

ENHANCING CHILI (*CAPSICUM ANNUUM* L.) GROWTH THROUGH THE COMBINED EFFECTS OF EARTHWORMS AND INDIGO (*INDIGOFERA TINCTORIA* L.) GREEN MANURING

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Abstract

A pot experiment was conducted from February to October 2023 in a net house at the Soil Science Field Laboratory, Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur, Bangladesh, to evaluate the response of earthworms to the application of indigo green manuring (IGM) and the growth and yield response of chili under the combined applications of IGM, earthworms, and cow dung. The experiment was designed using a Completely Randomized Design (CRD) with nine treatments and four replications. The results showed that IGM significantly enhanced earthworm activity, which, in turn, led to notable improvements in chili plant growth and yield. The highest growth and yield were observed in pots treated with IGM, ¼ cow dung by soil weight, and six earthworms, which also resulted in a significant increase in soil nutrient content. IGM played a crucial role in boosting earthworm activity, promoting improved soil structure and nutrient cycling, which ultimately contributed to better plant health and higher crop productivity. These findings demonstrate the synergistic effects of IGM, earthworms, and cow dung in enhancing both soil fertility and crop performance, suggesting that their combined use can be a sustainable approach to improving chili yield in similar agro-ecosystems.

Key words: Chili Indigo green manuring; Earthworms; Cowdung

Introduction

Chili (*Capsicum annum* L.), often referred to as the "King of Spices", belongs to the Solanaceae family, stands out as a paramount spice crop with significant commercial importance. It is commonly known as a fruiting plant (Naccarato *et al.*, 2016). It is one of the essential crops in global agriculture, primary crop for culinary utilization and economic benefits. Chili Peppers contains approximately 88 grams of water, 8.8 grams of carbohydrates, 1.9 grams of protein, and 0.4 grams of fat per 100 gram serving. It contains around 40 kilocalories and are important sources of vitamin C and vitamin B6 (Anon., 2016; Olatunji & Afolayan, 2018). Peppers offer diverse culinary forms, consumed as raw, cooked, pickled, roasted, or dehydrated (Swamy, 2023). Spicy pepper varieties serve as both condiments and seasoning

agents, imparting pungency and flavor to dishes, while certain types also contribute vibrant colors to various food products. Extracts from chilli peppers, known for their analgesic properties, have been utilized beyond culinary purposes, particularly in pharmaceutical products for treating conditions such as peripheral neuropathic pain and rheumatoid arthritis (Giacalone *et al.*, 2015; Moran & Szallasi, 2018; Koivisto *et al.*, 2022; Muratovska, 2023). Chili peppers, due to the pleiotropic pharmacological activities of capsaicin, is a functional compound as analgesic, anti-obesity, anti-pruritic, anti-inflammatory, anti-apoptotic, anti-cancer, antioxidant, and neuro-protective properties (Basith *et al.*, 2016). The chili fruit contains an essential oil Oleoresin that is used in pharmaceutical, food, and beverage industries for the preparation of value-added products (Pandit *et al.*, 2020).

Numerous reports highlighted the crops potential as an antioxidant and an anti-obesity agent (Azlan *et al.*, 2022).

In Bangladesh among all the popular edible spices of the world, chili is second most important spice after onion in terms of both production area and consumption. Over the years of 2017, 2018, 2019, 2020, and 2021, Bangladesh produced 135,000, 140,000, 150,000, 286,000, and 317,000 metric tons of chili, respectively (Anon., 2022). Despite the annual increase in chili production, the market value remains uncertain due to the consistent gap between production and demand. The reliance on imports adds to the unpredictability of the market, and there is a crucial need to boost chili production locally to meet demand and establish a more stable market scenario. To cultivate chili successfully in Bangladesh, careful attention should be given to various factors, including soil fertility and nutrient availability, as effective factors on plant growth. In recent years, sustainable agricultural practices have gained considerable attention to enhancing crop productivity while minimizing the environmental impact of conventional farming methods.

One such sustainable practice involves the use of earthworms as soil amendments, owing to their role in enhancing soil structure, nutrient cycling, and microbial activity (Hartemink *et al.*, 2008; Begna, 2021; Akhila & Entoori, 2022). Earthworms contribute to the overall health of the soil by improving soil aeration and water infiltration, facilitating nutrient mineralization, and producing nutrient-rich casts that improve soil organic matter (SOM) and fertility (Parthasarathi & Ranganathan, 2000a,b; Lavelle *et al.*, 2004; Mariani *et al.*, 2007; Edwards & Arancon, 2022). Earthworms accelerate nutrient cycling in the soil-plant system through fragmentation and mixing of plant debris by physical grinding and chemical digestion (Brady & Weil, 2009). As interest in organic and eco-friendly farming practices continues to increase, exploring the synergistic relationship between earthworms and specific green manures is crucial for optimizing chili cultivation.

Nitrogen-fixing legumes play a vital role in sustainable agriculture by establishing symbiotic relationships with nitrogen-fixing bacteria, enriching the soil with bioavailable nitrogen (N), and enhancing overall plant nutrient status (Islam *et al.*, 2021; El Sabagh *et al.*, 2020, 2022; Özyazici *et al.*, 2025). Indigo (*Indigofera tinctoria* L.) green manure, derived from the leguminous plant *Indigofera tinctoria* belongs to the Fabaceae family, has been recognized for its potential as a soil conditioner and nitrogen-fixing agent (Hossain *et al.*, 2019). As a leguminous crop, Indigo ecological benefits includes (N) fixation, increasing SOM thereby improving the soil fertility (Barrios & Cobo, 2004) and naturally control the root knot nematodes of crops (Hossain *et al.*, 2011). The integration of indigo, green manure into chili cultivation practices tap the potential for promoting a nutrient-rich environment that can be further enhanced by the presence of earthworms.

In this study, we aim to examine how the combined application of earthworms and indigo green manure influences the growth and yield of chili while sustaining soil fertility and concurrently minimizing production costs and environmental pollution. The findings from this research provide valuable insights into the optimization of

agro-ecosystem strategies, and offer effective tools for farmers to enhance crop yields while minimizing the reliance on synthetic fertilizers and other chemical inputs.

Materials and Methods

Location and duration: The study was conducted inside the net house of the department of Soil Science, Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur, Bangladesh during the term from February to October, 2023. Geographically, the experimental site is located between 25.13° N latitude and 88.23° E longitude and at an elevation of 37.5 m above the sea level. The experimental site belongs to the Old Himalayan Piedmont plain (AEZ-1) (Anon., 1988).

Weather condition: Data on temperature, rainfall, and relative humidity (RH) were systematically recorded at the HSTU Meteorological Station in Dinajpur throughout the experiment. During the growing season from February to October 2023, the minimum temperatures ranged from 18.08°C to 28.72°C, while maximum temperatures ranged from 30.63°C to 38.07°C. The average rainfall recorded was 201.39 mm, and relative humidity varied between 39.82% and 87.22%. A summary of these climatic variables is provided in Table 1.

Soil properties: Soil samples were collected from a depth of 0-15 cm in the experimental block for physico-chemical analysis. The soil used in the pot experiment was loam with a pH of 5.07. The initial soil analysis revealed 0.73% organic matter (OM), 0.04% total nitrogen (N), 78.69 ppm available phosphorus (P), 0.57 meq/100g exchangeable potassium (K), and 17.63 ppm available sulfur (S). The results of the soil properties are presented in Table 2.

Experimental treatments and design: The experiment consisted nine treatments *viz.* i) T₁ = Control (no indigo green manuring, IGM₀ and no earthworms, EW₀), ii) T₂ = IGM₀ + four EW (EW₄), iii) T₃ = IGM + EW₄, iv) T₄ = IGM + six EW (EW₆), v) T₅ = 25% cow dung (CD) of total soil (w/w) + EW₄, vi) T₆ = 25% CD of total soil + EW₆, vii) T₇ = IGM + 25% CD of total soil + EW₄, viii) T₈ = IGM + 25% CD of total soil + EW₆, ix) T₉ = IGM + 25% CD of total soil + eight EW (EW₈).

Soil collection and pot preparation: Soil was collected from Karnai village, Dinajpur at a depth of 0-15 cm. After the collected soil was dried by placing the samples under the sun over a week in (mention the surface, on which, the samples was dried), weeds are manually removed and the soil samples were grinded and sorted through mesh sieve. The soil was then treated with 3% formalin solution for sterilization. Six kilogram sterilized soil was transferred to each pot. Earthen plate (20 cm in diameter) was placed below each pot to retain excess fluid. Thus, the pots were ready for indigo seed sowing. The pots were arranged in 9 rows and 4 columns. The row to row and column to column distance was maintained randomly at 0.8 m and 0.8m respectively with a total number of pot 36 (4×9).

Planting materials: Indigo plant was used as green manuring crop, which seeds were collected from the Ekarchali union under the Taragonj upazila, Rangpur, Bangladesh. Earthworms (*Lumbricus terrestris*) were collected from the Karnai village under Dinajpur Sadar Upazila, Bangladesh and were applied to the pots according to the treatments. As a test crop chili, hybrid variety Bijlee Plus 2020 was used in this experiment.

Experimentation: Indigo seeds were collected from the Ekarchali union under the Taragonj upazila, Rangpur, Bangladesh and sowed in the pots. Germination was started from 3rd days after sowing (DAS), with germination percentage of 100% at 7 DAS. The germination rate of indigo seed was 92%. The pots watered with cool boiled water intervals at 3-day. First and second weeding process were conducted manually at 15 DAS and 30 DAS, respectively. The indigo plants were divided into pieces and mixed with the soil at 45 DAS. The cut pieces of plants were incorporated into soil and kept two weeks to decompose thoroughly. One fourth cow dung (CD) of total soil weight (6 kg soil in each pot; CD = $6 \times \frac{1}{4} = 1.5$ kg CD) was applied into the pots and mixed with soil in each treatment. Earthworms (EW) were collected from the farmer field at Karnai village

under Dinajpur Sadar Upazila, Bangladesh. Those collected EW were applied to the pots according to the treatments. Earthworms were collected and counted at two times after adding them into the pots. Counting and weighing of EW started at 30 days after addition (DAA), and second counting and weighing were completed at 60 DAA into the pots. The EW then were added again to the pots in order. After final counting and re-adding of EW into the pots, 25 days old healthy seedlings of chili were collected from the farmer seedbed and transplanted into the pots. Weeding process conducted twice at 20 and 40 DAT (Days after transplanting) to keep the pots free from any weeds. Maintenance of uniform soil moisture is essential to prevent blossom and fruit drop. The crop should be irrigated frequently depending upon the moisture retention capacity of soil, frequency and amount of rainfall. Although the initial soil was sterilized with a 3% formalin solution during the final pot preparation, some young plants were still affected by damping-off. To control the disease, Captan 50WP was applied as a foliar spray at a rate of 1.5 g per liter of water. At the maturity stage, fruits were harvested at 3 to 4-day intervals based on their ripening dates, from September 27, 2023, to October 20, 2023.

Table 1. Weather data of the experimental site from the period February to October 2023.

Months	Relative humidity (%)	Temperature		Average precipitation (mm)
		Minimum (° C)	Maximum (° C)	
February	45.93	18.08	31.58	11.51
March	39.82	22.20	36.51	18.79
April	57.74	25.17	38.07	96.10
May	75.75	26.65	37.24	241.46
Jun	83.66	28.37	36.21	361.32
July	87.22	28.38	34.92	415.83
August	84.27	28.72	35.64	307.29
September	86.66	27.27	34.60	354.97
October	71.23	19.82	30.63	5.2

Source: Meteorological Satation, HSTU, Dinajpur, Bangladesh

Table 2. Physio-chemical characteristics of the soil (0-15 cm depth) used for the experiment.

A. Physical characteristics of the initial soil	
Particle size distribution	Values
Sand (%) (0.2-0.02 mm)	38.4
Silt (%) (0.02-0.002 mm)	44
Clay (%) (<0.002 mm)	17.6
Textural class	Loam

Source: Results obtained from the mechanical analysis of the initial soil

B. Chemical characteristics of the initial soil			
Characteristics	Analytical data	Critical value	Extraction methods
pH	5.07	-	Glass electrode pH meter method (Thunjai <i>et al.</i> , 2001)
Organic carbon (%)	0.42	-	Wet oxidation method (Schumacher, 2002)
Organic matter (%)	0.73	-	Calculated by the van Bemmelen factor of 1.724 (Piper, 1950)
Total N (%)	0.04	0.10	Micro-Kjeldahl method (Bremner & Mulvaney, 1982)
Available P (ppm)	78.69	10.00	Extraction with sodium bicarbonate (Olsen, 1954)
Exchangeable K (meq 100 ⁻¹ g soil)	0.17	0.12	Flame photometer (Page <i>et al.</i> , 1989)
Exchangeable Ca (meq 100 ⁻¹ g soil)	2.76	2.00	Atomic Absorption Spectrophotometer (AAS) (Thomas, 1982)

Exchangeable Mg (meq100 ⁻¹ g soil)	2.74	0.50	Extractable method (Hunter, 1972).
Available S (ppm)	17.63	10.00	Turbidimetric method using BaCl ₂ (Fox <i>et al.</i> , 1964)
Available B (ppm)	0.16	0.20	Mono-calcium bi-phosphate method, determined by Spectrophotometer following Azomethine H method (Page <i>et al.</i> , 1989)
Available Zn (ppm)	0.85	0.60	AAS (Lindsay & Norvell, 1982)

Source: Results obtained from the chemical analysis of the initial soil from SRDI, Dinajpur

Data collection: To assess plant growth, data were collected on various parameters influenced by different treatments in the experiment. Morphological traits included plant height, number of leaves per plant, and root length. Growth parameters comprised shoot fresh weight, shoot dry weight, root fresh weight, and root dry weight. Yield attributes such as the number of fruits per plant, fruit diameter, and fruit length were also recorded, along with yield measured as the fresh weight of fruit per pot. Additionally, the number and weight of earthworms were assessed. Soil nutrient content, specifically nitrogen (N), phosphorus (P), potassium (K), and sulfur (S), was analyzed at different stages: initial soil (before indigo cultivation), soil after indigo cultivation, soil before chili transplanting, and post-harvest soil (after the final chili harvest). Furthermore, nitrogen content (%) in plant tissues, including the shoot, root, and fruit, was assessed to evaluate nutrient uptake and distribution.

Statistical analysis: The data were statistically analyzed using MSTAT-C software. A one-way analysis of variance (ANOVA) was performed to assess treatment effects, and Duncan's Multiple Range Test (DMRT) was used to identify significant differences between treatments at $p < 0.05$. The analysis followed the procedures outlined by Gomez and Gomez (1984) to ensure a robust evaluation of the experimental results.

Results and Discussion

1. Plant morphology

Plant height: The results showed that plant height was significantly influenced by treatments involving IGM, EW, and CD (Table 3). At 20 DAT, the tallest plants were recorded in T₈ (26.38 cm), which was statistically similar to T₇ (26.00 cm) and T₉ (26.13 cm). In contrast, the shortest plants were observed in the control (T₁), with an average height of 21.00 cm. At 40 DAT, T₈ treatment showed the maximum plant height average among other treatment, of 46.25 cm. however, no significant variation was found between T₈ treatment other treatments (T₉, T₆, T₇, T₅, T₄, T₃, and T₂), except T₁, where the shortest plants were recorded at 30.75 cm. By 60 DAT, the T₈ treatment maintained its lead with the tallest plants, measuring an average of 52.50 cm followed by the T₆ treatment, while the shortest plants were again found in the T₁ treatment, with an average height of 36.00 cm. The results clearly demonstrate the beneficial effects of the combined use of IGM, CD, and EW on plant growth across different stages of development. The increase in plant height due to the application of IGM, EW, and CD can be attributed to their individual and synergistic effects on soil fertility (are the plans belong to the same chilly variety? Is there any variation that can be attributed to genetic effect?), nutrient availability, and overall soil health. IGM enhances SOM, boosts nutrient cycling, and increases the

availability of key nutrients like N and P, which improves soil structure, reduces compaction, and increases water retention, leading to better root development and plant growth, which ultimately results in increased plant height (Bhardwaj *et al.*, 2011; Srinivasarao *et al.*, 2012). EW improve soil aeration and structure through burrowing, which enhances root penetration and water infiltration, while their decomposition of OM produces nutrient-rich vermicast, boosting nutrient availability and promoting plant growth (Lavelle & Spain 2001). CD is a rich source of OM and essential nutrients like N, P, and K, which enhance soil microbial activity, leading to improved nutrient mineralization and increased availability to plants (Gopinath *et al.*, 2008). The combination of IGM, EW, and CD creates a synergistic effect, where the decomposition of OM by earthworms, enriched by cow dung nutrients and green manuring, enhances nutrient availability and uptake by plants, leading to increased plant height (Sinha *et al.*, 2010; Bhardwaj *et al.*, 2011).

Number of leaves plant⁻¹: The results demonstrated that the application of IGM, EW, and CD significantly increased number of leaves per plant (NLPP) in chili plants at both sampling dates (Table 3). At 20 DAT, the highest NLPP was observed in the T₉ treatment, with an average of 48.00 leaves plant⁻¹. This result was statistically comparable to the T₈ treatment, averaged 47.75 leaves plant⁻¹. In contrast, the lowest NLPP was recorded in the control group (T₁), where plants had an average of just 17.75 leaves plant⁻¹. By 40 DAT, the NLPP remained revealing significant variation among other treatments. The maximum NLPP was recorded in the T₈ treatment, with an average of 120.00 leaves plant⁻¹. This was not significantly different to the T₉ treatment, which had 116.00 leaves plant⁻¹, and the T₇ treatment, with 111.5 leaves plant⁻¹. Meanwhile, the T₁ treatment consistently showed the lowest leaf count, with an average of 37.50 leaves plant⁻¹. These results highlight the effectiveness of combining IGM, EW, and CD in enhancing the vegetative growth of chili plants, as reflected in the increased number of leaves per plant. The increase in leaf production is due to addition of IGM, which improves soil fertility by increasing OM and nutrient availability, particularly N, enhancing soil structure and moisture retention, creating optimal conditions for vegetative growth (Ghosh *et al.*, 2004). EW enhances nutrient cycling by breaking down OM into nutrient-rich vermicast, improving soil aeration and structure, which together increase the availability of essential nutrients like N, P, and K, promoting better root growth, water uptake, and vegetative growth (Edwards & Arancon, 2004). CD supplies OM and essential nutrients like N while stimulating soil microbial activity, enhancing nutrient availability, and directly increasing leaf production (Jahiruddin *et al.*, 2012). The combined use of IGM, EW, and CD creates a synergistic effect, where EW

break down OM into nutrient-rich vermicast, enhancing N availability and promoting robust vegetative growth with more leaves per plant (Sinha *et al.*, 2010). The combination of these practices improves soil structure, OM content, and microbial activity, enhancing nutrient uptake and photosynthesis, which leads to a greater number of leaves per plant (Bhardwaj *et al.*, 2011). The increase in the NLPP is due to the enhanced nutrient availability, improved soil structure, and better overall soil health provided by the combined effects of IGM, EW, and CD. These factors work together to support vigorous vegetative growth and increased leaf production.

Root length: IGM, EW and CD resulted in significantly greater root lengths compared to control. Among the treatments, the longest root length, averaging 29.63 cm, was recorded from the T₈ treatment, followed by the T₆, T₇, T₉, and T₅ treatments, which also characterized by longer root lengths. IGM and moderate earthworms (EW₆) with CD (T₈) increased the root length by 14% without CD (T₄). In contrast, the control group (T₁) showed the shortest root length was 18.25 cm per plant (Table 3). Compared to the control (without IGM and EW), the use of sole EW (T₂) and combination of IGM with EW (T₃) increased the root lengths by 22.14 and 25.93 respectively. The increase in root length from IGM, EW, and CD was due to their synthetic effects on soil health, nutrient availability, and structure. IGM enhances soil fertility by adding OM and nutrients, improving root development and moisture retention (Ghosh *et al.*, 2004). EW improved soil aeration and structure, facilitating root growth and nutrient uptake, while their vermicast supports root development (Edwards & Arancon, 2004). CD provides essential nutrients like N, P, and K, and stimulates microbial activity, promoting root elongation (Jahiruddin *et al.*, 2012). Together, IGM, EW, and CD enhance soil structure, fertility, and microbial activity, creating optimal conditions for root growth and increased root length (Sinha *et al.*, 2010; Bhardwaj *et al.*, 2011).

2 Growth parameters

Fresh and dry weight of shoot: The results revealed that the combined application of IGM and EW significantly increased both fresh and dry shoot weights compared to the control treatment (Table 4). T₈ treatment was statistically superior to all other treatments in fresh shoot weight, reaching 34.56 g plant⁻¹. In contrast, the control treatment (T₁) had the lowest fresh shoot weight, at 15.56 g plant⁻¹. For dry shoot weight, the maximum was observed in the T₈ treatment, with an average of 12.05 g per plant, followed by the T₉ and T₇ treatments, which their dry shoots weighted second among other treatments. On the other hand, the minimum dry shoot weight of 5.50 g per plant was found in the control treatment (T₁). These results indicate that the combination of IGM and EW effectively enhances both fresh and dry shoot biomass, contributing to the improvement of plant growth. The increase in fresh and dry shoot weight due to IGM, EW, and CD can be attributed to their individual and synergistic effects on soil fertility, nutrient availability, and overall plant health. IGM boosts soil fertility by increasing OM, nutrients, and improving soil structure and moisture retention, leading to higher fresh and dry shoot weight. EW enhances nutrient cycling, soil aeration, and structure, promoting better shoot development and increased fresh and dry shoot weight (Edwards & Arancon, 2004). CD enriches soil with essential

nutrients and stimulates microbial activity, further increasing shoot weight (Jahiruddin *et al.*, 2012). Combining IGM, EW, and CD enhances soil fertility, OM, and microbial activity, optimizing growth conditions for higher fresh and dry shoot weight (Sinha *et al.*, 2010; Bhardwaj *et al.*, 2011).

Fresh and dry weight of root: Our findings revealed a significant increase in both fresh and dry root weights when IGM and EW were added, as well as the combination of IGM, CD, and various levels of EW. These amendments contributed to enhanced root development. In the case of fresh root weight, the highest value was observed in the T₈ treatment, where the roots weighed 0.98 g. This treatment, which involved the combined application of IGM, CD, and EW₆, demonstrated a statistically significant difference over other treatments, suggesting advantageous treatment of IGM and CD. On the other hand, the lowest fresh root weight was observed in the T₁ treatment (control), where no IGM, CD, or EW were applied, resulting in a root weight of only 0.37 g. This highlights the substantial impact of organic amendments and earthworm activity on enhancing root biomass. Similarly, for dry root weight, the T₈ treatment and T₉ treatment exhibited the highest values of the dry shoot weight, recorded at 0.41 g and 0.38 g, respectively. These treatments combined the benefits of IGM, CD, and EW and significantly outperformed the control (T₁) treatment that showed the lowest dry root weight of 0.17 g. The reasoning of the fresh and dry root weight increase from the addition of IGM, EW, and CD is attributed to their combined effect on enhancing the nutrient availability, soil structure, and microbial activity, this effect is resulted from a combination of improved soil fertility and OM, and promoting root growth resulted from IGM (Jia *et al.*, 2018), and the positive impact of EW on soil aeration and nutrient cycling which uphold root development (Lemtiri *et al.*, 2014). CD adds essential nutrients and boosts microbial activity, further enhancing root growth (Tagele *et al.*, 2023). Together, these factors create optimal conditions for increased root biomass and healthier plants (Ghosh *et al.*, 2014).

3. Yield contributing characteristics

Fruit number: The various combinations of IGM, EW and CD demonstrated significant variations in the number of fruits per plant (NFPP) in chili were (Table 5). However, the treatment T₈ was superior to other treatments with NFPP value 18.00 accompanied by notable enhancement in fruit production. In contrast, the control treatment (T₁) resulted in the lowest NFPP of 6.97. This substantial difference highlights the importance of the integrated application of IGM, EW and CD in increasing the NFPP significantly, which leads to improving fruit yield. The data underscores the efficacy of combining these practices to optimize fruit production in chili cultivation. IGM enhanced soil fertility by increasing OM and nutrient availability (Table 8), which led to promoting plant growth and fruit development (Tables 3, 4 & 5), and consequently, increasing NFPP. EW increased soil health and nutrients availability (Table 8) which tap the potential of enhancing plant growth (Tables 3 & 4), leading to higher NFPP. It is evident that EW enhanced plant growth and fruit production by enhancing aeration, water infiltration, and nutrient cycling through their burrowing activity, boosting soil structure through nutrient-rich casts facilitating root development and increased nutrient uptake (Osei &

Ntiamoah, 2021; Briones & Schmidt, 2022). CD is a significant source of OM and essential nutrients that improves soil fertility and microbial activity, leading to enhanced plant growth and fruit production (Pandey & Kumar, 2022; Khan & Khan, 2023). This approach can enhance the overall soil conditions to improve plant health, increase nutrient availability, and increase the number of

fruits per plant. Combined addition of IGM, CD and EW provides a synergistic effect that optimizes soil health and fertility (Zhang *et al.*, 2022; Kumar *et al.*, 2023). The improvement of soil and fertility due to integrated approaches contributed to better plant growth (Table 3 & 4) and higher NFPP (Table 5).

Table 3. Effect of IGM on the morphological characteristics of chili under different population density of earthworms.

Treatments	Plant height (cm)			No. of leaves plant ⁻¹		Root length (cm) FH
	20 DAT	40 DAT	FH	20 DAT	40 DAT	
T ₁	21.00 c	30.75 b	36.13 c	17.75 f	37.50 d	36.13 c
T ₂	22.50 bc	40.75 a	44.13 b	26.75 e	70.00 c	44.13 b
T ₃	24.00 abc	42.25 a	45.50 b	33.25 d	86.00 b	45.50 b
T ₄	24.75 ab	42.75 a	46.25 ab	36.25 cd	89.75 b	46.05 b
T ₅	25.00 ab	43.50 a	47.38 ab	38.25 bcd	93.50 b	47.38 ab
T ₆	25.75 ab	44.50 a	50.50 ab	40.75 bc	96.00 b	50.50 ab
T ₇	26.00 a	44.25 a	50.00 ab	44.25 ab	111.5 a	50.00 ab
T ₈	26.38 a	46.25 a	52.50 a	47.75 a	120.0 a	52.50 a
T ₉	26.13 a	43.50 a	49.50 ab	48.00 a	116.0 a	49.50 ab
LSD	3.038	5.060	5.90	5.910	11.51	5.904
CV %	8.46	8.24	8.63	10.94	8.65	8.63

i) T₁ = Control (IGM₀ + EW₀), ii) T₂ = IGM₀ + EW₄, iii) T₃ = IGM + EW₄, iv) T₄ = IGM + EW₆, v) T₅ = 25% CD of soil + EW₄, vi) T₆ = 25% CD of soil + EW₆, vii) T₇ = IGM + 25% CD of soil + EW₄, viii) T₈ = IGM + 25% CD of soil + EW₆, ix) T₉ = IGM + 25% CD of soil + EW₈. In the column, figures having similar letter(s) do not differ significantly at 5% level of significance

Table 4. Effect of IGM on shoot fresh and dry weight, root fresh and dry root weight of chili under different population density of EW on of chili.

Treatments	Shoot fresh weight (g plant ⁻¹)	Shoot dry weight (g plant ⁻¹)	Root fresh weight (g plant ⁻¹)	Root dry weight (g plant ⁻¹)
T ₁	15.56 i	5.50 f	0.37 e	0.17 e
T ₂	24.01 g	8.50 de	0.45 de	0.22 de
T ₃	24.42 f	8.60 de	0.51 d	0.23 d
T ₄	20.30 h	7.15 e	0.65 c	0.29 c
T ₅	27.28 e	9.58 cd	0.71 c	0.30 c
T ₆	29.35 d	10.30 bc	0.74 bc	0.31 c
T ₇	30.33 c	10.61 abc	0.86 ab	0.36 b
T ₈	34.56 a	12.05 a	0.98 a	0.41a
T ₉	33.88 b	11.77 ab	0.92 a	0.38 ab
LSD	0.2064	1.476	0.13	0.046
CV %	1.53	10.83	13.40	11.42

i) T₁ = Control (IGM₀ + EW₀), ii) T₂ = IGM₀ + EW₄, iii) T₃ = IGM + EW₄, iv) T₄ = IGM + EW₆, v) T₅ = 25% CD of soil + EW₄, vi) T₆ = 25% CD of soil + EW₆, vii) T₇ = IGM + 25% CD of soil + EW₄, viii) T₈ = IGM + 25% CD of soil + EW₆, ix) T₉ = IGM + 25% CD of soil + EW₈. In the column, figures having similar letter(s) do not differ significantly at 5% level of significance

Table 5. Effect of IGM on fruit length, fruit diameter, fruit weight and fruit number of chili under different population density of EW on of chili.

Treatments	No. of fruits plant ⁻¹	Fruit length (cm)	Fruit diameter (cm)	Fruit fresh weight (g)
T ₁	6.97 f	6.20 c	6.35 c	5.00 f
T ₂	9.10 e	7.50 b	7.58 b	6.67 e
T ₃	10.00 de	8.33 b	8.18 bc	9.28 d
T ₄	12.00 cd	8.50 ab	8.32 ab	10.81 cd
T ₅	14.00 bc	8.63 ab	8.88 ab	12.25 b
T ₆	14.92 b	8.67 ab	8.71 ab	12.59 b
T ₇	15.00 b	8.93 ab	9.06 ab	12.66 b
T ₈	18.00 a	9.60 a	9.48 a	15.50 a

T ₉	15.20 b	9.00 ab	9.28 a	12.77 b
LSD (0.05%)	2.23	1.33	1.44	1.20
CV (%)	12.04	10.72	11.73	7.63

i) T₁ = Control (IGM₀ + EW₀), ii) T₂ = IGM₀ + EW₄, iii) T₃ = IGM + EW₄, iv) T₄ = IGM + EW₆, v) T₅ = 25% CD of soil + EW₄, vi) T₆ = 25% CD of soil + EW₆, vii) T₇ = IGM + 25% CD of soil + EW₄, viii) T₈ = IGM + 25% CD of soil + EW₆, ix) T₉ = IGM + 25% CD of soil + EW₈. In the column, figures having similar letter(s) do not differ significantly at 5% level of significance

Fruit length: Fruit length (FL) is a critical yield attribute in chili production, playing a significant role in determining overall yield. In this study, the length of chili fruits was markedly influenced by various treatments involving IGM, CD and EW activity, as shown in Table 5. The results indicate that these factors have a synergistic effect on enhancing FL. Among all treatments, treatment T₈, which involved the application of IGM, 25% CD of soil, and the presence of six EW, reported the highest FL. This combination resulted in a substantial effect on FL valued 9.60 cm, suggesting the effectiveness of integrating these components in promoting chili growth. The superiority of T₈ was closer to treatments T₉, T₇, T₆, T₅, and T₄, all of which demonstrated substantial increases in FL compared to the control. In stark contrast, the control treatment (T₁) did not include any IGM, CD, or EW activity and resulted in the shortest FL of 6.20 cm. This result emphasize the importance of these organic amendments and biological activities in enhancing the physical growth parameters of chili. Overall, the results underscore the pivotal role that IGM, CD, and EW play in influencing FL, which is a key determinant of chili yield. The notable increase in FL under these treatments suggests that the integrated use of organic and biological inputs can significantly improve chili production. IGM enhanced soil fertility and structure by adding OM and increasing the availability of essential nutrients, particularly N in the soil profile (Table 8), leading to increased FL. Studies like Singh *et al.*, (2018) have shown that green manuring improves soil nitrogen, boosting plant growth and resulting in longer fruits. EW enhances soil structure, aeration, and nutrient cycling, leading to better nutrient uptake and increased fruit length (Edwards & Arancon, 2004). CD, rich in nutrients like N, P, and K, improves soil fertility and plant growth, contributing to longer fruit (Kale *et al.*, 2009). The combined application of IGM, EW, and CD creates a synergistic effect, optimizing soil conditions for greater fruit length, as demonstrated by Sharma *et al.*, (2020).

Fruit diameter: The fruit diameter (FD) is a major yield component in chili crop, it directly underlines the marketability and weight of the produce. The diameter of chili fruits was significantly affected by the application of IGM, CD, and the activity of EW, as detailed in Table 5. The results revealed that the highest FD (9.48 cm) is recorded in treatment T₈, making it the most effective in enhancing fruit size. Furthermore, the FD in T₈ value was close to treatments T₇, T₅, and T₆. These treatments, which varied in the proportions of IGM, CD, and EW, consistently produced larger FD compared to the control. The FD values of these treatments suggest that a certain threshold of organic amendments and biological activity is required to achieve optimal FD in chili. In contrast, the lowest FD, measuring 6.35 cm, was recorded in treatment

T₁, the control group, highlighting the importance of IGM, CD, or EW in promoting fruit growth which not only boosts fruit length but also has a substantial positive impact on FD. The significant difference between the FD in T₁ and the other treatments underscores the critical role that soil fertility, OM, and biological activity play in enhancing fruit dimensions in chili cultivation. IGM improves soil fertility and structure by increasing essential nutrient availability, supporting better fruit development. Research shows that green manures enhance larger fruits by enhancing soil nutrients and plant growth (Singh *et al.*, 2018; 2020). EW improve soil fertility through burrowing and nutrient-rich casts, enhancing nutrient availability and plant growth, which positively affects fruit size and yield (Lavelle and Spain, 2001; Edwards & Arancon, 2004). CD, rich in OM and nutrients, boosts soil fertility, microbial activity, and nutrient availability, promoting larger fruits (Kale *et al.*, 2009; Subba Rao & Sharma, 2009). Combining IGM, EW, and CD creates a synergistic effect that optimizes soil conditions and enhancing fruit development (Sharma *et al.*, 2020; Biswas & Sharma, 2021).

4. Fruit weight

The fruit weight per plant (FWPP) of chili was significantly influenced by the application of IGM, EW, and CD. The highest FWPP (15.50 g plant⁻¹), was observed in treatment T₈. This treatment, which combined IGM, 25% CD of soil, and 6 earthworms, demonstrated significant differences in FWPP compared to all other treatments. This superior performance can be attributed to the combined effects of enhanced soil fertility and structure provided by IGM, the nutrient-rich earthworm activity, and the nutrient addition from cow dung. Treatment T₉, resulted in a moderate FWPP of 12.77 g plant⁻¹. This weight was not significantly different to those observed in treatments T₇, T₆, and T₅, indicating that these treatments also had a beneficial impact on fruit weight, though slightly less pronounced than T₈. Conversely, the control treatment (T₁), which lacked IGM, CD, and EW, resulted in the lowest FWPP of 5.00 g. This significant difference suggest the major role that the combined application of IGM, CD, and EW plays in enhancing chili fruit weight. The combined use of IGM, EW, and CD enhances soil fertility, nutrient availability, and plant growth, leading to increased FWPP. IGM improves soil structure and nutrient content, boosting root development and nutrient uptake, which enhances photosynthesis and fruit biomass (Singh *et al.*, 2020; Patel *et al.*, 2023). EW improve aeration, water infiltration, and nutrient cycling, promoting root proliferation and nutrient assimilation, which increases fruit size and weight (Lavelle & Spain, 2001; Briones & Schmidt, 2022). CD enriches the soil with organic matter and essential

nutrients, enhancing microbial activity and supporting fruit growth through improved sugar translocation and starch accumulation (Subba Rao & Sharma, 2009; Khan & Khan, 2023). These amendments synergistically enhance soil health, photosynthesis, and hormonal balance, resulting in better fruit development, higher fresh fruit weight, and improved overall crop yield.

5. Nutrients uptake in plants

Nitrogen content in plant parts (shoot, root and fruit):

The N content in the shoot ranged from 0.13% to 0.25%. The highest shoot N content of 0.25% was observed in treatment T₈, while the lowest N content was 0.13% reported in treatment T₁. Followed by treatments T₅, T₆, T₇, and T₉, where the N content was 0.22% in all these treatments. The N uptake by the fruit varied from 0.16% to 0.33%, with significant differences observed among the treatments. Treatment T₉ had the highest fruit N content at 0.33%, while the T₈ ranked second. The lowest fruit N content of 0.16% was found in treatment T₁. There was no significant variation in fruit N content among treatments T₃, T₄, T₅, T₆, and T₇. The highest N content in roots was observed in treatments T₈ and T₇ (0.16% each), while the lowest was recorded in T₁ (0.10%). The increased N content in these treatments can be attributed to the enhanced soil fertility provided by organic amendments. IGM contributes organic nitrogen and other essential nutrients, improving microbial activity and accelerating nutrient mineralization. This process enhances root absorption capacity, facilitating higher nitrogen uptake, which is crucial for amino acid synthesis, protein formation, and overall plant metabolism. Higher nitrogen levels in the roots also promote better shoot growth and fruit development by supporting chlorophyll synthesis and enzymatic activities. The findings align with those of Singh *et al.*, (2018) and Yadav *et al.*, (2022), who reported that organic amendments significantly improve nitrogen availability in soil and plant tissues, leading to enhanced plant growth and yield (Table 6).

6. Properties of EW

Number of EW: Significant differences in the number of EW pot⁻¹ were found between treatments at 60 DAA (Table 7). The highest significant earthworm count (96.75 pot⁻¹) was recorded at 60 DAA in treatment T₉, where 8 EW was inoculated with IGM and CD, with minor variation observed compared to T₇ treatment. The second-highest EW count (85.75) was recorded in T₆ that demonstrated non-significant difference with T₈ (81.75). No EW were obtained in T₁ treatment. The addition of EW increased the earthworm count in chili crops under IGM and CD manured plots due to the enhanced soil environment created by these amendments. IGM and CD provide OM and nutrients, which improve soil structure, moisture retention, and microbial activity, creating a favorable habitat for earthworms to thrive and reproduce (Kumar *et al.*, 2020; Yadav *et al.*, 2021). EW, in turn, benefit from the nutrient-rich environment, leading to

increased population growth and activity in the soil (Singh *et al.*, 2019; Alam *et al.*, 2022).

Weight of EW: Significant variation in the weight of earthworms was observed at both 30 and 60 DAA across the different treatments. At 30 DAA, the highest earthworm weight (8.75 g) was recorded in treatment T₉, showing superiority over the other treatments, while no EW were found in the control treatment. By 60 DAA, the maximum EW weight (20.25 g) was noted in treatment T₈, with statistical variations with other treatments, while no EW present in treatment T₁ (Table 7). The weight of EW in the soil of chili crops was increased with their addition in plots treated with IGM and CD.

Table 6. Effect of IGM and EW on the total N content in the shoot, root and fruit of chili.

Treatments	Total N content (%)		
	Shoots	Fruits	Roots
T ₁	0.13 d	0.16 d	0.10 c
T ₂	0.15 c	0.17 d	0.11 bc
T ₃	0.17 bc	0.24 bc	0.12 b
T ₄	0.17 bc	0.23 bc	0.12 b
T ₅	0.22 ab	0.23 bc	0.12 b
T ₆	0.22 ab	0.22 bc	0.12 b
T ₇	0.22 ab	0.26 b	0.16 a
T ₈	0.25 a	0.32 a	0.16 a
T ₉	0.22 ab	0.33 a	0.15 a
LSD	0.065	0.065	0.046
CV %	9.64	7.52	9.90

i) T₁ = Control (IGM₀ + EW₀), ii) T₂ = IGM₀ + EW₄, iii) T₃ = IGM + EW₄, iv) T₄ = IGM + EW₆, v) T₅ = 25% CD of soil + EW₄, vi) T₆ = 25% CD of soil + EW₆, vii) T₇ = IGM + 25% CD of soil + EW₄, viii) T₈ = IGM + 25% CD of soil + EW₆, ix) T₉ = IGM + 25% CD of soil + EW₈. In the column, figures having similar letter(s) do not differ significantly at 5% level of significance

Table 7. Effect of IGM on the number and weight of EW.

Treatments	Number of EW (pot ⁻¹)		Weight of EW (g pot ⁻¹)	
	30 DAA	60 DAA	30 DAA	60 DAA
T ₁	0.00	0.00 e	0.00 e	0.00 e
T ₂	4.00	2.25 e	3.00 d	1.25 e
T ₃	4.00	25.00 d	4.00 d	8.50 d
T ₄	6.00	35.00 d	5.75 c	9.00 d
T ₅	4.00	70.00 c	5.50 c	13.00 c
T ₆	6.00	85.75 b	6.50 bc	17.00 b
T ₇	4.00	87.75 ab	6.00 c	16.25 b
T ₈	6.00	81.75 b	7.50 b	20.25 a
T ₉	8.00	96.75 a	8.75 a	16.00 b
LSD	0.00 ^(NS)	10.18	1.015	2.741
CV %	0.00	12.97	13.32	12.69

i) T₁ = Control (IGM₀ + EW₀), ii) T₂ = IGM₀ + EW₄, iii) T₃ = IGM + EW₄, iv) T₄ = IGM + EW₆, v) T₅ = 25% CD of soil + EW₄, vi) T₆ = 25% CD of soil + EW₆, vii) T₇ = IGM + 25% CD of soil + EW₄, viii) T₈ = IGM + 25% CD of soil + EW₆, ix) T₉ = IGM + 25% CD of soil + EW₈. In the column, figures having similar letter(s) do not differ significantly at 5% level of significance, NS: Not significant

Table 8. Effect of IGM on the soil pH, organic matter and total N content in the soil.

Treatments	pH	OM content (%)	Total N (%)
T ₁	5.07 c	0.73 d	0.04

T ₂	5.08 c	0.74 d	0.04
T ₃	5.39 ab	0.94 c	0.07
T ₄	5.35 b	0.96 c	0.08
T ₅	5.07 c	0.80 cd	0.05
T ₆	5.08 c	0.84 cd	0.06
T ₇	5.42 ab	1.79 ab	0.09
T ₈	5.52 a	1.90 a	0.12
T ₉	5.44 ab	1.50 b	0.08
LSD	0.131	0.092	0.12
CV %	1.70	5.72	4.77

i) T₁ = Control (IGM₀ + EW₀), ii) T₂ = IGM₀ + EW₄, iii) T₃ = IGM + EW₄, iv) T₄ = IGM + EW₆, v) T₅ = 25% CD of soil + EW₄, vi) T₆ = 25% CD of soil + EW₆, vii) T₇ = IGM + 25% CD of soil + EW₄, viii) T₈ = IGM + 25% CD of soil + EW₆, ix) T₉ = IGM + 25% CD of soil + EW₈. In the column, figures having similar letter(s) do not differ significantly at 5% level of significance

This enhancement is attributed to the improved soil environment fostered by these organic amendments. IGM and CD enrich the soil with OM and nutrients, which in turn boost soil moisture, aeration, and microbial activity. These factors create a more favorable habitat for earthworms, improving their food availability and overall growth. This optimal environment supports healthier earthworms, leading to an increase in their weight (Singh *et al.*, 2019; Kumar *et al.*, 2020; Yadav *et al.*, 2021). The enriched organic content in the soil allows earthworms to thrive, resulting in increased earthworm weight (Alam *et al.*, 2022).

7. Chemical properties of soil

7.1. After cultivation of IGM crop

Soil pH: The soil pH after the cultivation of IGM crops was strongly acidic, ranging from 5.07 to 5.52 (Table 8). Cultivating indigo green manuring crops resulted in a slight increase in soil pH compared to the initial pH (Table 2). The highest pH value of 5.52 was recorded in treatment T₈, which was not significantly different to T₉ (5.44) and T₇ (5.42). The lowest pH, 5.07, was observed in treatment T₁. The effect of IGM on soil pH can vary depending on soil type and conditions, but generally, IGM tends to slightly increase soil pH. This increase is due to the addition of OM and the resulting changes in soil microbial activity, which can help buffer soil acidity. Green manures can effectively raise soil pH, particularly in acidic soils, thereby creating a favorable environment for crop growth (Joshna *et al.*, 2024). In another study conducted by Xu *et al.*, (2024) green manures, including IGM, contributed to minor increase in the soil pH.

Organic matter content: The cultivation of IGM crops significantly increased the OM content of the soil. After indigo cultivation, the highest OM content of 1.90% was observed in treatment T₈, which was not significantly different to the 1.79% found in T₇ (Table 8). In contrast, the lowest OM content of 0.73% was recorded in the control treatment T₁, where neither indigo green manure nor earthworms were applied, the same content of OM was found in the initial soil level (Table 2). IGM increases SOM content through the addition of substantial

plant residues and organic material. As these residues decompose, they enrich the soil structure, enhance nutrient availability, and support beneficial microbial activity. This process improves soil aeration and moisture retention, thereby boosting soil OM and overall soil fertility (Hossain *et al.*, 2011; Singh *et al.*, 2023).

Total nitrogen content (%) in soil: No significant differences were observed in the N content in soil among the various treatments (Table 8). While there was some variation, the differences were not statistically significant. The total N content ranged from 0.04% to 0.12%. The highest N content of 0.12% was recorded in treatment T₈, while the lowest was 0.04% in treatment T₁. Green manuring, especially with legumes, enhances soil microbial biomass N and nitrate-nitrogen (NO₃⁻-N) concentrations, which are essential for plant growth. Additionally, incorporating green manure can reduce nitrogen leaching and ammonia volatilization, resulting in better nitrogen retention in the soil (Xu *et al.*, 2024). Green manuring combined with reduced inorganic fertilizers has been linked to similar crop yields and N uptake as full fertilizer applications, demonstrating its effectiveness in sustainable farming (Yang *et al.*, 2018). The combination of CD and EW (*Eisenia fetida*) during vermicomposting enhances total N content, with studies showing significant increases in total N from 0.538 g kg⁻¹ to 1.380 g kg⁻¹ (Raza *et al.*, 2020). EW facilitate nitrogen cycling by stimulating mineralization processes, thereby making nitrogen more available to plants (Cheng *et al.*, 2019). The application of CD with EW has been shown to improve nitrogen recovery from organic amendments, with EW density positively correlating with N uptake in grasslands (Rashid *et al.*, 2014). Earthworms facilitate nitrogen cycling by stimulating mineralization processes, thereby making nitrogen more available to plants.

7.2. After incorporation of indigo crop and addition of earthworms in the pots

Soil pH: The soil pH became slightly acidic after the incorporation of IGM and the addition of earthworms, with values ranging from 5.07 to 6.16 (Table 9). The highest pH (6.16) obtained from the IGM + EW + CD treatment, followed by IGM + EW (5.45) and IGM alone (5.31), showing notable differences. However, there was only a minor difference between IGM + EW (5.45) and IGM alone (5.31). The lowest pH (5.07) was observed in the non-treated soil (NS), which showed only a slight variation compared to the soil treated with IGM. The application of EW in indigo green-manured chili fields has been shown to positively impact soil pH and overall health. EW activity helps neutralize soil acidity, which is crucial in areas affected by long-term inorganic fertilizer use (Zhai *et al.*, 2021). Combining EW with organic amendments like green manure increases soil pH, enhancing nutrient availability and microbial activity (Rashid *et al.*, 2014). Additionally, the incorporation of CD with EW in indigo green-manured soil further boosts soil pH in acidic conditions (Zhang, 1998; Whalen *et al.*, 2000; Chan, 2003; Rashid *et al.*, 2014).

Organic matter content: The application of EW, both alone and in combination with CD, in indigo green-manured soil significantly affected the OM content. The highest OM content (2.75%) was observed in the IGM + EW + CD treatment (Table 9), while the lowest OM content (0.73%) was recorded in the non-treated soil (NS). The incorporation of organic amendments, such as industrial organic waste, compost, and manure, improves soil structure, increasing porosity and water retention, which creates favorable conditions for OM accumulation by enhancing aeration and microbial activity (Wardah *et al.*, 2014; Auler *et al.*, 2020). These amendments boost microbial populations and enzyme activities, accelerating decomposition processes and nutrient cycling, which contribute to OM formation and retention in the soil (Kabaivanova *et al.*, 2023; Woźniak *et al.*, 2023).

Total N content in soil: The total N content in the soil, following the incorporation of the IGM crop and EW, was significantly affected by the addition of IGM, EW, and CD (Table 9). The N content in the soil varied from 0.04% to 0.23%, with the highest N level (0.23%) observed under the IGM + EW + CD treatment. Treatments with IGM alone show non-significant increase in N compared to the non-treated soil (NS), where the lowest N content (0.04%) was recorded. The application of organic materials has been shown to significantly increase nitrogen availability in soils, indicating that organic amendments played a crucial role in N cycle, similar results were found by Wulansari *et al.*, (2024). The addition of organic amendments enhances nitrogen mineralization, promoting microbial activity and converting organic nitrogen into mineral forms, thereby increasing soil nitrogen availability (Fernández *et al.*, 2017; Xu *et al.*, 2024).

Available P content in soil: The available P content in the soil, after the incorporation of IGM, IGM + EW, and IGM + EW + CD into the pots, was significantly influenced (Table 9). The highest P content (131.2 ppm) was observed under the IGM + EW + CD treatment. A slight increase in P content was noted with the addition of EW to IGM compared to IGM alone. However, the lowest P content (110.5 ppm) was recorded in the non-treated soil (NS). IGM and CD provide OM that competes with P for adsorption sites on soil minerals, reducing P fixation and increasing its solubility, making it more available for plant uptake (Khan *et al.*, 2022; Mendez & Vargas, 2024). Additionally, EW promotes microbial activity, therefore it accelerated the breakdown of OM and facilitated P mineralization, further boosting P availability in the soil (Liao *et al.*, 2023). These factors jointly improved the overall P cycling and nutrient availability in the soil.

Exchangeable K content in soil: The addition of IGM, IGM + EW, and IGM + EW + CD led to an increase in the available sulfur (S) content in the collected soil, with values varied from 0.57 to 0.96 meq100⁻¹g soil (Table 9). The treatment of IGM + EW + CD resulted in the highest and statistically significant S content (0.96 meq 100⁻¹ g soil), while the non-treated soil (NS) had the lowest level at 0.57 meq100⁻¹ g soil. IGM contributes OM that decomposes to release K into the soil, enhancing its availability (Sindhu *et al.*, 2016). EW improve soil

structure, leading to better aeration and moisture retention, which are essential for nutrient uptake (Adekiya *et al.*, 2020). Additionally, CD is rich in K, and when combined with IGM, it increases the soil's cation exchange capacity, facilitating better retention of K (Mavi & Benbi, 2008). Together, these elements enhance K content in the soil through OM contribution, improved soil structure, and increased nutrient retention.

Available S content in soil: The available sulfur (S) content in the collected soil increased with the addition of IGM, IGM + EW, and IGM + EW + CD, ranging from 17.63 to 39.47 ppm (Table 9). The highest and statistically significant available S content (39.47 ppm) was observed with the addition of IGM + EW + CD, while the lowest (17.63 ppm) was recorded in the non-treated soil (NS). The addition of IGM, along with EW and CD, significantly enhances S content in soil through a synergistic process. IGM provides OM that decomposes, releasing nutrients, including S (Paul *et al.*, 2024). EW enhance soil aeration and structure, promoting microbial activity, which is crucial for sulfur transformation, converting organic sulfur into forms that plants can absorb (Adekiya *et al.*, 2020). Cow dung further enriches the soil with nutrients, and its organic content supports microbial growth, accelerating nutrient cycling and boosting S availability in the soil (Tripathi *et al.*, 2018).

7.3. Chemical properties of the post-harvest soil

Soil pH: The pH of the post-harvest soil was slightly acidic, ranging from 5.66 to 6.45 (Table 10). The highest pH (6.45) was observed in treatment T₈, which was not significantly different to T₉ (6.40) and T₇ (6.37), while the lowest pH (5.66) was recorded in treatment T₁. The study showed that the soil pH increased from the initial level to post-harvest and approached neutrality with the incorporation of IGM and CD under the activity of EW. Additionally, the post-harvest soil pH remained relatively stable compared to the initial soil pH in plots not treated with IGM. IGM combined with CD and EW significantly influences soil pH in post-harvest chili fields. CD application has been shown to increase soil pH, indicating a shift towards neutrality (Mubo, 2015). Introduction of OM through CD contributes to improved soil structure and nutrient availability, which can further stabilize pH levels (Hussain *et al.*, 2021). When introduced into cow dung-amended soils, EW enhance nutrient cycling and soil aeration, which improves pH levels. Their activity transforms OM into more soluble forms, making nutrients more accessible to plants and potentially stabilizing pH (Hussain *et al.*, 2021). Green manuring practices not only improve soil fertility but also help in managing soil pH effectively, as observed in various field experiments (Singh *et al.*, 2013).

Organic matter content: The OM content in the post-harvest soil was significantly influenced by the use of IGM, CD, and EW. The highest OM content was observed in treatment T₈ (2.65%), which was not significantly different from T₉ (2.55%) and T₇ (2.50%). Treatments T₅ and T₆ showed moderate OM contents of 1.98% and 2.10%, respectively. The lowest OM content was found in

treatment T₁ (0.60%), which was slightly lower than the initial soil OM content of 0.73% (Table 10). Incorporating green manures into the soil increases OM content by providing nutrient-rich material that enhances microbial activity, which converts nutrients into forms accessible to crops. Continuous use of green manures improves soil physical, chemical, and biological properties, leading to higher OM levels (Das *et al.*, 2020). EW play a critical role in soil structure and OM dynamics by enhancing the incorporation of organic residues into soil aggregates, which stabilizes OM (Lubbers *et al.*, 2017). CD is an effective organic amendment that promotes soil reclamation and enhances nutrient availability. It has been shown that CD boosts soil carbon and nitrogen levels essential for OM formation, enhances nutrient bio-assimilation, and reduces heavy metal concentrations, thereby improving soil health (Hussain *et al.*, 2021).

Total nitrogen content: The total nitrogen content in the soil varied significantly between treatments with the applications of IGM and EW (Table 10). The results reveal that the total N content in the soil ranged from 0.03% to 0.20%. The highest nitrogen level (0.20%) was recorded in treatment T₈, which was not statistically different from T₉, where the N content was 0.18%. Furthermore, no significant differences were observed among treatments T₃ to T₆, indicating that these treatments had similar nitrogen levels. In contrast, the lowest N content (0.03%) was observed in treatment T₁, highlighting its limited effectiveness in enhancing soil nitrogen availability due to the absence of manuring and EW activity. These results highlight the importance of specific treatments in improving nitrogen content and overall soil fertility. The addition of IGM, EW, and CD enhanced total N content in post-harvest chilli soil through by promoting microbial activity and improving nutrient dynamics through synergetic effects. Organic amendments play a crucial role in enhancing N availability by stimulating microbial activity and nutrient cycling. Farmyard manure, for example, has been shown to boost nitrogen mineralization, releasing 142.40 mg N kg⁻¹ during incubation (Sah *et al.*, 2022). Similarly, arbuscular mycorrhizal fungi (AMF) and rhizobia contribute to nitrogen fixation and elevate soil nitrogen levels (Alqahtani & Wu, 2024), while nitrogen-fixing bacteria further enhance

nitrogen content in correlation with microbial abundance (Chakraborty *et al.*, 2020). The addition of organic amendments has been consistently linked to improved nitrogen mineralization (Fernández *et al.*, 2017; Alam *et al.*, 2024; Xu *et al.*, 2024) reinforcing their role in sustainable soil fertility management. Furthermore, green manures improve soil structure and OM content, which are essential for nutrient retention (Das *et al.*, 2020; Singh *et al.*, 2023). Earthworms also contribute by accelerating OM decomposition, thereby increasing nitrogen availability and stimulating microbial activity (Sukri *et al.*, 2020). However, the effectiveness of these amendments varies by soil type and environmental conditions, emphasizing the need to maximize their benefits.

Available phosphorus content: The available P content in the post-harvest soil was significantly affected by various combinations of organic amendments and EW (Table 10). The highest and statistically significant P content (123.9 ppm) was observed in the T₈ treatment, indicating the effectiveness of this combination in enhancing nutrient availability. Conversely, the lowest P content (99.18 ppm) was observed in the T₁ treatment, highlighting the limited impact of the absence of amendments on P availability. These findings underscore the importance of specific organic amendments and EW activity in improving soil fertility and nutrient content. The addition of IGM, EW, and CD significantly increases P content in post-harvest chilli soil through multiple synergistic mechanisms. Organic amendments enhance P availability by competing for adsorption sites on soil minerals and altering soil chemistry (Mendez & Vargas, 2024). Earthworms improve soil structure and aeration, promoting microbial activity that facilitates nutrient cycling (El-Jawaher & Dohaish, 2020; Liao *et al.*, 2023). Additionally, CD enriches the soil with nutrients and organic matter, stimulating microbial populations that solubilize P (Banamtuan *et al.*, 2020; Khan *et al.*, 2022). Integrated nutrient management combining organic inputs with balanced strategies improves soil fertility and crop yield (Vanlauwe *et al.*, 2010). However, excessive reliance on organic amendments alone may lead to nutrient imbalances (Densilin & Srinivasan, 2014).

Table 9. Chemical properties of soil after incorporation of IGM, EW and CD in the pots.

Properties	pH	OM (%)	N (%)	P (ppm)	K (meq 100 ⁻¹ g soil)	S (ppm)
NS	5.07 c	0.73 d	0.04 d	108.69 c	0.57 c	17.63 c
IGM	5.31 bc	1.26 c	0.07 cd	112.23 bc	0.60 bc	20.36 bc
IGM+EW	5.45 b	1.94 b	0.16 b	117.70 b	0.68 b	26.81 b
IGM+EW+CD	6.16 a	2.75 a	0.23 a	131.20 a	0.92 a	39.47 a

Table 10. Impact of IGM and EW on chemical properties of post-harvest soil of chili.

Treatments	pH	OM content (%)	Total N (%)	Available P (ppm)	Exchangeable K (meq100 ⁻¹ g soil)	Available S (ppm)
T ₁	5.66 e	0.60 e	0.03 e	99.18 i	0.31 e	15.44 i
T ₂	5.69 de	1.20 d	0.06 d	103.90 h	0.34 e	17.68 g
T ₃	5.80 cd	1.85 c	0.11 c	109.40 g	0.50 d	15.88 h
T ₄	5.85 c	1.90 c	0.12 c	111.20 f	0.53 d	18.70 f
T ₅	6.04 b	1.98 bc	0.12 c	117.90 d	0.72 c	24.36 b

T ₆	6.06 b	2.10 b	0.13 bc	121.40 b	0.74 bc	21.77 c
T ₇	6.37 a	2.50 a	0.15 b	119.90 c	0.78 abc	20.34 d
T ₈	6.45 a	2.65 a	0.20 a	123.90 a	0.83 ab	28.07 a
T ₉	6.40 a	2.55 a	0.18 a	116.81 e	0.87 a	20.15 e
LSD	0.122	0.153	0.011	0.080	0.092	0.065
CV %	1.42	5.34	12.79	1.48	1.09	10.53

i) T₁ = Control (IGM₀ + EW₀), ii) T₂ = IGM₀ + EW₄, iii) T₃ = IGM + EW₄, iv) T₄ = IGM + EW₆, v) T₅ = 25% CD of soil + EW₄, vi) T₆ = 25% CD of soil + EW₆, vii) T₇ = IGM + 25% CD of soil + EW₄, viii) T₈ = IGM + 25% CD of soil + EW₆, ix) T₉ = IGM + 25% CD of soil + EW₈. In the column, figures having similar letter(s) do not differ significantly at 5% level of significance

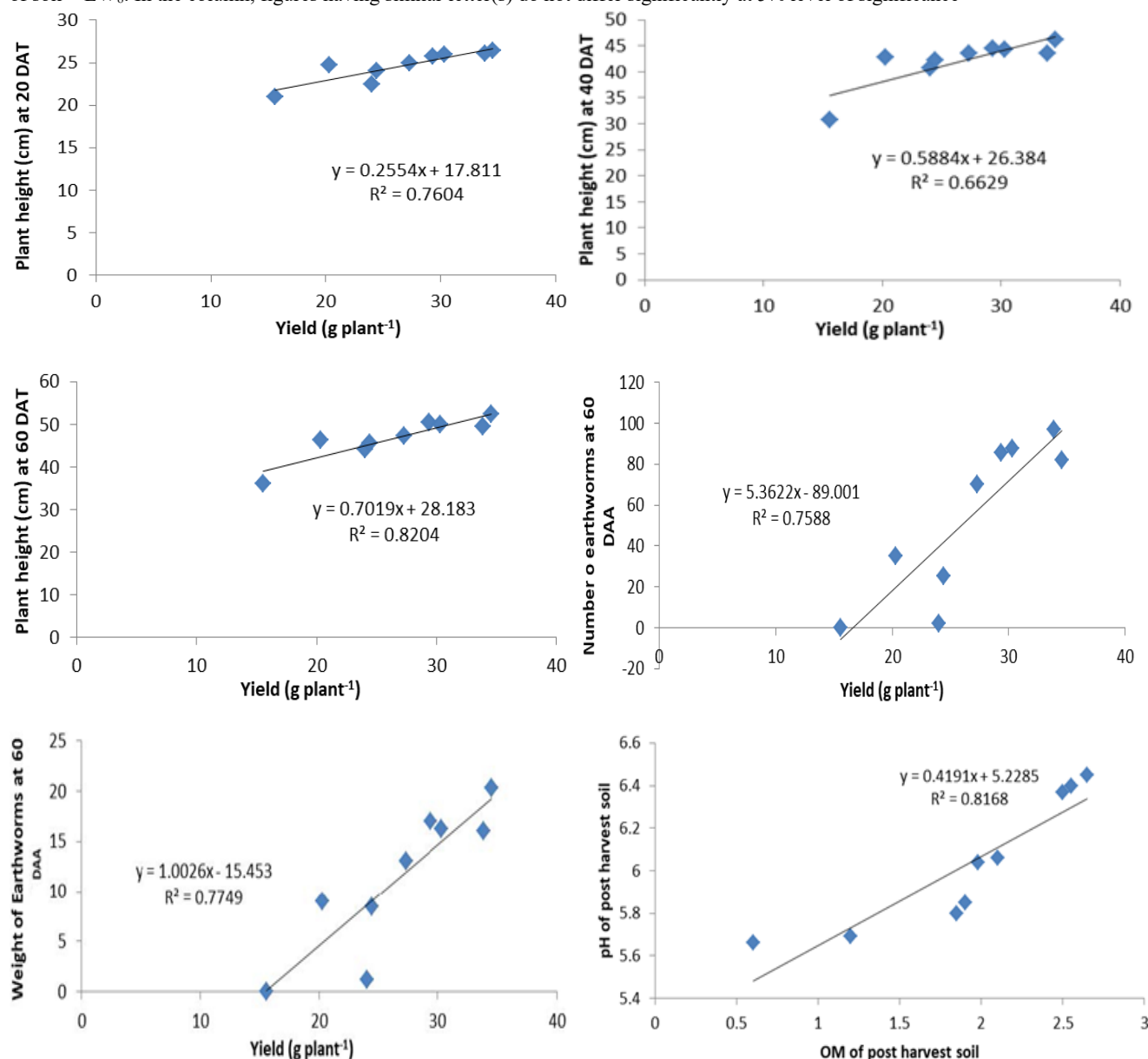


Fig. 1. Relationship between (a) plant height and yield of chili (g plant⁻¹) at 20 DAT, (b) plant height and yield of chili (g plant⁻¹) at 40 DAT, (c) plant height and yield of chili (g plant⁻¹) at 60 DAT, (d) number of EW and yield of chili, (e) weight of EW and yield of chili, (f) pH and OM content of the post-harvest soil.

Exchangeable potassium content: The exchangeable potassium (K) content in the soil varied significantly, ranging from 0.31 to 0.87 meq/100 g soil (Table 10). The highest value (0.87 meq/100 g soil) was recorded in the T₉ treatment, immediately preceded by the T₈ treatment at 0.83 meq/100 g soil, with T₇ also showing elevated levels. In contrast, the lowest exchangeable K content (0.31 meq/100 g soil) was recorded in the T₁ treatment. Our

findings indicates that T₁ and T₂ had similar exchangeable K levels, suggesting that the treatments applied in T₁ did not result in a notable increase in potassium availability compared to T₂. The addition of IGM, EW, and CD significantly enhances exchangeable K content in post-harvest chilli soil through improved nutrient dynamics and soil health. IGM contributes OM that, upon decomposition, releases K and improves soil structure and

nutrient retention (Sindhu *et al.*, 2016; Sharma *et al.*, 2024). EW increase microbial biomass, which aids in breaking down organic materials and promoting K solubilization (Adekiya *et al.*, 2020; Rathore *et al.*, 2020). CD, enriched with biofertilizers, enhances soil nutrient content, including K, and improves cation exchange capacity (Mavi & Benbi, 2008; Ayamba *et al.*, 2021). The integrated application of these organic inputs fosters a balanced nutrient profile, promoting overall soil fertility and maintaining K levels over time (Kumar & Pawar, 2018; Sindhu *et al.*, 2020). However, careful management is necessary to avoid nutrient imbalances or soil degradation (Densilin & Srinivasan, 2014).

Available sulfur: The different treatments had a significant impact on the available sulfur (S) content in the post-harvest soil. The available S content ranged from 15.44 to 28.07 ppm (Table 10). The greatest and statistically significant S content (28.07 ppm) was recorded in the T₈ treatment, while the lowest (15.44 ppm) was observed in the T₁ treatment. The incorporation of IGM, EW, and CD, whether applied individually or in combination, resulted in a notable increase in available S compared to the non-treated soil (T₁), highlighting the beneficial effect of these organic amendments on S availability. The addition of IGM, EW, and CD enhances S content in post-harvest chili soil through synergistic effects on OM and microbial activity. IGM enriches soil structure and microbial activity, promoting S mineralization (Singh & Singh, 2016). EW improve soil aeration and nutrient cycling, facilitating the breakdown of OM and sulfur compound release (Kolape *et al.*, 2024). CD acts as a nutrient-rich amendment that boosts sulfur levels and microbial diversity, essential for S transformation (Sukri *et al.*, 2020). This combination significantly increases soil OM, supporting sulfur levels and improving crop yield (Rakesh & Kumari, 2020; Filipek-Mazur *et al.*, 2022). However, monitoring nutrient balance is crucial to prevent deficiencies or toxicities from excessive OM (Tripathi *et al.*, 2018; Adekiya *et al.*, 2020; Das *et al.*, 2020; Paul *et al.*, 2024).

Correlation and regression studies: The Correlation studies among the different parameters are shown in Fig. 1. Crop yield was positively and significantly correlated with plant height, number of earthworm and weight of earthworm. Organic matter of post-harvest soil demonstrated a positive and significant correlation with soil pH. The incorporation of IGM, along with EW and CD, has significantly enhanced chili plant growth and soil health. The tallest plant height and maximum number of leaves were observed in treatment T₈, demonstrating that IGM effectively support vegetative growth. In contrast, the control treatment (T₁) consistently showed the lowest growth parameters, highlighting the importance of organic amendments. The integration of IGM also led to increased EW populations, with the highest numbers in treatment T₉. This boost in EW activity improved soil structure and nutrient availability, facilitating the breakdown of organic materials. Total N content in shoots, roots, and fruits was notably higher in treatments T₈ and T₉ compared to T₁, indicating the nutrient-enhancing effects of IGM and EW. Post-harvest soil analysis revealed elevated levels of total N, available P,

exchangeable K, and available S in treatments with IGM and EW, particularly in T₈. The correlation analysis highlighted significant relationships between plant height, earthworm activity, and nutrient availability, suggesting that these organic practices foster a beneficial cycle for crop productivity. However, the combined application of IGM, EW, and CD significantly enhances chili growth and yield while improving soil health.

Conclusion

The findings of this study emphasize the potential of organic amendments for sustainable agricultural practices, promoting both higher crop productivity and improved soil fertility. By integrating organic amendments such as IGM, along with earthworms (EW) and CD, the study demonstrates significant improvements in chili plant growth, including increased plant height, leaf number, and nutrient content. The positive combined effect of earthworm activity, nutrient availability, and plant growth suggests the synergistic benefits of organic amendments and soil biological processes. The enhanced soil health, as indicated by higher levels of total nitrogen, phosphorus, potassium, and sulfur, further supports the notion that organic amendments can improve nutrient cycling and soil structure, leading to enhanced soil fertility. This study provides evidence that organic practices, especially the combined use of IGM, EW, and CD, can develop a sustainable approach to chilli crop farming that enhances both crop yield and soil health. It underscores the importance of adopting such practices to reduce dependence on chemical fertilizers, and contribute to sustainable agriculture principle of minimizing environmental impact, and enhancing resilient agroecosystem. Therefore, incorporating these practices into chili farming systems can play a crucial role in addressing the soil degradation and crop sustainability.

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