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Organic plant nutrients in combination with inorganic sources of nutrients influence the productivity, quality, soil microbes, and nutrient use efficiency of bitter gourd (*Momordica charantia* L.)

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ABSTRACT

Sustainable bitter gourd production requires optimising the combined organic and inorganic nutrient management. Hence, a field experiment was conducted to evaluate the impact of combined organic and inorganic nutrient amendments on bitter gourd productivity, quality, nutrient use efficiency, soil microbial activity, soil health, and profitability. Treatments were T_1: control, T_2: recommended dose of inorganic N-P-K-S-Zn-B at 120-40-85-20-3-2 kg · ha^{-1}, T_3: 5 t · ha^{-1} vermicompost (VC) + 50% of NPKSZnB, T_4: 2.5 t · ha^{-1} poultry manure (PM) + 50% of NPKSZnB, T_5: 5 t · ha^{-1} VC + 75% of NPKSZnB, T_6: 2.5 t · ha^{-1} PM + 75% of NPKSZnB, T_7: 5 t · ha^{-1} cow dung (CD) + 75% of NPKSZnB, T_8: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of NPKSZnB, and T_9: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 25% of NPKSZnB. Integrating 5 t · ha^{-1} VC + 5 t · ha^{-1} CD with 50% of NPKSZnB fertiliser (T_8) significantly boosted the bitter gourd fresh fruit yield (13.1 t · ha^{-1}), a 192% higher over control, with larger fruits, higher fruit count, and greater vine length. Treatment T_8 also excelled in vitamin C (77.6 mg · 100 g^{-1}), β-carotene (122 mcg · 100 g^{-1}), protein (18.1%), moisture content (93.4%), and total soluble solids (4.0°Brix), alongside enhanced nutrient uptake, soil health, robust microbial populations, and economic returns (4552 US$ · ha^{-1}). Treatment T_4 exhibited the highest agronomic and removal efficiencies for key nutrients. Therefore, combined application of 5 t · ha^{-1} VC + 5 t · ha^{-1} CD with 50% of NPKSZnB fertiliser offer a promising approach for sustainable bitter gourd production. This method not only boosts yield and quality but also improves soil health and minimises environmental risks through reducing chemical fertiliser use.

Keywords: bitter gourd, nutrient uptake, profitability, quality, soil health, yield traits

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INTRODUCTION

Global food and nutritional security for a rising population, agricultural intensification, and acceleration have been suggested (Penuelas et al., 2023). The application of inorganic fertilisers usually dissolves quickly in soil water, making the nutrients immediately accessible to plant roots for increasing crop productivity (Serri et al., 2021). But, the excessive use of inorganic fertilisers poses a significant threat to environment and soil health and increases the production cost (Amiri et al., 2021; Serri et al., 2021; Hassan and Hussain, 2018). Conversely, relying solely on organic fertilisers may result in delayed nutrient release, hindered root development, and inadequate bitter gourd production potential (Iqbal et al., 2019). The modern attitude towards agricultural production and ecological balance needs a sustainable approach in all aspects of farming activity including organic and inorganic fertilisation (Najarian and Souri, 2020; Zargar Shooshtari et al., 2020; Ebrahimi et al., 2021). The appropriate integration of organic and inorganic fertilisers in bitter gourd cultivation is crucial for addressing these challenges effectively (Kumar et al., 2017).

Bitter gourd (*Momordica charantia* L.) belongs to the family Cucurbitaceae and is one of the most important and popular vegetables in Southeast Asia, including Bangladesh (El-Khayat et al., 2024). It is cultivated year-round but is predominantly grown during the summer season (Ghimire et al., 2023). Owing to its medicinal and nutritional value, bitter gourd is known to control many diseases such as diabetes and cancer (Hamaiel et al., 2015; Geethu et al., 2018; Bortolotti et al., 2019). In addition to its fruit, roots, leaves, and vines are used in folk medicine for treating tooth pain, diarrhoea, and skin issues such as pimples (Jia et al., 2017). Bitter gourd fruits are a rich source of iron, calcium, phosphorus, and carbohydrates, as well as vitamin C, vitamin A, and vitamin B (Hamaiel et al., 2015; Sangeeta et al., 2018).

Several factors contribute to decrease the bitter gourd yields, with poor farming practices and soil nutrient deficiency being a major obstacle to achieving higher agricultural productivity and quality (Maaz et al., 2021). The optimal application of fertiliser, whether organic or inorganic, significantly influences the productivity, quality, nutrient uptake, and nutrient use efficiency (NUE) of bitter gourd (Saygı, 2022; Ghimire et al., 2023). Organic farming systems enhance nutrient retention in the soil, leading to improved crop production, crop quality, soil health, and NUE (Penuelas et al., 2023). The organic management system involves the application of vermicompost (VC), cow dung (CD), and poultry manure (PM) to the soil, which increases organic matter (SOM), improves the C:N balance, and enhances nutrient absorption by plants. These improvements collectively contribute to enhancing plant growth and yield (Ghimire et al., 2023). Organic fertilisers, particularly VC, contain humic acid, which acts as a growth promoter and provides both macronutrients and micronutrients to plants, resulting in increased crop productivity (Villaver et al., 2019). The addition of PM to soil enhances physical, chemical and biological properties (Singh et al., 2020), promoting crop yields (Zahid et al., 2021). Organic management approaches also stimulate microbial activities in the soil, facilitating the steady release of nutrients (both macronutrients and micronutrients) through mineralisation, thereby increasing yields (Martínez-Alcántara et al., 2016; Thriveni et al., 2017; Ghimire et al., 2023). These integrated organic and inorganic approaches underline the importance of organic farming in improving bitter gourd yield and sustainability in agricultural systems (Ghimire et al., 2023).

A sustainable approach to fertilisation involves integrating organic and inorganic sources to minimise environmental pollution and ensures long-term soil fertility. Organic and inorganic fertilisers play a significant role in increasing the production and improving the nutritional quality of vegetables (Rathod et al., 2018). Integrating these fertilisers helps replenish deficient nutrients in the soil, facilitating optimal crop uptake and maximising yields (Arfan-ul-Haq et al., 2015; Rathod et al., 2018; Ghimire et al., 2023), while ensuring efficient nutrient use without causing environmental harm (Patel et al., 2020). Combining inorganic fertilisers with organic sources, such as VC, CD, and PM, can provide a sustainable solution for increasing productivity, maintaining soil nutrient status, and improving economic viability.

However, research on the combined effects of organic and inorganic fertiliser management on the growth and yield of bitter gourd is limited. Further information is needed to explore cost-effective, ecologically sustainable practices that increase NUE, microbial activity, and both the quality and quantity of bitter gourd produced. The aims of this study were to evaluate the influence of combined organic and inorganic fertilisers on bitter gourd productivity, fruit quality, soil microbial activity, and NUE as well as to identify optimal organic fertiliser types and suitable dosages. Understanding these interactions will provide valuable insights for optimising fertiliser management strategies and promoting sustainable bitter gourd production.

MATERIALS AND METHODS

Location details

The investigation was carried out at the experimental field of the Soil and Water Management Section under the Horticulture Research Centre (HRC), Bangladesh Agricultural Research Institute (BARI), Gazipur. The duration of the investigation was two consecutive seasons: 2020 and 2021. The experimental field is situated at 23°59′N and 90°24′E and 8.4 m above sea level. The area experiences a typical tropical and subtropical continental monsoon climate, characterised by a subhumid climate (Huq and Shoaib, 2013).

Meteorological data, including average minimum and maximum temperatures, humidity, sunshine hours, and rainfall, were recorded throughout the crop growing period at the research location (Table 1).

In 2021, the monthly mean minimum and maximum temperatures were relatively higher than those in 2020. In addition, there was considerably more rainfall in 2021, except for the months of April and May (Table 1).

The soil under investigation is classified as grey terrace soil according to the USDA Soil Taxonomy (USDA, 1975), specifically belonging to the Chhiata soil series within the Madhupur Tract (agroecological zone 28). Initial soil samples for the study were collected from a depth of 0–15 cm, and their physicochemical properties were analysed via standard procedures (Keeney and Nelson 1982) as detailed in Table 2.

Plant material, seedling raising, and experimental land preparation

Healthy seeds of bitter gourd (variety BARI Korola-3) were collected from the Olericulture Division under the Horticulture Research Centre of the Bangladesh Agricultural Research Institute (BARI). The seeds were sown manually into polythene bags (10 cm × 10 cm) filled with fine-textured clay loam soil on April 9, 2020 and April 10, 2021. Watering was then performed immediately after sowing. The emerging seedlings were irrigated twice a week and secured from diseases and insects via the application of Autostin® 50 WDG (carbendazim fungicide powder) fungicide and Sevin® insecticide. During the seedling growth period, the main research plots were prepared methodically via a tractor-driven chisel plough with four passes and were carefully levelled with a tractor-driven rotavator. The weeds and other debris were manually eradicated.

Experimental treatments, layout, and fertiliser application

The treatment plots were manually prepared with a size of 1.8 m × 2 m. The investigation was scheduled with nine treatments: T_1: control (no use of fertiliser), T_2: recommended dose of inorganic N-P-K-S-Zn-B at 120-40-85-20-3-2 kg · ha^{-1} (Ahmmed et al., 2018), T_3: 5 t · ha^{-1} VC + 50% of NPKSZnB, T_4: 2.5 t · ha^{-1} PM + 50% of NPKSZnB, T_5: 5 t · ha^{-1} VC + 75% of NPKSZnB, T_6: 2.5 t · ha^{-1} PM + 75% of NPKSZnB, T_7: 5 t · ha^{-1} CD + 75% of NPKSZnB, T_8: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of NPKSZnB, and T_9: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 25% of NPKSZnB. Detailed descriptions of the test treatments are presented in Table 3.

The VC, PM, and CD used in the experiment was obtained from a local businessperson in the Gazipur district of Bangladesh. The elemental nutrient compositions of VC, PM, and CD were determined using standard methods (Page et al., 1982), and the results are presented in Table 4. VC and PM outperformed CD in terms of key nutrients. VC, with its N-P-K-S-Zn-B composition of 12.0-12.4-9.9-5.0-0.17-0.14 g · kg^{-1}, and PM, at 12.6-10.0-9.0-3.4-0.19-0.12 g · kg^{-1}, demonstrated higher levels of essential elements compared to CD's 11.0-4.5-4.8-2.9-0.18-0.17 g · kg^{-1} (Table 4). The treatments used in this study were replicated three times via a randomised complete block design. The plots were spaced 1 m apart, and the replications were also separated by 1 m. The sources of nitrogen (N), phosphorus (P), potassium (K), sulphur (S), zinc (Z), and boron (B) were organic manures, such as VC, PM, and CD, and inorganic fertilisers, such as urea (46% N), triple superphosphate (20% P, 1.3% S), muriate of potash (50% K), gypsum (18% S and 20% Ca), zinc sulphate monohydrate (36% Zn and 18% S), and boric acid (17% B). Half (50%) of the organic manure was applied per treatment during plot preparation. During the final pit preparation, the full amounts of triple superphosphate (TSP), gypsum, zinc sulphate monohydrate, boric acid, the remaining 50% of organic combination, and 50% of muriate of potash (MoP) were applied to the pit based on the treatment and mixed thoroughly with the soil manually. Twenty-five-day-old seedlings were transplanted on May 3, 2020 and May 4, 2021 with a spacing of 1.8 m × 1.2 m. Only one seedling was planted into a pit, and irrigation was applied immediately.

Agronomic management

The research field was regularly monitored to ensure the health of the plants. As per routine work, any injured, dead or weak seedlings were replaced with vigorous new seedlings within 10 days. As per treatment, urea fertiliser was applied in three equal instalments. The

Table 1. Monthly mean values of temperature, humidity, sunshine hours, and total rainfall during the experimental period.

Months	Average temperature (°C)				Average humidity (%)		Sunshine (hrs. · day^{-1})		Rainfall (mm)	
	2020		2021		2020	2021	2020	2021	2020	2021
	Min.	Max.	Min.	Max.						
April	21.8	33.0	23.4	36.0	82.5	71.7	6.70	7.67	35.6	36.0
May	24.0	33.2	25.0	34.8	83.2	79.2	4.96	6.31	115	108
June	26.6	33.3	26.2	32.2	85.2	87.1	4.49	4.06	205	390
July	26.6	32.6	27.0	32.0	87.5	87.2	3.56	3.35	310	400
August	26.9	33.4	26.4	34.4	87.1	88.8	4.61	3.40	175	478

Source: Meteorological Station, Gazipur under the Ministry of Defence (near the field study).

Table 2. Physicochemical properties of preliminary soils in the experimental field.

Physical parameters	Unit	Test value
Sand	%	41.26
Silt	%	23.22
Clay	%	35.52
Textural class	–	Clay loam
Particle density	g · cm^{-3}	2.56
Bulk density	g · cm^{-3}	1.41
Porosity	%	44.92
Moisture	%	18.5
Field capacity	%	25.6
Chemical parameters		
pH	–	6.50
EC	dS · m^{-1}	0.61
OM	%	1.33
Ca	(meq. · 100 g^{-1} soil)	4.5
Mg	(meq. · 100 g^{-1} soil)	1.7
K	(meq. · 100 g^{-1} soil)	0.14
Total N	%	0.076
Available P	(µg · g^{-1})	11.9
Available S	(µg · g^{-1})	14.5
Available Zn	(µg · g^{-1})	0.88
Available B	(µg · g^{-1})	0.16

EC, electrical conductivity; OM, organic matter.

Table 3. Elemental form of nutrients attained from the applied inorganic and organic sources.

Treatment	N	P	K	S	Zn	B
	kg · ha^{-1}					
T_1	0	0	0	0	0	0
T_2	120	40	85	20	3	2
T_3	120	82	92	35	2.35	1.70
T_4	91.5	45	65	18.5	1.97	1.30
T_5	150	92	113.2	40	3.10	2.20
T_6	121.5	55	86.2	23.5	2.72	1.80
T_7	145	52.5	87.7	29.5	3.15	2.35
T_8	175	104.5	116	49.5	3.25	2.55
T_9	145	94.5	94.7	44.5	2.50	2.05

first 1/3 instalment was applied via the ring method under moist soil conditions at 15 days after transplanting, and it was mixed carefully into the soil. Half of the MoP and the second 1/3 instalment of urea were top-dressed properly via the ring method at the flower initiation stage. Treatment wise, the remaining 1/3 of the urea was applied through ring method in moist soil conditions at the fruiting stage. Weeding was performed at 25, 45 and 65 days after transplanting. Imitaf® 20 SL insecticide was applied twice at a concentration of 0.5 mL · L^{-1} water during the fruiting stage, with a 10-day interval, to reduce

Table 4. Nutrient composition of the VC, PM, and CD used in the experiment.

Components	Organic sources		
	VC	PM	CD
pH	7.4	7.7	7.5
Organic carbon (g · kg^{-1})	166	109	73
Total N (g · kg^{-1})	12	12.6	11
K (g · kg^{-1})	9.9	9.0	4.8
P (g · kg^{-1})	12.4	10.0	4.5
S (g · kg^{-1})	5.0	3.4	2.9
Zn (g · kg^{-1})	0.17	0.19	0.18
B (g · kg^{-1})	0.14	0.12	0.17

CD, cow dung; PM, poultry manure; VC, vermicompost.

fruit fly and white fly infestations. Pheromone traps have also been employed for insect management. The base of the bitter gourd plants was carefully earthed up. Bamboo poles were used to create horizontal pandals at a height of 1.5 m when the vines started to grow. Bamboo stakes were placed vertically to support the climbing vines and lateral stems of bitter gourd, with horizontal stakes connecting all beds at the top. Strings (kunchi) were used to secure adjoining stakes. However, the vines of the test crop climbed and reached the top according to their respective treatments. Young fruits of bitter gourd were harvested 10 times, starting from the first week of June until the second week of August, in accordance with the treatments conducted in 2020 and 2021.

Irrigation management

The amount of irrigation water used was estimated according to the procedure of Mridha (1993), who used the following equation:

$$d = \frac{FC - MC_i}{100} \times A_S \times D \quad (1)$$

where d = depth of irrigation, mm; FC = field capacity of the soil,%; MC_i = moisture content of the soil at the time of irrigation, %; As = apparent specific gravity of the soil; and D = root zone depth, mm.

The effective rainfall was calculated on a daily basis during the growing period following the procedures adopted by Mridha (1993).

The water productivity index (WPI) was used to measure the effectiveness of the irrigation system in terms of gross bitter gourd fresh fruit yield and the total volume of water applied. The WPI is expressed in the following formula outlined by Kamal et al. (2012):

$$WPI = \frac{Y}{Q} \quad (2)$$

where WPI = the water productivity index, kg · m^{-3}; Y = the yield (kg · ha^{-1}) for the season in the specific area; and Q = the total supply of water, including rainfall per ha for the season in the specific area, m^3 · ha^{-1}.

Data collection

The marketable fresh fruit yield of bitter gourd was calculated on a whole-plot basis and converted into $t \cdot ha^{-1}$; whereas, the dry plant yield was also recorded on a whole-plot basis as $kg \cdot ha^{-1}$. For each treatment, 20 dried fruit samples were weighed and converted into $kg \cdot ha^{-1}$ for dry fruit yield. Vine length was determined by measuring two plants per treatment using a measuring tape after final harvest. The lengths were then averaged. Fruit counts were recorded for each plant at every harvest. Subsequently, five fruits from each treatment were randomly selected. Fruit length was measured using a scale, while diameter was determined using vernier callipers. Individual fruit weights were recorded using a weighing machine. Finally, after the last harvest, mean fruit count per plant, mean fruit length, mean fruit diameter, and mean individual fruit weight were calculated for each treatment. Fresh bitter gourd fruit samples of second harvest (1 kg) were collected from each treatment plot and transported to the laboratory of the Postharvest Technology Section at the Horticulture Research Centre of BARI, where they were preserved in a refrigerator at −30°C for assessment of fruit quality. The total soluble solids (TSSs) content was determined by placing a drop of juice on the prism of a hand refractometer (Atago Ltd., PAL-1, Tokyo, Japan), and the results were expressed in °Brix according to an accepted method (Anonymous 1994). Each sample's juice was extracted from ground bitter gourd fruit. Titratable acidity was determined by diluting a 2 mL aliquot of juice to 10 mL with 8 mL of distilled water and two drops of phenolphthalein, with the pH adjusted to 8.2 via 0.1 N (w/v) NaOH, following the procedure of Ranganna (1986). The vitamin C (ascorbic acid) and β-carotene contents of the bitter gourd were determined according to the procedure of Ranganna (1986). The pH of the juice was measured via a digital pH meter (HANNA Instrument Inc., pH-211; Microprocessor, pH Meter, Italy). The total sugar and reducing sugar contents were determined according to the methods of Ranganna (1986). A fruit texture analyser (GUSS, model GS-25, Western Cape, South Africa) was used to determine fruit firmness in fresh samples, with an 8 mm diameter flat end probe inserted to a depth of 3 mm into the bitter gourd fruit (same position of each sample) at a speed of 5 mm · s. The maximum penetration force was recorded, and it was used as the firmness value. Three samples from each treatment were examined and averaged. The moisture content of the bitter gourd was measured via the following formula:

$$\text{Moisture content}(\%) = \frac{\text{Wet weight} - \text{Dry weight}}{\text{Wet weight}} \times 100 \quad (3)$$

Preparation and isolation of microbes

Soil samples were collected at a depth of 0–15 cm during the flowering stage of bitter gourd via a standard technique. Phosphate-solubilising bacteria (PSB), *Rhizobia*, total bacteria, fungi, and actinomycetes were cultured on different prepared media. The isolation of these microbes was performed following the procedure outlined by Pikovskaya (1948), as described briefly in the published research paper by Quddus et al. (2024a).

Soil sample analysis

Postharvest soil samples were collected from four locations in each treatment at depths ranging from 0 cm to 15 cm. These samples were then transferred to the laboratory and spread on brown paper for air drying. Once dried, the soil samples were ground, passed through a 2 mm sieve and stored in a labelled plastic container for chemical analysis via standard procedures. The physicochemical properties of the initial soil and the chemical properties of the postharvest soils were analysed as follows: the soil texture was determined via the hydrometer method (Keeney and Nelson, 1982), and the pH was measured with a glass electrode pH meter at a soil–water ratio of 1:2.5 (Keeney and Nelson, 1982). The soil moisture content was measured via the gravimetric method, and the field capacity was determined via the gravimetric water content. The particle density was measured via the volumetric flask technique; whereas, the bulk density was determined via the core sampler method (Black, 1965). Soil organic carbon levels were assessed through the wet oxidation procedure (Keeney and Nelson, 1982), and the soil organic matter content was calculated by multiplying the content (%) of organic carbon by the Van Bemmelen factor of 1.73. The electrical conductivity (EC) of the soil was determined with a Groline Direct Soil Conductivity Tester (HANNA Instruments HI98331, Romania). The total N content was estimated via the micro-Kjeldahl process (Keeney and Nelson, 1982). Exchangeable calcium (Ca) and magnesium (Mg) were extracted with a solution of 1 M NH_4OAc following the technique of Gupta (2007). The contents of Ca and Mg in the extract were determined via an atomic absorption spectrophotometer (Varian, Model SpectrAA 55B, Sydney, Australia). The exchangeable K was measured following the 1 N NH_4OAc procedure (Jackson 1973). Available P was assessed according to the methods of Bray and Kurtz (1945). Available S was estimated through turbidity via the $BaCl_2$ method (Fox et al., 1964). Available Zn was assessed via the diethylenetriamine pentaacetic acid (DTPA) technique (Lindsay and Norvell, 1978). The azomethine-H method was used to determine the available B content (Keeney and Nelson, 1982).

Plant sample analysis

The aboveground parts of the bitter gourd plants in each plot were collected for sun drying and then dried in a digital convection oven (Human Lab Instrument Co., model Co150, Seoul, Korea) at 68°C for 48 h. The dried plants were ground to pass through a 1 mm sieve. Fresh samples of bitter gourd from each treatment were washed and sliced into round or triangular shapes for sun

drying and then dried in a digital convection oven. The dried fruits were also ground to pass through a 1 mm sieve. Each sample of dried fruit and plant material was preserved in labelled polythene bags. The ground dry plant and dry fruit samples were digested with a diacid mixture (HNO_3–$HClO_4$: 5:1) according to the procedure of Piper (1964). The N content was measured via the micro-Kjeldahl technique; the P content, via a spectrophotometric procedure; the Ca, Mg and K contents, via an atomic absorption spectrophotometer system; the S content, via a turbidity procedure with $BaCl_2$ via a spectrophotometer; and the B content, via a spectrophotometer following the azomethine-H method. The zinc content in the digest was directly determined via an atomic absorption spectrophotometer (Varian, SpectrAA 55B, Sydney, Australia).

Protein content and nutrient uptake calculations

The protein content in the dry fruit of bitter gourd was measured by multiplying the N content by the constant food factor of 6.25 delineated by Hiller et al. (1948).

The nutrient uptake by dry fruit and dry bitter gourd plants was assessed according to the following formula (Sharma et al., 2012):

$$\text{Nutrient uptake}\left(\text{kg}\cdot\text{ha}^{-1}\right) = \left(\begin{array}{c}\text{Nutrient content}(\%)\\ \times\,\text{Dry fruit/plant yield}\left(\text{kg per ha}\right)\end{array}\right)/100 \quad (4)$$

NUE calculation

The agronomic efficiency (AE; kg dry fruit yield increase kg^{-1} applied nutrient) was measured according to the following formula (Baligar et al., 2001):

$$\text{AE} = \frac{\text{Dry fruit yield}\left(\text{kg}\cdot\text{ha}^{-1}\right)\text{ with applied nutrient} - \text{Dry fruit yield}\left(\text{kg}\cdot\text{ha}^{-1}\right)\text{ without nutrient}}{\text{Rate of applied nutrient}\left(\text{kg}\cdot\text{ha}^{-1}\right)} \quad (5)$$

The physiological efficiency (PE) of nutrients was calculated following the formula of Paul et al. (2014):

$$PE = \frac{Y - Y_0}{U - U_0} \quad (6)$$

where Y is the dry fruit yield receiving fertiliser, Y_0 is the dry fruit yield receiving no fertiliser, U is the total nutrient uptake by plants receiving fertiliser and U_0 is the total nutrient uptake by plants receiving no fertiliser.

The removal efficiency (RE) of nutrient removal/uptake by the harvested portion of the test crop per unit nutrient applied was measured via the following formula:

$$\text{RE} = \frac{\text{Total nutrient removal or uptake}\left(\text{kg}\cdot\text{ha}^{-1}\right)}{\text{Applied nutrient}\left(\text{kg}\cdot\text{ha}^{-1}\right)} \times 100 \quad (7)$$

Cost and return analysis

In the present investigation, the benefit–cost ratio (BCR) was documented for a hectare of land. The treatment wise operational cost of the study was determined on the basis of the cost of worker wages, ploughing and the cost of inputs, including fertiliser, seeds, and pesticides. The fresh fruit yield of bitter gourd was converted into $t \cdot ha^{-1}$. This yield was used to compute the gross return. The rental of land was not measured in this experiment. The gross return of every treatment was computed by multiplying the fresh fruit yield by the current unit price (farm gate) of bitter gourd, such as gross return = fresh fruit yield × unit price of product. The gross margin was calculated by the deduction of the operational (variable) cost from the gross return. The BCR was measured via the following formula:

$$\text{BCR} = \text{GR} \div \text{TVC} \quad (8)$$

where GR = gross return and TVC = total variable cost.

Statistical analysis

The collected data were subjected to two-way analysis of variance (ANOVA) using the Statistix 10 software (www.statistix.com; accessed on January 27, 2025). The mean separation was performed by the least significant difference (LSD) test at a significance level of $p \leq 0.05$ or $p \leq 0.01$ (Statistix-10, 1985).

RESULTS

Growth and yield attributes of bitter gourd

The year of cultivation employed a significant influence on bitter gourd growth and yield attributes. The test crop cultivated in the second year demonstrates significantly enhanced performance across growth and yield traits, as detailed in Table 5. A significant enhancement in bitter gourd growth and yield attributes was observed with the combined application of organic and inorganic fertilisers (Table 5). Significantly, treatment T_8 (5 $t \cdot ha^{-1}$ VC + 5 $t \cdot ha^{-1}$ CD + 50% of NPKSZnB) resulted in the longest vines at 417 cm, while T_1 exhibited the shortest at 239 cm. The same T_8 treatment significantly boosted the number of fruits per plant, reaching 45.1, surpassing all other treatments (Table 5). The combined application of organic and inorganic fertilisers significantly influenced fruit length, diameter, and individual fruit weight (Table 5). Treatment T_8 (5 $t \cdot ha^{-1}$ VC + 5 $t \cdot ha^{-1}$ CD + 50% of NPKSZnB) generated the most impressive results, producing fruits with the longest length (15.2 cm), largest diameter (5.83 cm), and heaviest individual weight (101 g), while the control treatment (T_1) exhibited the least result values in all these parameters (Table 5).

Yields of bitter gourd

The year of cultivation had a significant effect on the dry plant yield of bitter gourd; whereas, the fresh fruit yield and fruit dry matter yield were not statistically different between the 2 years. The yields of bitter gourd responded significantly to the application of various organic and inorganic fertilisers (Figures 1A and 1B).

The combined application of 5 $t \cdot ha^{-1}$ VC + 5 $t \cdot ha^{-1}$ CD along with 50% of the NPKSZnB fertiliser (T_8)

Table 5. Effect of year of cultivation and combined use of organic and inorganic fertilisers on growth and yield attributes of bitter gourd.

Year of cultivation (Y)	Vine length (cm)	No. of fruits · plant^{-1}	Fruit length (cm)	Fruit diameter (cm)	Individual fruit wt. (g)
2020	336 ± 9.34 b	34.6 ± 1.25 b	12.2 ± 0.26 b	4.80 ± 0.07 b	85.1 ± 2.30 b
2021	346 ± 9.18 a	39.7 ± 1.21 a	13.7 ± 0.25 a	5.99 ± 0.06 a	88.0 ± 2.30 a
F-test	*	**	**	**	**
CV (%)	5.00	7.24	5.05	2.56	3.18
LSD (0.05)	9.32	1.49	0.36	0.08	1.52
Treatment (T)					
T_1	239 ± 5.58 e	22.7 ± 1.34 f	10.5 ± 0.37 e	4.82 ± 0.27 e	59.3 ± 0.91 f
T_2	347 ± 7.84 cd	37.1 ± 2.06 de	12.6 ± 0.42 cd	5.23 ± 0.26 c	81.8 ± 1.08 e
T_3	320 ± 5.90 e	35.2 ± 1.79 e	12.2 ± 0.55 d	5.02 ± 0.28 d	83.7 ± 1.11 e
T_4	332 ± 6.59 de	35.6 ± 1.37 e	12.7 ± 0.34 cd	5.30 ± 0.27 c	87.3 ± 0.69 d
T_5	371 ± 7.99 b	41.0 ± 1.33 b	13.8 ± 0.44 b	5.62 ± 0.29 b	95.8 ± 2.19 b
T_6	359 ± 3.97 bc	40.4 ± 1.13 bc	13.3 ± 0.38 bc	5.60 ± 0.27 b	92.4 ± 0.71 c
T_7	355 ± 7.64 bc	39.3 ± 1.14 bc	13.6 ± 3.34 b	5.64 ± 0.27 b	95.8 ± 0.99 b
T_8	417 ± 4.92 a	45.1 ± 1.75 a	15.2 ± 0.37 a	5.83 ± 0.28 a	101 ± 1.37 a
T_9	325 ± 6.84 e	37.4 ± 1.33 c–e	12.8 ± 0.42 cd	5.50 ± 0.27 b	81.3 ± 0.93 e
F-test	**	**	**	**	**
CV (%)	5.00	7.24	5.05	2.56	3.18
LSD (0.05)	19.7	3.15	0.77	0.16	3.22
Interaction (Y × T)	ns	ns	ns	ns	ns

The mean values in a column with a common letter (s) do not differ significantly according to the LSD at the 5% level via the LSD test. The values are the means ± standard errors ($n = 3$).
Note: ns indicates not significant at $p > 0.05$.
*indicates significance at $p \leq 0.05$.
**indicates significance at $p \leq 0.01$ according to ANOVA.
Here, T_1: control, T_2: recommended dose of inorganic N-P-K-S-Zn-B at 120-40-85-20-3-2 kg · ha^{-1}, T_3: 5 t · ha^{-1} VC + 50% of NPKSZnB, T_4: 2.5 t · ha^{-1} PM + 50% of NPKSZnB, T_5: 5 t · ha^{-1} VC + 75% of NPKSZnB, T_6: 2.5 t · ha^{-1} PM + 75% of NPKSZnB, T_7: 5 t · ha^{-1} CD + 75% of NPKSZnB, T_8: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of NPKSZnB, and T_9: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 25% of NPKSZnB.
ANOVA, analysis of variance; CD, cow dung; CV, coefficient of variation; LSD, least significant difference; PM, poultry manure; VC, vermicompost.

resulted in the maximum fresh fruit yield (13.1 t · ha^{-1}) (Figure 1A), fruit dry matter yield (1299 kg · ha^{-1}), and dry plant yield (3909 kg · ha^{-1}) (Figure 1B) of bitter gourd. Treatment T_5 (5 t · ha^{-1} VC + 75% NPKSZnB) showed statistically similar results, with 12.5 t · ha^{-1} fresh fruit, 1255 kg · ha^{-1} fruit dry matter, and 3702 kg · ha^{-1} dry plant yield. The lowest yields of bitter gourd were found in the control treatment (T_1) (Figures 1A and 1B).

WPI

Table 6 shows the seasonal water use and WPI throughout the crop seasons of 2020 and 2021. The overall yield in the second year was significantly greater due to more efficient water management during the vegetative stage of bitter gourd cultivation (Table 6). In the first year, the crop received 12 irrigations; whereas in the second year, 10 irrigations were applied due to higher rainfall incidence. Specifically, during the experimental period in 2020, there was 841 mm of precipitation; whereas in 2021, it increased to 1412 mm (Table 1). The WPI was recorded higher (4.90 kg · m^{-3}) in 2021 than in 2020. In 2021, a higher WPI (4.90 kg · m^{-3}) was obtained with 10 irrigations totalling 269.20 mm of seasonal water use; whereas in 2020, a WPI of 4.14 kg · m^{-3} was achieved with 12 irrigations totalling 311.36 mm of seasonal water use (Table 6).

Quality attributes of bitter gourd

The quality traits of bitter gourd, viz. the TSSs, vitamin C, beta carotene, moisture, fruit firmness, and reducing sugar, total sugar, and protein contents significantly differed due to the combined application of organic and inorganic fertilisers; however, the year of cultivation and their interaction (year × treatment) revealed non-significant effects (Table 7). The highest TSS content (^{0}Brix 4.00) in bitter gourd was found with the application of 5 t · ha^{-1} VC + 5 t · ha^{-1} CD, along with 50% of the NPKSZnB fertiliser (T_8), which was similar to the T_2 (recommended dose of N-P-K-S-Zn-B at 120-40-85-20-3-2 kg · ha^{-1}) treatment. The vitamin C content alternated between 70.9 mg · 100 g^{-1} and 77.6 mg · 100 g^{-1} across the treatments; the increase in the content of vitamin C (77.6 mg · 100 g^{-1}) in T_8 was not statistically different from most of the treatments; whereas, the decrease in

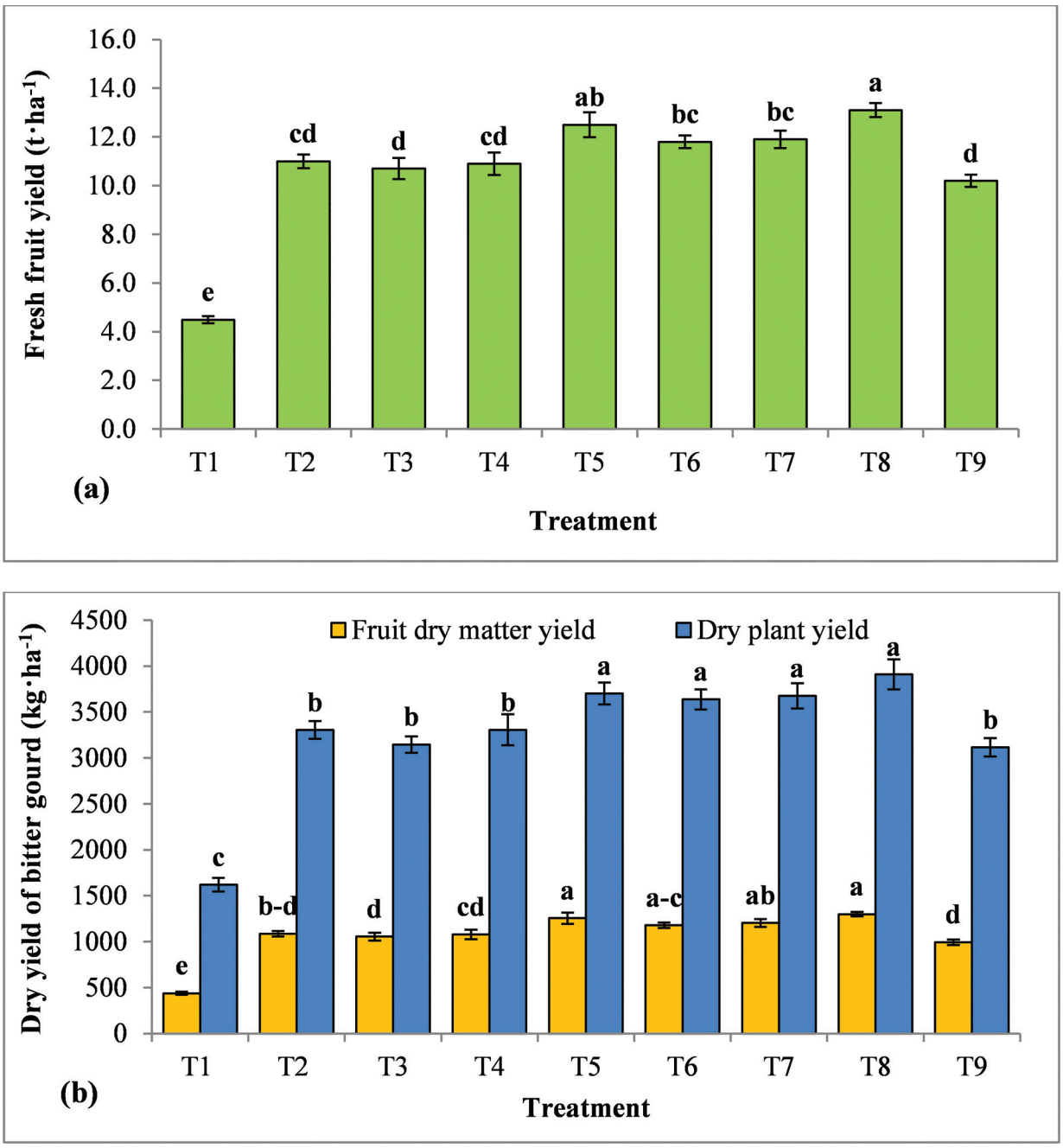


Figure 1. (A) Fresh fruit yield in t · ha^{-1} and (B) fruit dry matter in kg · ha^{-1} and dry plant yield in kg · ha^{-1} of bitter gourd affected by the combined application of organic and inorganic fertilisers. The error bars represent the ± standard error of the mean (n = 3). The mean values indicated by the uncommon letters in the bars are significantly different at the 5% level according to the LSD test. T_1: control, T_2: recommended dose of inorganic N-P-K-S-Zn-B at 120-40-85-20-3-2 kg · ha^{-1}, T_3: 5 t · ha^{-1} VC + 50% of NPKSZnB, T_4: 2.5 t · ha^{-1} PM + 50% of NPKSZnB, T_5: 5 t · ha^{-1} VC + 75% of NPKSZnB, T_6: 2.5 t · ha^{-1} PM + 75% of NPKSZnB, T_7: 5 t · ha^{-1} CD + 75% of NPKSZnB, T_8: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of NPKSZnB, and T_9: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 25% of NPKSZnB. CD, cow dung; LSD, least significant difference; PM, poultry manure; VC, vermicompost.

Table 6. Seasonal water uses and WPI during the 2020 and 2021 crop seasons.

Year of cultivation	Irrigation frequency (no.)	Amount of irrigation water (mm)	Water for plant establishment (mm)	Effective rainfall (mm)	Total seasonal water use (mm)	Fresh fruit yield (t · ha^{-1})	WPI (kg · m^{-3})
2020	12	180	10	121.36	311.36	12.9	4.14
2021	10	140	10	119.20	269.20	13.2	4.90

WPI, water productivity index.

the value of vitamin C was similar to that in the control (T_1) treatment. The highest content of β-carotene (122 mcg · 100 g^{-1}) was associated with the application of 5 t · ha^{-1} VC + 5 t · ha^{-1} CD along with 50% of the NPKSZnB fertiliser (T_8), which was on par with the application of 5 t · ha^{-1} VC with 50% of the NPKSZnB fertiliser (T_5), although a lower content of β-carotene was detected in the control treatment (T_1). The maximum moisture content (93.4%) of bitter gourd was recorded in the T_8 treatment, which was not significantly different from that of most of the other treatments. The fruit firmness of bitter gourd was also highest (2.26 kgf) in T_8, which was comparable with that in most of the treatments; whereas, the firmness was lowest in the control treatment (Table 7). The values of reducing sugars and total sugars were inconsistent among the treatments. The increase in protein content (18.1%) in the T_8 treatment was similar to that in the T_5 treatment; whereas, a decrease in protein content (14.5%) was detected in the control (T_1) treatment (Table 7).

Total uptake of N, P, K, S, Zn, and B by bitter gourd

The cultivation year significantly affected the total uptake of N, P, K, S, Zn, and B by bitter gourd. The highest total uptake of N, P, K, S, Zn, and B was observed in the second year (2021); whereas, the lowest uptake occurred in 2020 (data not shown). All the treatments containing combined organic and inorganic fertilisers had a significant effect on the total nutrient uptake by bitter gourd. The total uptake value of nitrogen (167 kg · ha^{-1}) significantly increased with the application of 5 t · ha^{-1} VC + 5 t · ha^{-1} CD along with 50% of the NPKSZnB fertiliser (T_8), which was statistically similar to the T_5 (5 t · ha^{-1} VC + 75% NPKSZnB fertiliser) treatment; whereas the lowest total uptake value of N was obtained in the control treatment. Compared with the control (T_1), the T_8 treatment led to a significant increase in total P uptake (22.8 kg · ha^{-1}) (Figure 2A).

In this study, the maximum total K uptake (96.5 kg · ha^{-1}) by the test crop was obtained from the T_8 treatment followed by the T_5 treatment, although the minimum total uptake of K was from the T_1 (control) treatment. Similarly, the highest total S uptake by bitter gourd (18.0 kg · ha^{-1}) occurred in the T_8 treatment; whereas, the lowest total S uptake (4.65 kg · ha^{-1}) occurred in the T_1 (control) treatment (Figure 1A). Furthermore, the T_8 treatment resulted in the highest total Zn uptake (0.249 kg · ha^{-1}) and total B uptake (0.191 kg · ha^{-1}) by bitter gourd; whereas, both were lowest in the T_1 (control) treatment (Figure 2B). These results underscore the significant influence of fertilisation strategies on nutrient uptake by bitter gourd, emphasising the effectiveness of organic amendments in combination with reduced inorganic inputs.

The NUE of bitter gourd

The application rates of organic and inorganic fertilisers positively influence the NUE of bitter gourd. Various indicators, such as AE, PE, and RE, were employed to assess NUE. The AE of N, P, K, S, Zn, and B responded significantly to the application of combined organic and inorganic fertilisers to the soil (Table 8).

For N, the AE values ranged from 3.83 kg · kg^{-1} to 6.98 kg · kg^{-1} across the treatments, with the highest AE observed in T_4 (2.5 t · ha^{-1} PM + 50% of the NPKSZnB fertiliser), which was statistically similar to that in the T_6 treatment; whereas, the lowest AE of N was noted in T_9 (Table 8). The highest AE value for P (16.2 kg · kg^{-1}) was achieved in the T_2 treatment, followed by the T_7 and T_4 treatments; whereas, the lowest AE value was observed in the T_9 treatment. Similarly, the highest AE value of K (9.83 kg · kg^{-1}) was found in the T_4 treatment, followed by the T_7 and T_6 treatments, with the lowest AE value in the T_9 treatment (Table 8). In terms of S, the highest AE value (34.5 kg · kg^{-1}) was observed in T_4, which was statistically similar to that in the T_2 and T_6 treatments (Table 8). The maximum AE value of Zn (324 kg · kg^{-1}) was registered in the T_4 treatment, which was statistically identical to that in the T_6 treatment, with the minimum AE value in the T_2 treatment. For B, the AE value was highest (492 kg · kg^{-1}) in T_4, while the lowest AE value was in the T_9 treatment (Table 8).

The PE of P, K, S, Zn, and B in bitter gourd was significantly influenced by the combined management of organic and inorganic fertilisers, except for the PE of N (Table 9).

The PE of N was not significantly different among the treatments having the combination of organic and inorganic fertilisers. In this study, the highest PE of P (68.1 kg · kg^{-1}) in bitter gourd was noted in the T_9 treatment (5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 25% NPKSZnB fertiliser), which was similar to that in the T_3 treatment (5 t · ha^{-1} VC + 50% of the N-P-K-S-Zn-B fertiliser); whereas, the lowest PE of P was listed in the T_8 treatment (5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of the NPKSZnB fertiliser). The PEs of K (16.5 kg · kg^{-1}) and S (94.0 kg · kg^{-1}) in bitter gourd was increased significantly in T_3 (5 t · ha^{-1} VC + 50% of the NPKSZnB fertiliser); whereas, decreases in the PEs of K and S were detected in the T_8 treatment. Greater PEs of Zn (6.29 mg · kg^{-1}) and B (8.25 mg · kg^{-1}) were detected in the T_3 treatment; whereas, both were lower in the T_8 (5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of the NPKSZnB fertiliser) treatment (Table 9). The RE of N, P, K, S, Zn, and B in bitter gourd was significantly influenced by the combined application of organic and inorganic fertilisers (Table 10). The RE of N varied between 78.0% and 135% among the treatments, where the highest RE of N was observed in T_4 (2.5 t · ha^{-1} PM + 50% of the NPKSZnB fertiliser); whereas, the lowest was in the T_9 treatment. A significant increase in the RE of P (44.2%) in bitter gourd was registered in the T_2 (recommended dose of N-P-K-S-Zn-B at 120-40-85-20-3-2 kg · ha^{-1}) treatment; whereas, a decrease in the RE of P was computed in the T_9 treatment. In our study, a significant improvement in the RE of K (107%) and the RE of S (69.7%) in bitter gourd was obtained in the T_4 (2.5 t · ha^{-1} PM + 50% of the NPKSZnB fertiliser) treatment; whereas, a decrease

Table 7. Effects of year of cultivation (Y), combined organic and inorganic fertilisers (T) and their interaction (Y × T) on the quality traits of bitter gourd.

Treatment	TSS (^{0}Brix)	Vitamin C (mg · 100 g^{-1})	β-Carotene (mcg · 100 g^{-1})	Moisture (%)	Fruit firmness (kgf)	Reducing sugar (%)	Total sugar (%)	Protein content (%)
T_1	3.76 ± 0.022 d	70.9 ± 0.73 b	112 ± 1.47 c	90.1 ± 0.37 d	2.02 ± 0.061 b	2.32 ± 0.065 d	15.5 ± 0.25 b	14.5 ± 0.32 c
T_2	3.99 ± 0.002 a	75.2 ± 1.8 1 a	115 ± 1.03 bc	92.3 ± 0.38 a–c	2.16 ± 0.057 ab	2.49 ± 0.015 c	15.8 ± 0.17 b	17.6 ± 0.44 ab
T_3	3.82 ± 0.001 b–d	76.3 ± 1.3 9 a	116 ± 3.32 bc	91.6 ± 0.55 b–d	2.15 ± 0.064 ab	2.54 ± 0.016 bc	16.6 ± 0.09 a	16.5 ± 0.70 ab
T_4	3.50 ± 0.003 e	74.8 ± 0.4 7 a	114 ± 1.54 c	92.3 ± 0.73 a–c	2.16 ± 0.024 ab	2.52 ± 0.052 c	15.5 ± 0.16 b	16.4 ± 1.00 ab
T_5	3.90 ± 0.002 b	76.7 ± 0.53 a	121 ± 1.94 ab	92.7 ± 0.38 ab	2.22 ± 0.075 a	2.59 ± 0.056 bc	16.5 ± 0.17 a	18.0 ± 0.63 a
T_6	3.86 ± 0.003 bc	75.8 ± 0.79 a	117 ± 2.25 a–c	91.3 ± 0.46 b–d	2.23 ± 0.047 a	2.57 ± 0.060 bc	15.7 ± 0.14 b	17.5 ± 0.51 ab
T_7	3.79 ± 0.003 cd	76.1 ± 0.40 a	116 ± 0.611 bc	92.1 ± 0.73 a–c	2.24 ± 0.049 a	2.67 ± 0.022 ab	16.5 ± 0.37 a	17.6 ± 0.37 ab
T_8	4.00 ± 0.090 a	77.6 ± 0.99 a	122 ± 3.88 a	93.4 ± 0.42 a	2.26 ± 0.057 a	2.73 ± 0.081 a	16.5 ± 0.20 a	18.1 ± 0.72 a
T_9	3.77 ± 0.003 cd	75.9 ± 0.74 a	114 ± 1.47 c	91.1 ± 0.37 cd	2.20 ± 0.035 a	2.76 ± 0.057 a	16.6 ± 0.26 a	16.0 ± 0.26 bc
F-test	**	*	*	**	*	**	**	**
CV (%)	2.16	3.57	4.23	1.47	5.92	4.67	3.17	9.05
LSD (0.05)	0.01	3.16	5.77	1.58	0.15	0.14	0.60	1.79
Interaction (Y × T)	ns	ns	ns	ns	ns	ns	ns	ns

The mean values in a column with a common letter (s) do not differ significantly according to the LSD at the 5% level via the LSD test. The values are the means ± standard errors ($n = 3$).
Note: ns indicates not significant at $p > 0.05$.
*indicates significance at $p \leq 0.05$.
**indicates significance at $p \leq 0.01$ according to ANOVA.
Here, T_1: control, T_2: recommended dose of inorganic N-P-K-S-Zn-B at 120-40-85-20-3-2 kg · ha^{-1}, T_3: 5 t · ha^{-1} VC + 50% of NPKSZnB, T_4: 2.5 t · ha^{-1} PM + 50% of NPKSZnB, T_5: 5 t · ha^{-1} VC + 75% of NPKSZnB, T_6: 2.5 t · ha^{-1} PM + 75% of NPKSZnB, T_7: 5 t · ha^{-1} CD + 75% of NPKSZnB, T_8: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of NPKSZnB, and T_9: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 25% of NPKSZnB.
ANOVA, analysis of variance; CD, cow dung; CV, coefficient of variation; LSD, least significant difference; PM, poultry manure; TSS, total soluble solid; VC, vermicompost.

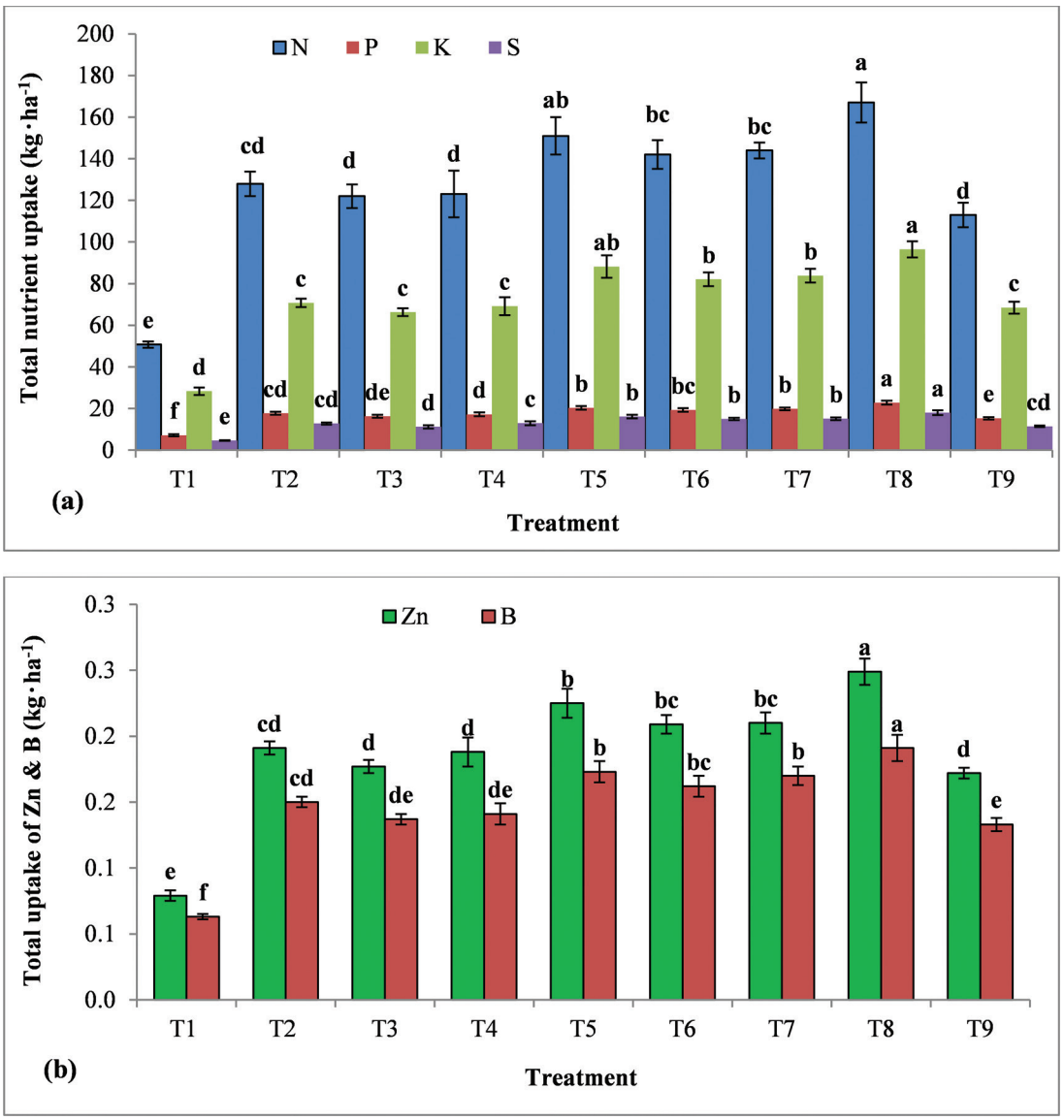


Figure 2. (A) Total uptake of N, P, K, and S by bitter gourd and (B) total uptake of Zn and B by bitter gourd as affected by the combined application of organic and inorganic fertilisers. The error bars represent the ± standard error of the mean (n = 3). The mean values indicated by the uncommon letters in the bars are significantly different at the 5% level according to the LSD test. T_1: control, T_2: recommended dose of inorganic N-P-K-S-Zn-B at 120-40-85-20-3-2 kg · ha^{-1}, T_3: 5 t · ha^{-1} VC + 50% of NPKSZnB, T_4: 2.5 t · ha^{-1} PM + 50% of NPKSZnB, T_5: 5 t · ha^{-1} VC + 75% of NPKSZnB, T_6: 2.5 t · ha^{-1} PM + 75% of NPKSZnB, T_7: 5 t · ha^{-1} CD + 75% of NPKSZnB, T_8: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of NPKSZnB, and T_9: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 25% of NPKSZnB. CD, cow dung; LSD, least significant difference; PM, poultry manure; VC, vermicompost.

in the RE of K and S was observed in the T_9 treatment. The highest RE values of Zn (9.58%) and RE values of B (10.8%) were attained in the T_3 treatment; whereas, the lowest RE value for Zn was in the T_2 treatment, and the lowest RE value for B was found in the T_9 treatment (Table 10).

The microbial population in soil at the flowering stage

Organic and inorganic fertilisation significantly affected PSB, *Rhizobia*, fungi, total bacteria, and actinomycetes in the soil of bitter gourd at the flowering stage (Table 11). The PSB population was significantly greater (100×10^5 cfu · g^{-1} soil) in T_8 than in the other treatments. The highest population of *Rhizobia* (110×10^5 cfu · g^{-1} soil) was obtained in T_8, followed by the T_5 treatment. Similarly, the maximum fungal population (100×10^5 cfu · g^{-1} soil) was recorded in the T_8 and T_4 treatments. The largest population of total bacteria (1900×10^5 cfu · g^{-1} soil) was significantly greater in the T_8 treatment than in the other treatments. The population of actinomycetes was greatest (130×10^5 cfu · g^{-1} soil) in T_8, significantly surpassing those in the other treatments. The minimum populations of PSB, Rhizobia, fungus, total bacteria, and actinomycetes were observed in the control treatment (Table 11).

Table 8. Effects of combined use of organic and inorganic fertilisers on the AE of N-P-K-S-Zn-B in bitter gourd (pooled data from 2 years).

Treatments	N	P	K	S	Zn	B
	AE (kg · kg^{-1})					
T_2	5.40 ± 0.55 bc	16.2 ± 1.64 a	7.63 ± 0.77 bc	32.4 ± 3.30 a	216 ± 21.7 c	324 ± 32.9 cd
T_3	5.14 ± 0.22 bc	7.52 ± 0.32 cd	6.70 ± 0.28 cd	17.6 ± 0.76 cd	262 ± 11.0 bc	363 ± 15.4 bc
T_4	6.98 ± 0.53 a	14.2 ± 1.09 ab	9.83 ± 0.75 a	34.5 ± 2.66 a	324 ± 24.8 a	492 ± 37.8 a
T_5	5.44 ± 0.49 bc	8.87 ± 0.79 c	7.21 ± 0.64 b–d	20.4 ± 1.82 c	263 ± 23.3 bc	371 ± 33.2 bc
T_6	6.09 ± 0.18 ab	13.5 ± 0.40 b	8.58 ± 0.25 ab	31.5 ± 0.92 a	272 ± 8.08 ab	411 ± 12.1 b
T_7	5.27 ± 0.23 bc	14.6 ± 0.63 ab	8.71 ± 0.38 ab	25.9 ± 1.12 b	243 ± 10.6 bc	325 ± 14.1 cd
T_8	4.89 ± 0.19 cd	8.20 ± 0.32 cd	7.38 ± 0.29 b–d	17.3 ± 0.66 cd	264 ± 10.4 bc	336 ± 13.3 b–d
T_9	3.83 ± 0.35 d	5.88 ± 0.53 d	5.87 ± 0.53 d	12.5 ± 1.13 d	222 ± 19.9 bc	271 ± 24.2 d
F-test	**	**	**	**	*	**
CV (%)	12.1	12.7	11.7	12.8	11.8	12.1
LSD (0.05)	1.14	2.47	1.59	5.37	53.4	76.7

Values in a column with a common letter (s) do not differ significantly according to the LSD test at $p \leq 0.05$. The values are the means ± standard errors ($n = 3$).
Note: ns indicates not significant at $p > 0.05$.
*indicates significance at $p \leq 0.05$.
**indicates significance at $p \leq 0.01$ according to ANOVA.
T_1: control, T_2: recommended dose of inorganic N-P-K-S-Zn-B at 120-40-85-20-3-2 kg · ha^{-1}, T_3: 5 t · ha^{-1} VC + 50% of NPKSZnB, T_4: 2.5 t · ha^{-1} PM + 50% of NPKSZnB, T_5: 5 t · ha^{-1} VC + 75% of NPKSZnB, T_6: 2.5 t · ha^{-1} PM + 75% of NPKSZnB, T_7: 5 t · ha^{-1} CD + 75% of NPKSZnB, T_8: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of NPKSZnB, and T_9: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 25% of NPKSZnB.
AE, agronomic efficiency; ANOVA, analysis of variance; CD, cow dung; CV, coefficient of variation; LSD, least significant difference; PM, poultry manure; VC, vermicompost.

Table 9. Effects of combined use of organic and inorganic fertilisers on the PE of N-P-K-S-Zn-B in bitter gourd (pooled data from 2 years).

Treatment	N	P	K	S	Zn	B
	PE					
	kg · kg^{-1}				mg · kg^{-1}	
T_2	8.57 ± 1.41 a	63.0 ± 4.45 a–c	15.2 ± 0.93 a–c	79.6 ± 3.04 bc	5.81 ± 0.10 ab	7.38 ± 0.24 b–d
T_3	8.64 ± 0.37 a	67.2 ± 2.29 ab	16.5 ± 1.92 a	94.0 ± 2.25 a	6.29 ± 0.41 a	8.25 ± 0.22 a
T_4	8.84 ± 0.25 a	63.8 ± 0.63 a–c	15.6 ± 0.23 ab	77.4 ± 3.80 bc	5.84 ± 0.11 ab	8.13 ± 0.30 ab
T_5	8.24 ± 0.39 a	61.7 ± 4.26 bc	13.6 ± 0.31 bc	71.3 ± 1.16 cd	5.59 ± 0.15 bc	7.38 ± 0.29 b–d
T_6	8.28 ± 0.73 a	60.9 ± 1.37 c	13.7 ± 0.22 bc	71.5 ± 1.43 cd	5.69 ± 0.06 b	7.47 ± 0.17 a–c
T_7	8.15 ± 0.10 a	60.6 ± 1.56 cd	13.7 ± 0.27 bc	73.5 ± 1.67 b–d	5.85 ± 0.08 ab	7.09 ± 0.15 cd
T_8	7.55 ± 0.95 a	54.8 ± 1.21 d	12.5 ± 0.29 c	64.1 ± 2.38 d	5.04 ± 0.11 c	6.66 ± 0.24 d
T_9	9.24 ± 1.72 a	68.1 ± 0.64 a	14.0 ± 1.05 a–c	82.8 ± 9.77 b	5.99 ± 0.15 ab	7.80 ± 0.51 a–c
F-test	ns	**	*	**	*	*
CV (%)	13.7	5.40	10.6	7.96	5.50	6.09
LSD (0.05)	2.03	5.91	2.69	10.7	0.56	0.80

The values in a column with a common letter (s) do not differ significantly according to the LSD test at $p \leq 0.05$. The values are the means ± standard errors ($n = 3$).
Note: ns indicates not significant at $p > 0.05$.
*indicates significance at $p \leq 0.05$.
**indicates significance at $p \leq 0.01$ according to ANOVA.
T_1: control, T_2: recommended dose of inorganic N-P-K-S-Zn-B at 120-40-85-20-3-2 kg · ha^{-1}, T_3: 5 t · ha^{-1} VC + 50% of NPKSZnB, T_4: 2.5 t · ha^{-1} PM + 50% of NPKSZnB, T_5: 5 t · ha^{-1} VC + 75% of NPKSZnB, T_6: 2.5 t · ha^{-1} PM + 75% of NPKSZnB, T_7: 5 t · ha^{-1} CD + 75% of NPKSZnB, T_8: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of NPKSZnB, and T_9: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 25% of NPKSZnB.
ANOVA, analysis of variance; CD, cow dung; CV, coefficient of variation; LSD, least significant difference; PE, physiological efficiency; PM, poultry manure; VC, vermicompost.

Table 10. Effects of combined use of organic and inorganic fertilisers on the RE of N-P-K-S-Zn-B by bitter gourd (pooled data from 2 years).

Treatment	N	P	K	S	Zn	B
	RE (%)					
T_2	107 ± 3.21 bc	44.2 ± 2.45 a	83.2 ± 1.15 c	63.8 ± 1.48 b	6.35 ± 0.17 e	7.50 ± 0.18 cd
T_3	102 ± 3.87 bc	19.9 ± 1.07 cd	72.1 ± 0.15 d	32.1 ± 1.50 e	7.56 ± 0.15 bc	8.08 ± 0.22 c
T_4	135 ± 9.38 a	38.3 ± 0.84 b	107 ± 1.59 a	69.7 ± 0.001 a	9.58 ± 0.10 a	10.8 ± 0.04 a
T_5	101 ± 8.39 bc	22.1 ± 1.25 c	78.0 ± 7.11 cd	40.3 ± 2.99 d	7.26 ± 0.47 b–d	7.86 ± 0.43 cd
T_6	117 ± 8.12 ab	35.0 ± 1.58 b	95.2 ± 5.37 b	64.0 ± 3.20 b	7.70 ± 0.37 b	9.00 ± 0.43 b
T_7	99.6 ± 2.88 bc	37.6 ± 0.41 b	95.6 ± 1.93 b	51.1 ± 0.80 c	6.66 ± 0.06 de	7.25 ± 0.02 d
T_8	95.3 ± 5.36 cd	21.8 ± 0.38 c	83.1 ± 1.14 c	36.5 ± 0.52 de	7.68 ± 0.17 b	7.50 ± 0.11 cd
T_9	78.0 ± 3.46 d	16.2 ± 0.03 d	72.3 ± 4.02 d	25.7 ± 1.10 f	6.87 ± 0.05 c–e	6.52 ± 0.04 e
F-test	**	**	**	**	**	**
CV (%)	9.94	7.74	7.02	6.11	5.69	4.81
LSD (0.05)	18.1	3.98	10.5	5.13	0.74	0.68

Values in a column with a common letter (s) do not differ significantly according to the LSD test at $p \leq 0.05$. The values are the means ± standard errors ($n = 3$).
Note: ns indicates not significant at $p > 0.05$.
*indicates significance at $p \leq 0.05$.
**indicates significance at $p \leq 0.01$ according to ANOVA.
T_1: control, T_2: recommended dose of inorganic N-P-K-S-Zn-B at 120-40-85-20-3-2 kg · ha^{-1}, T_3: 5 t · ha^{-1} VC + 50% of NPKSZnB, T_4: 2.5 t · ha^{-1} PM + 50% of NPKSZnB, T_5: 5 t · ha^{-1} VC + 75% of NPKSZnB, T_6: 2.5 t · ha^{-1} PM + 75% of NPKSZnB, T_7: 5 t · ha^{-1} CD + 75% of NPKSZnB, T_8: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of NPKSZnB, and T_9: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 25% of NPKSZnB.
ANOVA, analysis of variance; CD, cow dung; CV, coefficient of variation; LSD, least significant difference; PM, poultry manure; RE, removal efficiency; VC, vermicompost.

Postharvest soil chemical properties affected by the combined application of organic and inorganic fertilisers

The year of cultivation had no significant effect on the chemical properties of the postharvest soil (Table 12). However, the combined application of organic and inorganic fertilisers affected the total N, exchangeable K, and available Zn and B; whereas, the postharvest soil pH, organic matter, and available P and S did not significantly change (Table 12). The results of the experiment revealed a slight increase or decrease in postharvest soil pH across treatments relative to the initial soil pH values. Among the treatments, higher levels of soil organic matter, total N, exchangeable K, and available P, S, Zn, and B were mostly observed in T_8; whereas, lower levels of these properties were observed in the control (no use of fertiliser) treatment (Table 12). A comparison of the chemical properties of the postharvest soil with those of the initial soil revealed that nutrient concentrations were mostly greater in the postharvest soil across all the treatments (Table 12).

Cost and return analysis

The year of cultivation did not affect the gross return, gross margin or BCR of bitter gourd (data not presented). However, the gross return, gross margin and BCR of bitter gourd responded significantly to the combined application of organic and inorganic fertilisers (Figures 3A and 3B).

Output price: Fresh fruits of bitter gourd at US$ 0.35 · kg^{-1}, and **input price:** urea fertiliser = US$ 0.16 · kg^{-1}, triple superphosphate = US$ 0.28 · kg^{-1}, muriate of potash = US$ 0.20 · kg^{-1}, gypsum = US$ 0.17 · kg^{-1}, zinc sulphate (lab grade) = US$ 13.9 · kg^{-1}, boric acid (lab grade) = US$ 12.8 · kg^{-1}, bamboo = US$ 3.49 · piece^{-1}, jute rope = US$ 1.40 · kg^{-1}, wage rate = US$ 6.98 · day^{-1}, tilling (single pass) = US$ 16.3 · ha^{-1}, Bavistin fungicide = US$ 2.33 · 100 g^{-1}, Thiovit 80 (water dispersible granules) = US$ 1.63 · 100 g^{-1}, Ripcord insecticide = US$ 1.51 · 100 mL^{-1}, Karate 2.5 EC = US$ 5.23 · 500 mL^{-1}, VC organic fertiliser = US$ 0.11 · kg^{-1}, poultry manure = US$ 0.10 · kg^{-1}, and cow dung = the gross returns are considered on the basis of the farm gate price (fresh fruit of bitter gourd) of the Gazipur district in Bangladesh. 1 US$ = 86 BDT. BDT is the Bangladesh currency.

The highest gross return (US$ 4552 · ha^{-1}) was computed in the T_8 (5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of the NPKSZnB fertiliser) treatment, followed closely by the T_5 treatment. In contrast, the maximum gross margin (US$ 2295 · ha^{-1}) (Figure 3A) and highest BCR (2.25) were observed in the T_6 treatment (2.5 t · ha^{-1} PM + 75% NPKSZnB fertiliser), which was comparable to those of most of the other treatments, while both were lowest in the control treatment (T_1) (Figures 3A and 3B).

DISCUSSION

Combinations of organic and inorganic nutrient sources provide multidimensional benefits for

Table 11. Populations of PSB, rhizobia, fungi, total bacteria, and actinomycetes in the soil of bitter gourd at the flowering stage as influenced by combined use of organic and inorganic fertilisers (pooled data from 2 years).

Treatments	Population ($\times 10^5$ cfu $\cdot$ g^{-1} soil)				
	PSB	Rhizobia	Fungus	Total bacteria	Actinomycetes
T_1	1.00 ± 0.06 b	1.50 ± 0.12 c	1.00 ± 0.06 b	120 ± 5.77 e	1.10 ± 0.06 c
T_2	2.00 ± 0.12 b	4.00 ± 0.58 c	1.20 ± 0.12 b	1300 ± 57.7 c	2.00 ± 0.17 c
T_3	2.00 ± 0.09 b	2.50 ± 0.12 c	2.00 ± 0.09 b	1400 ± 57.7 c	2.20 ± 0.12 c
T_4	1.00 ± 0.05 b	3.00 ± 0.20 c	100 ± 5.77 a	400 ± 28.9 d	2.50 ± 0.12 c
T_5	4.00 ± 0.58 b	100 ± 5.77 b	1.40 ± 0.12 b	1600 ± 57.7 b	100 ± 5.77 b
T_6	2.00 ± 0.15 b	2.00 ± 0.09 c	2.00 ± 0.12 b	510 ± 5.77 d	2.00 ± 0.12 c
T_7	3.00 ± 0.29 b	2.00 ± 0.04 c	1.50 ± 0.17 b	1400 ± 57.7 c	1.20 ± 0.06 c
T_8	100 ± 8.66 a	110 ± 5.77 a	100 ± 5.77 a	1900 ± 57.7 a	130 ± 5.77 a
T_9	1.00 ± 0.05 b	7.00 ± 0.17 c	2.00 ± 0.06 b	500 ± 28.8 d	2.40 ± 0.06 c
F-test	**	**	**	**	**
CV (%)	38.4	17.3	21.3	7.78	16.3
LSD (0.05)	8.57	7.73	8.66	137	7.63

The mean values in a column with a common letter (s) do not differ significantly according to the LSD at the 5% level via the LSD test. The values are the means ± standard errors ($n = 3$).
Note: ns indicates not significant at $p > 0.05$.
*indicates significance at $p \leq 0.05$.
**indicates significance at $p \leq 0.01$ according to ANOVA.
Here, T_1: control, T_2: recommended dose of inorganic N-P-K-S-Zn-B at 120-40-85-20-3-2 kg $\cdot$ ha^{-1}, T_3: 5 t $\cdot$ ha^{-1} VC + 50% of NPKSZnB, T_4: 2.5 t $\cdot$ ha^{-1} PM + 50% of NPKSZnB, T_5: 5 t $\cdot$ ha^{-1} VC + 75% of NPKSZnB, T_6: 2.5 t $\cdot$ ha^{-1} PM + 75% of NPKSZnB, T_7: 5 t $\cdot$ ha^{-1} CD + 75% of NPKSZnB, T_8: 5 t $\cdot$ ha^{-1} VC + 5 t $\cdot$ ha^{-1} CD + 50% of NPKSZnB, and T_9: 5 t $\cdot$ ha^{-1} VC + 5 t $\cdot$ ha^{-1} CD + 25% of NPKSZnB.
ANOVA, analysis of variance; CD, cow dung; CV, coefficient of variation; LSD, least significant difference; PM, poultry manure; PSB, phosphate-solubilising bacteria; VC, vermicompost.

optimising bitter gourd (*Momordica charantia* L.) cultivation. Bitter gourd, a nutrient-rich vegetable, is a valuable food source for many communities (Nieves-Cordones et al., 2020; Ghimire et al., 2023). Our findings reveal that integrating organic and inorganic fertilisers outperformed the use of solely inorganic fertilisers. This integrated approach significantly enhanced bitter gourd growth, productivity, fruit quality, soil microbial activity, and NUE (Tadesse et al., 2021).

In our study, bitter gourd plants exhibited the longest vine in treatment T_8, which involved the application of 5 t $\cdot$ ha^{-1} VC + 5 t $\cdot$ ha^{-1} CD with 50% of the recommended NPKSZnB fertiliser. VC plus CD manure significantly enhanced plant growth, particularly vine length, by enhancing soil health. This beneficial effect demonstrated in improved soil structure, increased activity of beneficial soil organisms, and efficient nutrient cycling. These findings align with the findings of Ghimire et al. (2023) and Quddus et al. (2024b) in Indian spinach. Similar observation is outlined by Gu et al. (2019) who found that organic fertilisers can improve soil health by influencing microbial activity. These beneficial microbes can even produce substances that boost plant growth like vine length. Our study demonstrates that synergistically combining the immediate nutrient release of inorganic fertilisers with the sustained nourishment provided by organic sources significantly boosts bitter gourd plant growth, a concept supported by the bitter gourd research of Ghimire et al. (2023). Building on these findings might have integrating inorganic fertilisers for immediate nutrient supply with organic sources for long-term soil health and sustained plant vigour, a strategy consistent with the observations of Roba (2018) and Wang et al. (2021).

Our study found that treatment T_8, combining 5 t $\cdot$ ha^{-1} VC + 5 t $\cdot$ ha^{-1} CD with a 50% of the recommended NPKSZnB fertiliser, resulted in the highest number of fruits per plant. While, bitter gourd from this T_8 treatment was exhibited a larger size (fruit length and diameter) of fruit and greater weight. Organic sources, such as VC and CD, when used alongside inorganic fertilisers, significantly boost fruit production. Inorganic fertilisers stimulate growth during both the vegetative and reproductive phases, while organic sources provide a steady supply of essential nutrients, ensuring sustained productivity and larger, heavier fruits as stated by Ebrahimi et al. (2020) and Baghel et al. (2017). Several studies have shown that readily available inorganic nutrients boost plant growth in several ways. These nutrients stimulate the production of plant hormones such as gibberellic acid and IAA (indole-3-acetic acid), which in turn activate enzymes involved in carbon and nitrogen metabolism. This amplified movement enhances the plant's ability to absorb and utilise nutrients, leading to improved growth during both the vegetative and reproductive phases (Baghel et al., 2017; Hasanuzzaman et al., 2018; Quddus et al., 2024b). As a

Table 12. Effects of year of cultivation (Y), combined use of organic and inorganic fertilisers (T) and their interaction (Y × T) on postharvest soil chemical properties associated with the initial soil.

Year of cultivation (Y)	pH	OM (%)	Total N (%)	K	P	S	Zn	B
				meq · 100 g^{-1}			mg · g^{-1}	
Initial status	6.50	1.33	0.076	0.14	11.9	14.5	0.88	0.16
2020	6.51 ± 0.039 a	1.37 ± 0.013 a	0.086 ± 0.001 a	0.134 ± 0.003 a	12.3 ± 0.22 a	15.4 ± 0.25 a	0.927 ± 0.011 a	0.180 ± 0.005 a
2021	6.53 ± 0.039 a	1.39 ± 0.014 a	0.088 ± 0.001 a	0.139 ± 0.004 a	12.4 ± 0.22 a	15.5 ± 0.26 a	0.930 ± 0.011 a	0.182 ± 0.005 a
F-test	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)	3.01	4.28	6.56	11.4	9.61	7.96	3.23	7.08
LSD (0.05)	0.11	0.03	0.003	0.009	0.66	0.68	0.02	0.007
Treatment (T)								
T_1	6.61 ± 0.180 a	1.33 ± 0.050 a	0.075 ± 0.005 b	0.112 ± 0.004 c	11.3 ± 0.37 a	14.2 ± 0.80 a	0.790 ± 0.007 b	0.148 ± 0.004 f
T_2	6.32 ± 0.075 a	1.36 ± 0.015 a	0.087 ± 0.002 a	0.132 ± 0.004 b	12.3 ± 0.37 a	15.2 ± 0.09 a	0.952 ± 0.004 a	0.162 ± 0.007 ef
T_3	6.52 ± 0.040 a	1.36 ± 0.020 a	0.088 ± 0.002 a	0.142 ± 0.007 ab	12.6 ± 0.36 a	15.4 ± 0.37 a	0.942 ± 0.004 a	0.152 ± 0.004 f
T_4	6.41 ± 0.037 a	1.38 ± 0.031 a	0.087 ± 0.001 a	0.143 ± 0.008 ab	12.0 ± 0.34 a	14.9 ± 0.66 a	0.932 ± 0.020 a	0.172 ± 0.004 de
T_5	6.51 ± 0.040 a	1.40 ± 0.030 a	0.089 ± 0.002 a	0.153 ± 0.005 a	12.7 ± 0.37 a	15.7 ± 0.26 a	0.962 ± 0.020 a	0.191 ± 0.004 bc
T_6	6.60 ± 0.037 a	1.39 ± 0.024 a	0.088 ± 0.002 a	0.142 ± 0.004 ab	12.7 ± 0.26 a	15.8 ± 0.37 a	0.952 ± 0.003 a	0.201 ± 0.007 ab
T_7	6.51 ± 0.070 a	1.40 ± 0.030 a	0.090 ± 0.002 a	0.133 ± 0.008 b	12.6 ± 0.58 a	15.6 ± 0.91 a	0.942 ± 0.004 a	0.211 ± 0.004 a
T_8	6.61 ± 0.073 a	1.41 ± 0.035 a	0.091 ± 0.001 a	0.145 ± 0.006 ab	12.7 ± 0.84 a	16.1 ± 0.37 a	0.952 ± 0.020 a	0.211 ± 0.006 a
T_9	6.61 ± 0.009 a	1.40 ± 0.011 a	0.090 ± 0.006 a	0.132 ± 0.004 b	12.1 ± 0.37 a	15.8 ± 0.29 a	0.932 ± 0.007 a	0.182 ± 0.004 cd
F-test	ns	ns	**	**	ns	ns	**	**
CV (%)	3.01	4.28	6.56	11.4	9.61	7.96	3.23	7.08
LSD (0.05)	0.23	0.07	0.007	0.02	1.39	1.44	0.04	0.02
Y × T	ns	ns	ns	ns	ns	ns		

The mean values in a column with a common letter (s) do not differ significantly according to the LSD test at $p \leq 0.05$. The values are the means ± standard errors ($n = 3$).
Note: ns indicates not significant at $p > 0.05$.
*indicates significance at $p \leq 0.05$.
**indicates significance at $p \leq 0.01$ according to ANOVA.
Here, T_1: control, T_2: recommended dose of inorganic N-P-K-S-Zn-B at 120-40-85-20-3-2 kg · ha^{-1}, T_3: 5 t · ha^{-1} VC + 50% of NPKSZnB, T_4: 2.5 t · ha^{-1} PM + 50% of NPKSZnB, T_5: 5 t · ha^{-1} VC + 75% of NPKSZnB, T_6: 2.5 t · ha^{-1} PM + 75% of NPKSZnB, T_7: 5 t · ha^{-1} CD + 75% of NPKSZnB, T_8: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of NPKSZnB, and T_9: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 25% of NPKSZnB.
ANOVA, analysis of variance; CD, cow dung; CV, coefficient of variation; LSD, least significant difference; OM, organic matter; PM, poultry manure; VC, vermicompost.

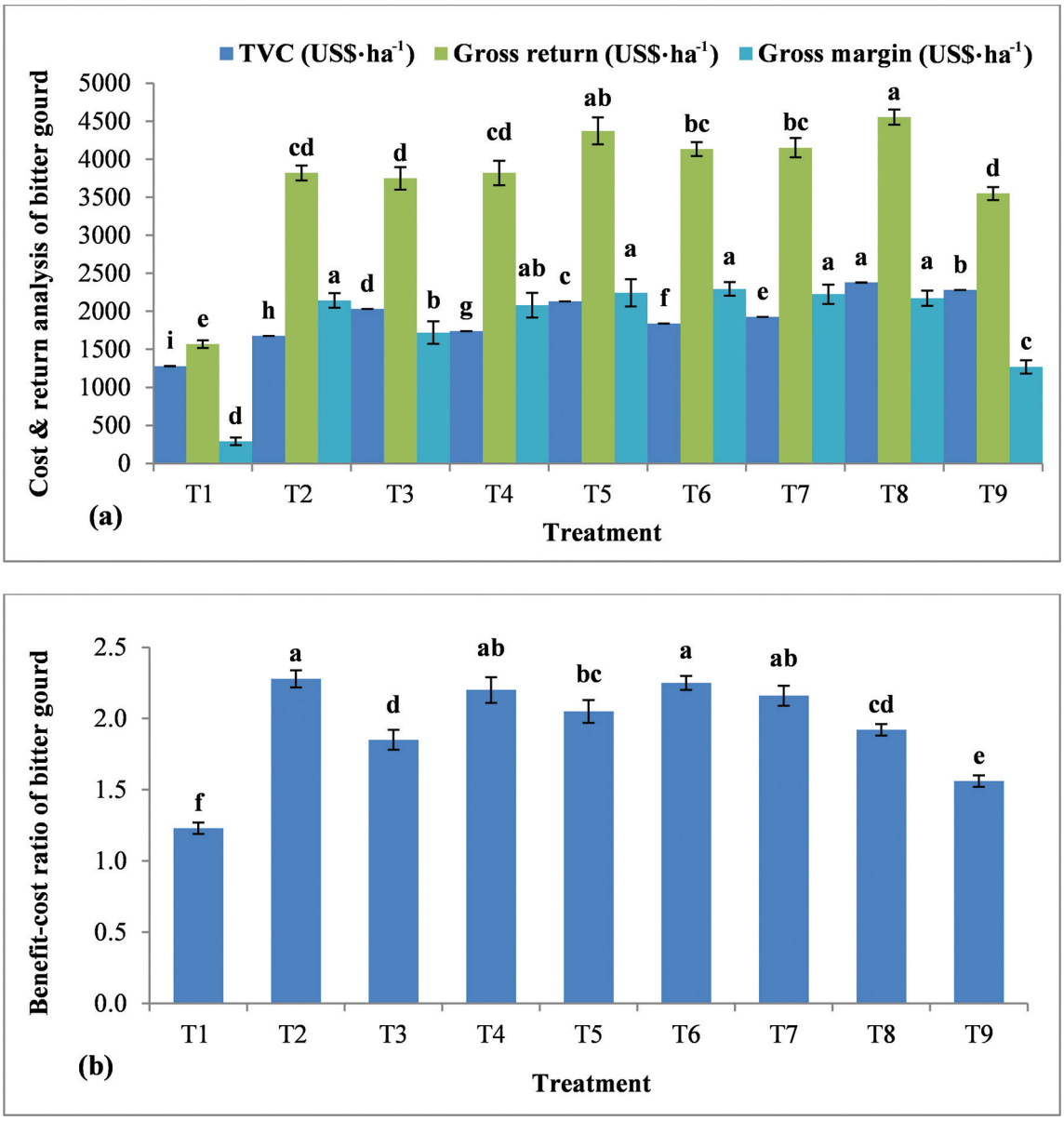


Figure 3. Influence of combined use of organic and inorganic fertiliser practices on the (A) cost, gross return, gross margin, and (B) BCR of bitter gourd. The error bars represent the ± standard error of the mean ($n = 3$). The mean values indicated by the uncommon letters in the bars are significantly different at the 5% level according to the LSD test. T_1: control, T_2: recommended dose of inorganic N-P-K-S-Zn-B at 120-40-85-20-3-2 kg · ha^{-1}, T_3: 5 t · ha^{-1} VC + 50% of NPKSZnB, T_4: 2.5 t · ha^{-1} PM + 50% of NPKSZnB, T_5: 5 t · ha^{-1} VC + 75% of NPKSZnB, T_6: 2.5 t · ha^{-1} PM + 75% of NPKSZnB, T_7: 5 t · ha^{-1} CD + 75% of NPKSZnB, T_8: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 50% of NPKSZnB, and T_9: 5 t · ha^{-1} VC + 5 t · ha^{-1} CD + 25% of NPKSZnB. BCR, benefit–cost ratio; CD, cow dung; LSD, least significant difference; PM, poultry manure; VC, vermicompost.

result, bitter gourd plants produce the more, larger and weightiest fruits. Uranw et al. (2022) and Quddus et al. (2024b) emphasised the broader benefits of organic manures on soil health. These include improving soil pH, providing essential plant nutrients, and fostering a thriving soil fauna, ultimately resulting in increased fruit yield, size, and weight (Urmi et al., 2022).

In this study, we observed that an increase in fresh fruit yield, dry fruit yield, and dry plant yield of bitter was achieved with the application of 5 t · ha^{-1} VC + 5 t · ha^{-1} CD with 50% of the recommended NPKSZnB fertiliser (T_8). This was followed by the application of 5 t · ha^{-1} VC and 75% of the recommended NPKSZnB fertiliser (T_5). The improved fresh fruit yield and dry yield of bitter gourd in the T_8 treatment was associated with increased organic manure solubilisation, which made essential nutrients more readily available improving soil structure and water-holding capacity (Quddus et al., 2024b; Wang et al., 2021). This process promoted physiological activities that increased food reserves, leading to an increase in the number of fruits and increasing fruit size, ultimately increasing yield. The similar assessment

was introduced by Baghel et al. (2017) in their study in bottle gourd. They reported that the availability of plant nutrients from inorganic sources increased the synthesis of photosynthates and the production of growth-promoting substances, viz. gibberellic acid and IAA (indole-3-acetic acid). This resulted in an increase in both the vegetative and reproductive phases of the test crop, ultimately improving productivity. Similar findings were corroborated by Sangeeta et al. (2018) in bitter gourd, where the fresh fruit yield was 192% greater than that of the control and 19.1% greater than the yield from inorganic fertiliser. The increase in yield was attributed to the addition of VC, CD, and 50% of the NPKSZnB fertiliser, which released nutrients into the soil and created favourable conditions for the proliferation of the root zone and nutrient uptake by plants. Akther et al. (2019) reported similar results in Indian spinach, showing that the combined application of organic and inorganic fertilisers contributed 81%–212% greater yield increases than did the control treatment. The dry fruit yield and dry plant yield were greater when 5 t · ha^{-1} VC + 5 t · ha^{-1} CD and 50% of the recommended NPKSZnB fertiliser (T_8) were applied. These findings indicate a direct relationship between fresh fruit yield and improvements in dry fruit and plant yield. Ayuningtias et al. (2023) reported a similar phenomenon in *Basella alba*; whereas, Paithankar and Gore (2019) reported that the integrated use of inorganic and organic fertilisers was more beneficial for yield increases than the sole use of other nutrients. Organic fertiliser, such as VC, can considerably improve soil health and structure, making the supplied nutrients easily available for plant uptake and leading to an increase in crop yield (Wang et al., 2021).

The application of 5 t · ha^{-1} VC + 5 t · ha^{-1} CD and 50% of the recommended NPKSZnB fertiliser (T_8) resulted in higher-quality traits in bitter gourd. Quality traits, such as TSSs, vitamin C, beta carotene, fruit moisture, fruit firmness, and protein content, were also greater in the T_8 treatment. However, the values for reducing sugars and total sugars were inconsistent among the treatments. The use of organic fertiliser helps in the absorption of moisture and nutrients (major and trace elements) in the soil over prolonged periods. This, in turn, improves the physical, chemical and biological properties of the soil, leading to the development of quality characteristics in the crops (Quddus et al., 2024b). Major and trace elements, including carbon, hydrogen, and oxygen, are essential for human health and can be obtained from food systems that utilise both inorganic and organic amendments (Brown et al., 2022). However, the combined application of inorganic and organic sources has better effects on quality traits (Ishfaq et al., 2023). Organic (VC and CD) and inorganic fertiliser application contribute to a better C/N ratio and provide the desired plant nutrients to increase metabolic activities in the plant, triggering increases in vitamin C, beta-carotene, fruit firmness, and protein content in bitter gourd. Inorganic and organic fertilisation might improve the physicochemical properties, microbial diversity, and eco-functionality of the soil, consequently favouring root growth and increasing the availability of nutrients to plant roots (Chauhan et al., 2023; Ishfaq et al., 2023). Similar findings have been reported by several researchers in different crops (Upadhyay et al., 2012; Islam et al., 2020; Sultana et al., 2022).

The uptake and contents of N, P, K, S, Zn, and B in dry fruit and dry plants of bitter gourd were significantly greater when 5 t · ha^{-1} VC + 5 t · ha^{-1} CD and 50% of the recommended NPKSZnB fertiliser (T_8) were applied. Nutrient content data were not presented. The greater acquisition and uptake of all nutrients in bitter gourd under the T_8 treatment might be attributed to the deployment of inorganic fertiliser with organic VC and CD fertiliser. This combination likely facilitates the dynamics of microbial activities in the soil (Rehman et al., 2023; Quddus et al., 2024b), increasing the organic matter content and improving the physical and chemical properties of the soil. As a result, nutrients became more available for plant uptake, leading to increased accumulation and uptake of N, P, K, S, Zn, and B in both the fruits and plants of bitter gourd. Similar findings were reported by Konyak and Sanjay (2018) in cabbage, indicating that the combination of organic manures and inorganic fertiliser contributed to increased uptake of N, P, K, S, Zn, and B nutrients. Corresponding judgements were also detailed for diverse crops by Reza et al. (2016) and Ali and Kashem (2018) for ridge gourd, Chaitanya et al. (2013) for tomato, and Zahid et al. (2021) for cucumber. This study demonstrated enhanced growth, fruit quality, and nutrient uptake of bitter gourd in the second year. This improvement might be associated with the residual effects of organic manures, fostering improved soil health and fertility (Quddus et al., 2024b). Alongside, higher water productivity in the second year further contributed to the observed enhancement in bitter gourd performance.

Fertiliser adjustment and achieving higher NUE are vital issues in agriculture without compromising economic viability. The degree of NUE is affected by the crop yield, crop type, inherent soil fertility, amount of organic and inorganic fertilisers applied, and nature of crop management practices (Jayara et al., 2023). In this study, the combined application of organic and inorganic fertilisers affected the AE of N, P, K, S, Zn, and B in bitter gourd. The higher AE of N, K, S, Zn, and B in bitter gourd were found with the application of 2.5 t · ha^{-1} PM and 50% of the recommended NPKSZnB fertiliser (T_4), except for the AE of P, which was highest in the T_2 (recommended $N_{120}P_{40}K_{85}S_{20}Zn_3B_2$ kg · ha^{-1}) treatment. The higher AE of N, K, S, Zn, and B in T_4 (2.5 t · ha^{-1} PM and 50% of the recommended NPKSZnB fertiliser) may be associated with the application of organic manure (PM), which releases nutrients steadily for efficient uptake of N, K, S, Zn, and B by the plants. However, the AE of P was greater in T_2, indicating that inorganic fertiliser releases P rapidly, which is crucial, as P is relatively immobile in soil, which is consistent with findings in rice by Hoque et al. (2022). Combined organic and inorganic fertiliser management affected the

PEs of P, K, S, Zn, and B in bitter gourd, with higher PEs observed in T_4 (5 t · ha^{-1} VC + 50% of the recommended NPKSZnB fertiliser), except for P, which had the highest PE in T_9. The RE of P, K, S, Zn, and B by bitter gourd was significantly influenced by the combined application of organic and inorganic fertilisers. The changeability in NUE can be attributed to factors such as growing environment, soil type, seasonal changes (Rakshit, 2019), and fertiliser management practices impacting crop yield (Kumar et al., 2015). Similar observations were reported in rice-based cropping systems by Salam et al. (2014). These findings emphasise the critical role of fertilisation strategies in optimising NUE in bitter gourd cultivation, highlighting the probable of specific organic and inorganic fertiliser combinations to enhance nutrient uptake and utilisation by the crop (Baligar et al., 2001).

The microbial populations, viz. PSB, *Rhizobia*, total bacteria, fungi, and actinomycetes, in the soil at the flowering stage of bitter gourd are influenced by the combined application of organic and inorganic fertilisers. All microbial populations were significantly greater when 5 t · ha^{-1} VC + 5 t · ha^{-1} CD was applied along with 50% of the recommended NPKSZnB fertiliser (T_8). The increased isolation of PSB in the rhizospheric soil under the T_8 treatment might be related to the development of physical, chemical and biological soil properties. The combination of VC, CD, and 50% of the recommended NPKSZnB fertiliser contributed significantly to improving those properties, resulting in the highest PSB population in the T_8 treatment (Abderrazak et al., 2017). Significantly, greater populations of *Rhizobia*, fungi, total bacteria, and actinomycetes were also detected in the T_8 treatment. The greater microbial populations likely resulted from the application of VC and CD with 50% of the recommended NPKSZnB fertiliser, which increased the enzymatic activities of microbes. This treatment helps to neutralise soil pH, improve soil aggregate stability, and enhance soil aeration, thereby increasing enzymatic activities and promoting microbial populations, ultimately increasing nutrient cycling and creating a more resilient and productive soil ecosystem (Yang et al., 2012). These phenomena are supported by the findings of several researchers, such as Vieira and Nahas (2005) and Saliha et al. (2021), and are consistent with those of Naher et al. (2013), who noted that balanced fertilisation led to increased populations of PSB, total bacteria, fungi, and actinomycetes.

The combined application of organic and inorganic fertilisers has positive effects on the soil pH; organic matter; total N; exchangeable K; and available P, S, Zn, and B contents. Compared with the initial soil levels, the postharvest soil pH either improved or remained stable across the treatments. Among the treatments, T_8 (5 t · ha^{-1} VC + 5 t · ha^{-1} CD and 50% of the NPKSZnB fertiliser) presented relatively high levels of soil organic matter, total N, S, Zn, and B; whereas, the exchangeable K content increased with the application of 5 t · ha^{-1} VC and 75% NPKSZnB fertiliser (T_5). Several researchers have reported that the combination of VC, cattle manure, and adjusted inorganic fertiliser enhances soil microbial activity, leading to increased organic matter content, total N, and other macronutrient and micronutrient levels in postharvest soil (Warman and AngLopez, 2010; Villaver et al., 2019). The available P had no significant effect. Most of the parameters, including the available P, S, Zn, and B contents, were higher across the treatments than under the initial soil conditions. The improvement in the fertility of postharvest soil can be attributed to the application of organic and inorganic fertilisers. Specifically, VC and cattle dung in agroecosystems help maintain vital microbial biomass and microbial activity in the soil, which contributes to soil structure enhancement, increased organic matter content, balanced pH, and improved nutrient availability, thereby increasing crop yield (Das et al., 2017; Ebrahimi et al., 2020; Senta and Purohit, 2023).

Cost and return analysis is vital for determining the adoption of technologies by growers, as highlighted by Maroušek and Marouškova (2021). The application of 5 t · ha^{-1} VC + 5 t · ha^{-1} CD and 50% of the recommended NPKSZnB fertiliser, followed by 5 t · ha^{-1} VC and 75% of the recommended NPKSZnB fertiliser, led to a substantial increase in gross returns, which were 190% and 179% greater, respectively, than those in the control (T_1) treatment. However, we observed that higher gross margins and BCRs were achieved with the application of 2.5 t · ha^{-1} PM and 75% of the recommended NPKSZnB fertiliser. This variation might be attributed to the lower amount of PM supplied, which was almost 50% less than the quantity of VC and cattle dung.

CONCLUSIONS

The results and discussion in the previous section emphasise that the combined application of organic and inorganic amendments significantly contributes to increasing growth, yield, profitability, quality, nutrient uptake, and effective NUE in bitter gourd while considering sustainable soil fertility and environmental potency. Compared with the use of either organic or inorganic fertilisers alone, the integrated approach resulted in improved bitter gourd growth and productivity. Specifically, the application of 5 t · ha^{-1} + 5 t · ha^{-1} CD combined with 50% of the recommended NPKSZnB fertiliser has emerged as a promising fertiliser management strategy for bitter gourd cultivation, enhancing microbial activity, nutrient availability, and nutrient uptake. The present findings provide a valuable recommendation to farmers for implementing sustainable and cost-effective practices to improve both the yield and quality of bitter gourd. Future research should focus on optimising the ratios of organic and inorganic inputs to achieve the most significant benefits for bitter gourd production under different agro-ecological conditions. Long-term studies are also needed to assess the long-term impacts of integrated

nutrient management on soil health, biodiversity, and overall ecosystem sustainability.

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AUTHOR CONTRIBUTIONS

M.A.Q. and M.A.R. helped in conceptualisation and implementation of trial. M.A.Q., S.T., and M.A.H. contributed to methodology, data collection, and formal analysis. M.P.K., A.G., and A.H. performed statistical analysis. M.A.Q., S.T., B.A., M.P.K., A.G., and A.H. contributed to writing and original draft preparation. M.A.Q., M.A.R., M.A.H., M.P.K., A.G., and A.H. helped in writing, reviewing, and editing. The final manuscript was approved by all the authors.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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