro aggregates (>0.25 mm); POMI=Percentage of micro aggregates (<0.25 mm); TWSA: Total water stable aggregates; BD=Bulk density ( $\text{Mg m}^{-3}$ ); MWD=Mean weight diameter (mm);SMBC=Soil microbial biomass carbon ( $\mu\text{g g}^{-1}$  soil); FDA: ( $\text{mg kg}^{-1}$  soil  $\text{h}^{-1}$ ); DHA = ( $\mu\text{g TPF g}^{-1}$  soil  $\text{h}^{-1}$ ); Acid-P ( $\mu\text{g PNP g}^{-1}$  soil  $\text{h}^{-1}$ ); Urease ( $\mu\text{g NH}_3\text{-N g}^{-1}$ soil  $\text{h}^{-1}$ );  $\beta$ -glucosidase ( $\mu\text{g PNP g}^{-1}$ soil  $\text{h}^{-1}$ )

The relationship between green cob yield and overall soil physical, chemical, and biological characteristics indicated a noteworthy positive correlation ( $p < 0.01$  and  $p < 0.05$ ) in most cases, except for a negative correlation with *pb*. The utilization of organic nutrient sources reduced soil *pb* and enhanced various other soil attributes, leading to an eventual increase in green cob yield (Inamullah

et al. 2011; Khan et al. 2018). Path analysis was used to determine the amount to which the predictors contributed to the response variable after assigning soil chemical qualities as predictor (independent) variables and the green cob yield of maize as the response (dependent) variable. The results of path analysis indicated that available K with a higher direct path coefficient (2.01) was the most

relevant feature affecting green cob yield of maize followed by available N which could be because K is involved in plant metabolism, facilitates cellular energy transfer, respiration, and photosynthesis, which eventually influence crop development and yield (Muneeb et al. 2013; Musa and Yusuf 2016; Verma et al. 2024).

### Energy dynamics

To achieve a green economy, improving energy efficiency is a key strategy (Rathore et al. 2022). Energy-based crop productivity, energy output, net energy returns, energy intensiveness, energy productivity, specific energy, energy profitability, energy intensity in economic terms, energy output efficiency, and energy use efficiency are some of the useful indicators for efficient assessment of energy utilization in the organic production system (Houshyar et al. 2015; Basavalingaiah et al. 2020; Kumar et al. 2023a, b). A number of factors determine how much energy is needed and how much can be produced, including inputs used, crops/cultivars, organic sources of nutrients, cropping systems, and practices for the establishment of crops (Harish et al. 2021; Rathore et al. 2022). A system that is energy efficient must be able to produce more economic output per unit of energy used (Yadav et al., 2018). In the current investigation, the utilization of a combination of diverse organic nutrient sources exhibited a marked (statistically significant at  $p < 0.05$ ) influence on various energy-related parameters, including gross return, net return, productivity, intensiveness, profitability, specific energy, intensity, and output efficiency. The total energy input requirement was the highest in the 100% RDN through VC, which was ~47% higher than that of the control. The majority of the energy input for various farm operations came from organic manures. Organic manures and seeds were also identified as significant contributions to energy use (Rathore et al. 2022). Under the organic production system, energy consumption positively correlated with inputs and their associated energy value (Babu et al. 2020c). Total biomass production, including byproducts and main products, determines the energy output of diverse production systems. An energy-efficient system provides a given level of service with less energy input, or it provides a greater number of services with a given energy input. It is calculated as the

amount of energy required per unit output of an activity, which means that a product produced with less energy will have a lower intensity. Our study results showed that 50% RDN through FYM and 50% RDN through MC + BFs resulted in a significant increase of gross energy return, net energy return, energy intensity, and energy output efficiency by ~24 to 26.4% owing to higher green cob, total biomass production and energy input used (Table 3). The increased net energy gain and efficiencies could be attributed to higher yields from the relevant management strategies (Chinyo et al. 2023). Energy productivity indicates the economic benefits received from each unit of energy investment (Yadav et al. 2020). In the present study, energy productivity, energy profitability, and energy use efficiency of the control treatment were ~34.8–39% higher due to the minimum energy input involved (Singh et al. 2019; Yadav et al. 2020). Ghosh et al. (2021) reported that the range of EUE values for maize, rice, and green gram was raised to 1.54–7.76%, 0.95–1.65%, and 3.33–6.5%, respectively where organic manure was supplemented with nitrogen dose. The energy cost associated with a particular treatment is known as its energy intensiveness (Singh et al. 2019). There was a noteworthy variation in energy intensiveness among different treatments. Among the different treatments lowest energy intensiveness was noticed under the control plot. The percent increment of energy intensiveness by 32.2% was noticed under 100% RDN through FYM-applied treatment as compared to the control plot. It might be due to less energy input and costs incurred on the cultivation under this treatment combination. The specific energy of a crop can be calculated as the product of the input energy, the higher the value more efficient the crop or cropping system (Rathore et al. 2022). In the present study, 100% RDN through VC recorded a significant increase in the specific energy by 35% followed by 50% RDN through FYM and 50% RDN through VC + BFs.

### Economic productivity

The productivity of crops within organic farming systems is influenced by key factors including genetic characteristics of the plants, agronomic practices, microclimate, and overall soil health. Maize, being a nutrient-demanding crop, can achieve its full potential only under organic management conditions through

improved nutrient management practices (Beyza 2014; Wailare and Kumar 2017). Utilizing a dual strategy involving organic nutrient sources alongside tailored field management presents substantial possibilities for improving soil fertility, optimizing input utilization, and elevating crop yields. Employing a diverse range of integrated organic nutrient sources rather than depending on a singular source has demonstrated the ability to elevate maize crop productivity and foster soil well-being (Singh et al. 2018). By combining FYM with MC, a notable 23% rise in crop yield was achieved accompanied by enhancements in soil health (Singh et al. 2021a). In the present study, the conjoint use of diverse organic sources of nutrients expresses a significant effect on the yield of the maize. In contrast to the methods employed by farmers, the implementation of 50% RDN through FYM and 50% RDN through MC + BFs resulted in a substantial increase of 26.3% in green cob yield, 23.6% in green stover yield, and 24.8% in biological yield. Possibly stemming from the consistent application of organic nutrient sources, this outcome could be attributed to their positive impact on maintaining prolonged nutrient availability in the soil (Verma et al. 2023). This, in turn, might have stimulated amplified cell differentiation, meristematic cell division, and the movement of essential nutrients within plants. Ultimately, these factors contributed to improving yield attributes and overall crop productivity (Babu et al. 2020c; Singh et al. 2021a). Through the utilization of organic nutrient resources, it is plausible that an increased release of growth hormones occurred. This could have resulted in enhanced pollen grain viability leading to a greater quantity of grains per cob and an augmented weight of corn cobs (Bai et al. 2018; Singh et al. 2021b). Elevated availability of nutrients contributed to the augmentation of green cob yields primarily attributed to taller plants and the accumulation of greater dry matter at various growth stages. This facilitated efficient photosynthetic transfer from source to sink ultimately resulting in increased cob weight and consequently, a higher cob yield (Singh et al. 2020, 2021a). Singh et al. (2017) obtained a comparable outcome demonstrating that the combined utilization of FYM and MC resulted in a noteworthy 7.87% increase in yield as compared to the exclusive application of MC and an even more substantial 20.4% improvement over the sole application of FYM. Patel et al. (2018) reported

that vermicompost helps crops grow more effectively and improves soil aeration, structure, and aggregation. Most of the nutrients, such as  $\text{NO}_3^-$ , phosphates, exchangeable  $\text{Ca}^{++}$ , and soluble potassium are readily available to plants increasing beneficial microbial populations, improving soil water-holding capacity, supplying vitamins, enzymes, and hormones as well as accelerating earthworm population and activity. In comparison to other lower levels of organic nutrients, continuous application of mixed organic manures improved soil fertility status and met the nutrient requirement during peak growth periods of crops (Moasunep et al. 2019; Ghasal et al. 2022). A lower dose of nutrients under the farmers' practices (control treatment) failed to meet the nutrient requirements of the crop leading to lower yields during all the years (Babu et al. 2015; Choudhary et al. 2018).

#### Profitability

Integrated use of organic nutrient sources had a significant ( $p < 0.05$ ) effect on gross return, net return, B: C ratio, profitability, and production efficiency during all the years of experimentation. Among the different treatments, the cost of cultivation (COC) was in the range of 636.6 to 907.5 US\$  $\text{ha}^{-1}$  (three-year mean). The minimum COC (636.6 US\$  $\text{ha}^{-1}$ ) was recorded under the control plot (farmers' practice) because less input was involved whereas the maximum COC (907.5 US\$  $\text{ha}^{-1}$ ) was incurred under 100% RDN through VC. This might be because VC applied plot involved more input costs, labor, and other costs (Avasthe et al. 2020). The significant increase in the gross return by 26.3%, net return by 29%, B: C ratio by 15.3%, profitability by 29.4%, and production efficiency by 26% were obtained under 50% RDN through FYM and 50% RDN through MC + BFs as compared to the farmers' practice. Consequently, the utilization of organic nutrients imparts beneficial impacts on the physical, chemical, and biological attributes of the soil ultimately enhancing economic production (Babu et al. 2020a; Patel and Painkara 2022). Singh et al. (2021a) reported that the B: C ratio was 15.1% and 11.7% higher under 75% recommended dose of N + maize/pea stover and 100% recommended dose of N over farmers' practice, respectively. According to Singh et al. (2018), the application of FYM + VC in comparison to VC or FYM alone resulted in significantly higher net returns



of 17.2% and 36.6%, respectively. A favorable environment for crop growth and yield which ultimately led to a high economic return is provided by organic manures which enhance the soil's physico-chemical properties, and biological qualities and conserve soil moisture (Kalantri et al. 2011; Kumar et al. 2023a, b). King et al. (2020) found that the application of organic manure at 100% RDN through organic sources with biofertilizers proved optimum for higher productivity, profitability, and better soil health. Higher yield and net return have also been noted when FYM is applied to other crops in ecologically similar environments (Choudhary and Kumar 2013; Singh et al. 2023).

## Conclusion

The findings of the study revealed the significance of long-term judicious application of organic sources of nutrients on productivity, profitability, and soil health in the Himalayan region of India. The three-year mean results revealed that fertilization with 50% RDN through FYM+50% RDN through MC+BFs significantly increased the yield of green cob by 26.3%, net return by 29%, B: C ratio by 15.3%, profitability by 29.4% and production efficiency by 26.4% over control. Likewise, augmentation in energy net return by 24% and energy output efficiency by 24.7% was also documented under 50% RDN through FYM+50% RDN through MC+BFs. The relatively lower soil *pb* and significantly ( $p < 0.05$ ) higher TWSA, MWD, SOC, and available nutrients in soil were obtained in soil under 50% RDN through FYM+50% RDN through MC+BFs as compared to the farmers' practice. Similarly, significantly higher microbial activity viz., SMBC, FDA, DHA, acid-P, UA, and  $\beta$ -glucosidase activity in soil was registered under 50% RDN through FYM+50% RDN through MC+BFs over farmers' practice. Thus, the conjoint application of 50% RDN through FYM+50% RDN through MC+BFs is a viable, economical, and best alternative for organic maize production in the Indian Himalayan region or other similar ecoregions.

**Author contributions** Amit Kumar, Raghavendra Singh: Conceptualization, methodology and visualization; investigation; Subhash Babu: visualization, formal analysis, writing original draft preparation; R.K. Avasthe: supervision and project administration; Anup Das, Aastika Pandey, B.A. Gudade,

Ramgopal Devdas, Saurav Saha: writing review and editing Aastika Pandey: writing review and editing. Snajy Singh Rathore and Saurav Saha: prepared all figures.

**Funding** There was no specific funding for this research.

**Data availability** The recorded data was statistically analysed and presented in the manuscript.

## Declarations

**Competing interests** The authors declare no competing interests.

## References

- Adugna GA (2016) Review on the impact of compost on soil properties, water use and crop productivity. *Acad Res J Agric Sci Res* 4:93–104
- Avasthe RK, Babu S, Singh R, Yadav GS, Kumar A (2020) Productivity and profitability assessment of organically grown vegetables embedded in rice-based cropping sequences in Sikkim Himalayas, North East India. *J Environ Biol* 41:111–117
- Babicki S, Arndt D, Marcu A, Liang Y, Grant JR, Maciejewski A, Wishart DS (2016) Heatmapper: web-enabled heat mapping for all. *Nucleic Acids Res* 44(8):147–153. <https://doi.org/10.1093/nar/gkw419>
- Babu S, Singh R, Avasthe RK, Yadav GS, Chettri TK, Phepunadi CD (2015) Effect of organic nitrogen sources on growth, yield, quality, water productivity and economics of rice (*Oryza sativa* L.) under different planting methods in mid hills of Sikkim Himalayas. *Res Crops* 16(3):389–400
- Babu S, Mohapatra KP, Das A, Yadav GS, Lal R, Singh R, Avasthe RK, Das A, Chandra P, Gudade BA, Kumar A (2020a) Soil carbon dynamics in diverse organic land-use systems in North-Eastern Himalayan ecosystem of India. *CATENA* 194:104785. <https://doi.org/10.1016/j.catena.2020.104785>
- Babu S, Mohapatra KP, Das A, Yadav GS, Tahasildar M, Singh R, Panwar AS, Yadav V, Chandra P (2020b) Designing energy efficient, economically sustainable and environmentally safe cropping system for the rainfed maize-fallow land for the Eastern Himalayas. *Sci Total Environ* 722:137874. <https://doi.org/10.1016/j.scitotenv.2020.137874>
- Babu S, Singh R, Avasthe RK, Yadav GS, Das A, Singh VK, Mohapatra KP, Rathore SS, Chandra P, Kumar A (2020c) Impact of land configuration and organic nutrient management on productivity, quality and soil properties under baby corn in Eastern Himalayas. *Sci Rep* 10:16129. <https://doi.org/10.1038/s41598-020-73072-6>
- Babu S, Singh R, Avasthe RK, Yadav GS, Mohapatra KP, Thiru S, Das A, Singh VK, Valente D, Petrosillo I (2020d) Soil carbon dynamics in Indian Himalayan intensified organic rice-based cropping sequences. *Ecol Indic* 114:106292. <https://doi.org/10.1016/j.ecolind.2020.106292>

- Babu S, Singh R, Avasthe RK, Kumar S, Rathore SS, Singh VK, Ansari MA, Valente D, Petrosillo I (2023a) Soil carbon dynamics under organic farming: impact of tillage and cropping diversity. *Ecol Indic*. <https://doi.org/10.1016/j.ecolind.2023.109940>
- Babu S, Das A, Singh R, Mohapatra KP, Kumar S, Rathore SS, Yadav SK, Yadav P, Ansari MA, Panwar AS, Wani OA, Singh M, Ravishankar N, Chandra P, Singh VK (2023b) Designing an energy efficient, economically feasible, and environmentally robust integrated farming system model for sustainable food production in the Indian Himalayas. *Sustain Food Technol* 1(1):126–142. <https://doi.org/10.1039/D2FB00016D>
- Bai Z, Caspari T, Gonzalez MR, Batjes NH, Mäder P, Büemann EK, de Goede R, Brussaard L, Xu M, Ferreira CSS, Reintam E, Fan H, Mihelič R, Glavan M, Tóth Z (2018) Effects of agricultural management practices on soil quality: a review of long-term experiments for Europe and China. *Agric Ecosyst Environ* 265:1–7. <https://doi.org/10.1016/j.agee.2018.05.028>
- Basavalingiah K, Ramesha YM, Paramesh V, Rajanna GA, Jat SL, Misra SD, Gaddi AK, Girisha HC, Yogesh GS, Raveesha S, Roopa TK (2020) Energy budgeting, data envelopment analysis and greenhouse gas emission from rice production system: a case study from puddled transplanted rice and direct-seeded rice system of Karnataka India. *Sustainability* 12(16):6439
- Beyza MR (2014) Outcome of rich farmyard manure and inorganic fertilizers on grain yield and harvest index of hybrid maize (BH-140) at Chiro, eastern Ethiopia. *Afr J Agric* 2(8):194–199
- Bhutia K, Bhutia PT, Pradhan Y, Avasthe RK, Babu S (2016) Organic farming in Sikkim: Traditional system and intensification. In: *Transforming Rural Sikkim: Year-round organic crop production*, Edit. Avasthe, R., Pradhan, Y., Bhutia, K., Jointly published by Sikkim Organic Mission, GOI of Sikkim, Gangtok, Sikkim, India and ICAR Research complex for NEH region, Sikkim center (ICAR-NOFRI), Tadong, Gangtok, Sikkim, pp 1–14
- Boone L, Roldán-Ruiz I, Linden VV, Muylle H, Dewulf J (2019) Environmental sustainability of conventional and organic farming: Accounting for ecosystem services in life cycle assessment. *Sci Total Environ* 695:133841
- Bray RH, Kurtz LT (1945) Determination of total organic and available forms of phosphorus in soils. *Soil Sci* 59:39–45. <https://doi.org/10.1097/00010694-194501000-00006>
- Chen XF, Li ZP, Liu M, Jiang CY, Che YP (2015) Microbial community and functional diversity associated with different aggregate fractions of a paddy soil fertilized with organic manure and/or NPK fertilizer for 20 years. *Int J Soil Sediment Water* 15:292–301
- Chinyo M, Singh R, Gautam M (2023) Conservation-agriculture practices and weed-management effects on productivity, water and energy-use efficiency of rainfed pearl millet *Pennisetum glaucum*. *Indian J Agron* 68(1):110–114. <https://doi.org/10.59797/ija.v68i1.214>
- Chopra SL, Kanwar JS (1991) *Analytical Agricultural Chemistry*. Kalyani Publishers, New Delhi, India, p 488
- Choudhary VK, Kumar PS (2013) Maize production, economics and soil productivity under different organic source of nutrients in eastern Himalayan region India. *Int J Plant Prod* 7(2):167–186
- Choudhary M, Rana KS, Bana RS, Ghasal PC, Choudhary GL, Jakhar P, Verma RK (2017) Energy budgeting and carbon footprint of pearl millet-mustard cropping system under conventional and conservation agriculture in rainfed semi-arid agro-ecosystem. *Energy* 141:1052–1058
- Choudhary M, Panday SC, Meena VS, Singh S, Yadav RP, Mahanta D, Mondal T, Mishra PK, Bisht JK, Pattanayak A (2018) Long-term effects of organic manure and inorganic fertilization on sustainability and chemical soil quality indicators of soybean-wheat cropping system in the Indian mid-Himalayas. *Agric Ecosyst Environ* 257:38–46
- Devasenapathy P, Senthil KG, Shanmugam PM (2009) Energy management in crop production. *Indian J Agron* 54(1):80–90
- Dhillon BS, Sohu VS (2024) Climate change shocks and crop production: The food grain bowl of India. *Indian J Agron* 69(1):1–10. <https://doi.org/10.59797/ija.v69i1.5474>
- Dou S, Shan J, Song X, Cao R, Wu M, Li C, Guan S (2020) Are humic substances soil microbial residues or unique synthesized compound. *Pedosphere* 30(2):159–167. [https://doi.org/10.1016/S10022-0160\(17\)60473-9](https://doi.org/10.1016/S10022-0160(17)60473-9)
- Eivazim F, Tabatabai MA (1988) Glucosidases and galactosidases in soils. *Soil Biol Biochem* 20:601–606. <https://doi.org/10.1016/0038-0717>
- Ghasal PC, Mishra RP, Choudhary J, Dutta D, Bhanu C, Meena AL, Kumar K, Kumar A, Ravisankar N, Panwar AS (2022) Performance of cultural and mechanical practices on weed-control efficiency, productivity and economics of Indian mustard (*Brassica juncea*) under organic production. *Indian J Agron* 67(1):67–72. <https://doi.org/10.59797/ija.v67i1.90>
- Ghosh D, Brahmachari K, Das A, Hassan MM, Mukharjee PK, Sarkar S, Dinda NK, Pramanick B, Moulick D, Mitra S, Hossain A (2021) Assessment of Energy budgeting and its indicator for sustainable nutrient and weed management in a rice-maize-green gram cropping system. *Agronomy* 11(1):166. <https://doi.org/10.3390/agronomy11010166>
- Green BN, Johnson CD, Adams A (2006) Writing narrative literature reviews for peer-reviewed journals: Secrets of the trade. *Chiro Medi* 5:101–117
- Halvorson AD, Stewart CE, Del Grosso SJ (2016) Manure and inorganic nitrogen affect irrigated maize yields and soil properties. *Agron J* 108:519–531
- Harish MN, Choudhary AK, Singh YV, Pooniya V, Das A, Babu S, Dass A, Varatharajan T (2021) Nutrient management practices for improved crop and water productivity, grain quality and energy productivity of promising rice cultivars in eastern Himalayas. *J Environ Biol* 42(2):309–318
- Haynes RJ (1993) Effect of sample pre-treatment on aggregate stability measured by wet sieving or turbimetry on soils of different cropping history. *Soil Sci* 44:261–270
- Houshyar E, Dalgaard T, Tarazkar MH, Jorgensen U (2015) Energy input for tomato production what economy says, and what is good for the environment. *J Clean Prod* 89:99–109
- Inamullah NR, Shah NH, Arif M, Siddiq M, Mian IA (2011) Correlations among grain yield and yield attributes in

- maize hybrids at various nitrogen levels. *Sarhad J Agric* 27(4):531–538
- Jackson ML (1973) *Soil Chemical Analysis*, Prentice Hall of India Private Limited. New Delhi, pp 187
- Jarvan M, Edesi L, Adamson A, Vosa T (2014) Soil microbial communities and dehydrogenase activity depending on farming systems. *Plant Soil Environ* 10:459–463
- Kaiser HF (1960) The application of electronic computers to factor analysis. *Educ Psychol Meas* 20:141–151
- Kalantri S, Ardalon MM, Alikhani HA, Shorafa M (2011) Comparison of compost and vermicompost of yield leaf manure and inorganic fertilizer on yield of corn. *Commun Soil Sci Plant Anal* 42:123–131
- Khan AS, Ullah H, Shahwar D, Fahad S, Khan N, Yasi M, Wahid F, Adnan M, Noor M (2018) Heritability and correlation analysis of morphological and yield traits in Maize. *J Plant Bio Crop Res* 2:1–8
- Khomtchouk BB, Van Booven DJ, Wahlestedt C (2014) Heatmap Generator: high performance RNAseq and microarray visualization software suite to examine differential gene expression levels using an R and C++ hybrid computational pipeline. *Source Code Biol Med* 9:30. <https://doi.org/10.1186/s13029-014-0030-2>
- King AE, Congreves KA, Deen B, Dunfield KE, Simpson MJ, Voroney RP, Wagner-Riddle C (2020) Crop rotations differ in soil carbon stabilization efficiency, but the response to quality of structural plant inputs is ambiguous. *Plant Soil*. <https://doi.org/10.1007/s11104-020-04728-5>
- Klein DA, Loh TC, Goulding RLA (1971) Rapid procedure to evaluate dehydrogenase activity of soils low in organic matter. *Soil Biol Biochem* 3:385–387
- Kumar A, Avasthe RK, Singh R, Babu S, Das SK, Ravisanakar N, Panwar AS, Qureshi AA, Laha RG, Mishra VK, Bhupenchandra I, Prasad SK (2023a) Productivity and profitability of maize (*Zea mays*) cultivars under organic management condition in mid hills of Sikkim. *Indian J Agron* 68(1):21–25. <https://doi.org/10.59797/ija.v68i1.198>
- Kumar J, Singh B, Yadav DB, Yadav A, Yadav PK, Nibhoria A (2023b) Energy consumption and its indices under different tillage methods in mungbean (*Vigna radiata*)–wheat (*Triticum aestivum*) system in semi-arid conditions of Haryana. *Indian J Agron* 68(3):273–278. <https://doi.org/10.59797/ija.v68i3.2806>
- Lei XM, Wang F, Zhou BQ, Yang WH, Nie SA, Xing SH (2019) Effects of long-term fertilization on soil soluble organic nitrogen and free amino acid profile variations in paddy fields. *J Agro Envir Sci* 7:1550–1559 (**in Chinese**)
- Li J, Cooper JM, Lin ZA, Li YT, Yang XD, Zhao BQ (2015) Soil microbial community structure and function are significantly affected by long-term organic and mineral fertilization regimes in the North China Plain. *Appl Soil Ecol* 96:75–87
- Lindsay WL, Norwell WA (1978) Development of DTPA of soil test for Zn, Fe, Mn and Cu. *Soil Sci Soc Am J* 42:421–428
- Lorenz K, Lal R (2016) Environmental impact of organic agriculture. *Adv Agron* 139:99–152. <https://doi.org/10.1016/bs.agron.2016.05.003>
- Manjappa K (2023) Organic farming practices in rainfed lowland rice in hill zone of Karnataka India. *Indian J Agron* 68(4):343–350. <https://doi.org/10.59797/ija.v68i4.5452>
- Masmoudi S, Magdich S, Rigane H, Medhioub K, Rebai A, Ammar E (2018) Effects of compost and manure application rate on the soil physico-chemical layers properties and plant productivity. *Waste Bio Valor* 11:1883–1894
- Mittal JP, Dhawan KC (1988) *Research manual on energy requirements in agricultural sector*. New Delhi: ICAR, pp 150
- Moasunep JK, Choudhary N, Khumdemo E (2019) Study on maize-sesamum cropping system as influenced by weed and organic nutrient management on yield and soil health under rainfed condition of North East India. *Int J Curr Microbiol Appl Sci* 8(9):398–414. <https://doi.org/10.20546/ijcmas.2019.809.049>
- Mulyati, Baharuddin AB, Tejowulan RS (2021) Improving Maize (*Zea mays* L.) growth and yield by the application of inorganic and organic fertilizers plus. *IOP Conf Series: Environ Earth Sci* 712:012027. <https://doi.org/10.1088/1755-1315/712/1/012027>
- Muneeb M, Muhammad S, Ghazanfar H, Muhammad Y (2013) Correlation and path analysis of grain yield components in exotic maize (*Zea mays* L.) Hybrids. *Inter J Sci Basic Appl Res* 12(1):22–27
- Musa UT, Yusuf MJ (2016) Correlation and path coefficient analysis of maize (*Zea mays* L.) grain yield and yield characters in Anyigba Kogi State. *J Global Agric Eco* 4(4):210–214
- Nallagatla VK, Patil MB (2024) Effect of different organic amendments on phosphorus dynamics of blackgram (*Vigna mungo*). *Indian J Agron* 69(1):108–111. <https://doi.org/10.59797/ija.v69i1.5493>
- Onte S, Singh M, Kumar S, Pyat PS (2019) Impact of organic nutrient management on crop quality, yield and soil health: a Review. *Int J Curr Microbiol Appl Sci* 8:394–402
- Patel A, Painkara SK (2022) Economics and fertility status of organic and inorganic fertilizer-applied soil in sweet corn (*Zea mays*) cultivation. *Indian J Agron* 67(4):442–446. <https://doi.org/10.59797/ija.v67i4.153>
- Patel BD, Chaudhari DD, Patel HK, Mishra A, Patel VJ, Parmar DJ (2018) Effect of organic manures and weed management practices on weeds, yield and soil microbial properties in fennel. *Crop Res* 53(5 & 6):247–251
- Paul EA (2016) The nature and dynamics of soil organic matter: plant inputs, microbial transformations, and organic matter stabilization. *Soil Biol Biochem* 98:109–126
- Piper C (1950) *Soil and Plant Analysis*. International Public Inc., New York
- Ponisio LC, M'Gonigle LK, Mace KC, Palomino J, de Valpine P, Kremen C (2015) Diversification practices reduce organic to conventional yield gap. *Proc R Soc b: Biol Sci* 282:20141396
- Rathore SS, Subhash B, Shekhawat K, Singh R, Yadav SK, Singh VK, Singh C (2022) Designing energy cum carbon-efficient environmentally clean production system for achieving green economy in agriculture. *Sustain Energy Technol Assess*. <https://doi.org/10.1016/j.seta.2022.102190>
- Röös E, Mie A, Wivstad M, Salomon E, Johansson B, Gunnarsson S, Wallenbeck A, Hoffmann R, Nilsson U, Sundberg C, Watson CA (2018) Risks and opportunities of increasing yields in organic farming. a review. *Agron Sustain Dev* 38(14). <https://doi.org/10.1007/s13593-018-0489-3>

- Saha R, Chaudhary RS, Somasundaram J (2012) Soil health management under hill agroecosystem of North East India. *Appl Environ Soil Sci* 9:2012
- Schlegel AJ, Assefa Y, Bond HD, Haag LA, Stone LR (2017) Changes in soil nutrients after 10 years of cattle manure and swine effluent application. *Soil Tillage Res* 172:48–58
- Singh L, Kumar S, Singh K, Singh D (2017) Effect of integrated nutrient management on growth and yield attributes of maize under winter season (*Zea mays* L.). *J Pharmacogn Phytochem* 6(5):1625–1628
- Singh R, Babu S, Avasthe RK, Yadav GS, Chettri TK, Singh A (2018) Effect of organic mulches and vermicompost on productivity, profitability and energetic of mustard (*Brassica campestris*) in popcorn (*Zea mays everta*) - mustard cropping system in rainfed Sikkim Himalaya. *Indian J Agric Sci* 88(11):1735–1739
- Singh P, Singh G, Sodhi GPS (2019) Energy auditing and optimization approach for improving energy efficiency of rice cultivation in south-western Punjab, India. *Energy* 174:269–279
- Singh A, Pandey AK, Singh U (2020) Physical characteristics of soil as influenced by integrated organic nutrient management practices- a review. *Int Res J Pure Appl Chem* 21:48–53
- Singh R, Babu S, Avasthe RK, Yadav GS, Das A, Mohapatra KP, Kumar A, Singh VK, Chandra P (2021a) Crop productivity, soil health, and energy dynamics of Indian Himalayan intensified organic maize-based systems. *Int Soil Water Conserv Res* 9(2):260–270
- Singh R, Babu S, Avasthe RK, Meena RS, Yadav GS, Das A, Mohapatra KP, Rathore SS, Kumar A, Singh C (2021b) Conservation tillage and organic nutrients management improve soil properties, productivity, and economics of a maize-vegetable pea system in the Eastern Himalayas. *Land Degrad Dev* 1–18. <https://doi.org/10.1002/ldr.4066>
- Singh R, Kumar A, Babu S, Avasthe R, Das A, Rathore SS, Kumar S, Singh C, Sharma V, Bhupenchandra I (2023) Development of organic nutrients management system for profitable and soil-supportive French bean (*Phaseolus vulgaris* L.) farming in North Eastern Himalayas India. *Fronti Sustai Food Sys* 7:1115521. <https://doi.org/10.3389/fsufs.2023.1115521>
- Subbiah BV, Asija GL (1956) A rapid procedure for estimation of available nitrogen in soils. *Current Sci* 25:259–260
- Tabatabai MA (1994) Soil enzymes. In: Weaver RW, Angel JS, Bottomley PS (eds) *Methods of soil analysis, part 2. Microbiological and biochemical properties*. Soil Science Society Am Book Series no 5, SSSA, Madison, WI, pp 775–833
- Tal A (2018) Making conventional agriculture environmentally friendly: moving beyond the glorification of organic agriculture and the demonization of conventional agriculture. *Sustainability* 10(4):1078. <https://doi.org/10.3390/su10041078>
- Tamilselvi SM, Chinnaduraim C, Ilamurugu K, Arulmozhiselvan K, Balachandar D (2015) Effect of long-term nutrient managements on biological and biochemical properties of semi-arid tropical alfisol during maize crop development stages. *Ecol Indic* 48:76–87
- Vance ED, Brookes PC, Jenkinson DS (1987) An extraction method for measuring soil microbial biomass C. *Soil Biol Biochem* 19:703–707
- Verma SK, Kumar S, Pandey AK (2023) Potential organic nutrient management practices for wheat (*Triticum aestivum*) in south-eastern Rajasthan. *Indian J Agron* 68(4):363–367. <https://doi.org/10.59797/ija.v68i4.5454>
- Verma G, Dhaka AK, Singh B, Kumar A, Choudhary AK, Kumar A, Kamboj NK, Hasanain M, Singh S, Bhupenchandra I, Shabnam SP, Kumar S (2024) Productivity, soil health, and carbon management index of soybean-wheat cropping system under double zero-tillage and natural-farming based organic nutrient management in north-Indian plains. *Sci Total Environ* 917:170418. <https://doi.org/10.1016/j.scitotenv.2024.170418>
- Wailare AT, Kumar A (2017) Effect of integrated nutrient management on growth and yield parameters of maize (*Zea mays* L) as well as soil physico-chemical properties. *Biomed J Sci & Tech Res* 1(2):000178. <https://doi.org/10.26717/BJSTR.2017.01.000178>
- Walkley A, Black IA (1934) An examination of the Degtjoret method for determining soil organic matter and a proposal for modification of the chromic acid titration method. *Soil Sci* 37:29–38
- Wang C, Ning P, Li J, Wei X, Ge T, Cui Y, Deng X, Jiang Y, Shen W (2022) Responses of soil microbial community composition and enzyme activities to long-term organic amendments in a continuous tobacco cropping system. *Appl Soil Ecol* 169:104210
- Willer H, Lernoud J (2019) *The world of organic agriculture. statistics and emerging trends 2019* (p. 351p). Bonn: Research Institute of Organic Agriculture (FiBL), Frick, and IFOAM-Organic International
- Wortman SE, Galusha TD, Mason SC, Francis CA (2011) Soil fertility and crop yields in long-term organic and conventional cropping systems in Eastern Nebraska. *Renew Agric Food Syst* 27:200–216
- Yadav SK, Babu S, Singh Y, Yadav MK, Yadav GS, Pal S, Singh R, Singh K (2013) Effect of organic nutrient sources on yield, nutrient uptake and soil biological properties of rice (*Oryza sativa*) based cropping sequence. *Indian J Agron* 58(3):70–75
- Yadav GS, Das A, Lal R, Babu S, Meena RS, Saha P, Singh R, Datta M (2018) Energy budget and carbon footprint in a no-till and mulch-based rice-mustard cropping system. *J Clean Prod* 191:144–157. <https://doi.org/10.1016/j.jclepro.2018.04.173>
- Yadav GS, Babu S, Das A, Bhowmik SN, Datta M, Singh R (2019) Soil carbon dynamics and productivity of rice-rice system under conservation tillage in submerged and unsubmerged ecologies of Eastern Indian Himalaya. *Carbon Manag* 10(1):51–62. <https://doi.org/10.1080/17583004.2018.1545518>
- Yadav A, Babu S, Krishnan P, Kaur B, Bana RS, Chakraborty D, Kumar V, Joshi B, Lal SK (2024) Zinc oxide and ferric oxide nanoparticles combination increase plant growth, yield, and quality of soybean under semiarid region. *Chemosphere*. <https://doi.org/10.1016/j.chemosphere.2024.141432>
- Yadav GS, Babu S, Das A, Mohapatra KP, Singh R, Avasthe RK, Roy S (2020) No-till and mulching enhance energy

- use efficiency and reduce carbon footprint of a direct-seeded upland rice production system. *J Clean Prod.* <https://doi.org/10.1016/j.jclepro.2020.122700>.
- Yadav D, Singh D, Babu Subhash, Madegowda M, Singh DV, Mandal D, Rathore AC, Sharma VK, Singhal V, Kumawat A, Yadav DK, Yadav R K, Kumar S (2023) Intensified cropping reduces soil erosion and improves rainfall partitioning and soil properties in the marginal land of the Indian Himalayas. *Int. Soil Water Conserv Res.* <https://doi.org/10.1016/j.iswcr.2023.10.002>.
- Yang F, Tian J, Fang H, GaoY XuM, Lou Y, Zhou B, Kuzyakov Y (2019) Functional soil organic matter fractions, microbial community, and enzyme activities in a mollisol under 35 years manure and mineral fertilization. *J Soil Sci Plant Nutr* 19:430–439
- Yu HY, Ding WX, Chen ZG, Zhang HJ, Luo JF, Bolan N (2015) Accumulation of organic C components in soil and aggregates. *Sci Rep* 5:13804
- Zhang S, Li H, Yang X, Sun B (2015) Effects of soil management regimes on biochemical properties of a loess soil. *J Soil Sci Plant Nutr* 15:711–725
- Zhang S, Wang R, Yang X, Sun B, Li Q (2016) Soil aggregation and aggregating agents as affected by long term contrasting management of an anthrosol. *Sci Rep* 6(1):39107

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.