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ORIGINAL RESEARCH

# Impact of Water Hyacinth Vermicompost on Rice (*Oryza sativa*) Growth and Soil Properties in Organic Farming Systems

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**Abstract**

**Purpose:** Water hyacinth (*Eichhornia crassipes L.*) is an invasive aquatic weed that threatens freshwater ecosystems, while fly ash (FA), a by-product of coal-based power plants, poses significant environmental disposal challenges. This study aimed to evaluate the potential of vermicomposting water hyacinth with fly ash to produce a nutrient-rich organic amendment and assess its effects on soil properties and rice (*Oryza sativa L.*) seedlings growth.

**Methods:** Vermicompost was prepared using different ratios of water hyacinth and fly ash (R1-R5) with *Eisenia foetida*, while conventional compost of the same substrate served as the control. Soils were amended with 0-50% compost or vermicompost, and rice seeds were sown in triplicate for a duration of 60 days. Plant growth parameters, soil physicochemical properties and heavy metals concentrations were analysed.

**Results:** Vermicompost significantly improved soil properties compared to compost, enhancing pH, EC, organic carbon, organic matter, phosphate content, and water-holding capacity. Rice seedlings grown with vermicompost exhibited superior growth, with optimal effects at 40% application (T5vc). Heavy metals concentrations decreased over time, indicating its remediation potential. Principal component and cluster analysis confirmed that vermicompost exerted a stronger and more consistent positive impact on both soil quality and seedling growth compared to compost.

**Conclusion:** Vermicomposting of water hyacinth with fly ash offers a sustainable approach to converting invasive aquatic weed and industrial waste into a nutrient rich soil amendment. A 40% vermicompost application optimally enhances soil fertility, promotes the growth of rice seedling, improves physiological performance, and reduces heavy metal risks, supporting its use in sustainable agricultural practices.

**Keywords:** Compost, Vermicompost, Water hyacinth, Rice seedlings, Soil quality



## 1. Introduction

Water hyacinth (*Eichhornia crassipes*) is a free-floating perennial aquatic weed belonging to the family *Pontederiaceae*. Water hyacinth adversely affects the ecological health of the freshwater ecosystem due to its higher multiplication rate (Lahon et al., 2023). it is one of the most noxious aquatic weeds and continues to spread aggressively throughout temperate, tropical, and sub-tropical climates (Dagno et al., 2007). It forms rapid mat-like proliferation, which covers the entire freshwater posing a major problem in Indian water bodies as it induces evapotranspiration rate leading to more loss of water from aquatic bodies. Its rapid growth blocks water bodies and interrupts the functioning of power plants, creating a global problem (Nandiyanto et al., 2024). Additionally, water hyacinths can block sunlight from penetrating the water bodies and reduce oxygen levels, disrupting aquatic bodies due to lack of oxygen (Madikizela, 2021). There are 4 commonly used control methods to suppress the growth of water hyacinth, such as physical, cultural, biological, and chemical control. However, Abbasi and Ramasamy (Abbasi & Ramasamy, 2001)have reported that water hyacinth has compressively resisted physical, chemical, and biological hybrid means used to eliminate it.

Fly ash (FA) is generated in large quantities by coal- and lignite-based thermal power plants, requiring extensive land for disposal and posing serious risks to air and water quality. During 2022–2023, data from 175 thermal power plants indicated a total coal consumption of 401.15 million tons, with an installed capacity of 205,623 MW. The average ash content was 35.41%, resulting in the generation of 142.07 million tons of fly ash, of which 111.01 million tons (78.14%) were utilized across various sectors (Central Electricity Authority, 2023). Despite this level of utilization, fly ash production continues to present significant environmental challenges due to its fine particle size, non-reactive nature, presence of toxic elements, and the sheer volume generated. Disposal remains a critical concern, as fly ash is predominantly stored in ash ponds, creating continuous pressure to identify additional land for disposal. Moreover, the rapid expansion of coal-based thermal power generation can severely disrupt natural ecosystems through deforestation, population displacement, and the release of solid wastes, effluents, and gaseous emissions. Therefore, there is an urgent need to adopt improved processing and management strategies for fly ash and related industrial wastes to transform them into valuable resources.

Biological approaches such as composting and vermicomposting have been widely adopted for the management of solid organic wastes, as they convert waste materials into nutrient-rich organic fertilizers. Among these methods, vermicomposting offers several advantages over conventional composting, including shorter processing time and the production of a physically, nutritionally, and biochemically superior end product. Vermicomposting is a biological process in which earthworms and associated microorganisms act synergistically to decompose and stabilize organic matter, resulting in a homogeneous, stable, humus-like material known as vermicompost. During this process, essential nutrients such as nitrogen, phosphorus, potassium, and calcium are transformed into soluble forms that are readily available for plant uptake. Vermicompost improves soil organic matter content, porosity, and water-holding capacity, while supplying readily available macro- and micronutrients that promote root growth, shoot development, and leaf expansion (Karademir & Kibar, 2022; Rehman et al., 2023). In addition, vermicompost serves as a rich source of organic carbon and provides numerous microsites for microbial activity, enhancing nutrient retention and soil fertility (Arancon et al., 2004, 2006; Edwards et al., 2011; Nielson, 1965; Tomati et al., 1988). Furthermore, studies by Nielson , 1965 and Tomati et al. , 1988 have reported that earthworms secrete plant growth–promoting substances, including auxins, cytokinins, and gibberellin-like compounds, during the vermicomposting process.

Several studies have demonstrated that vermicompost can serve as an effective alternative to inorganic fertilizers for promoting plant growth (Ansari et al., 2016; Chauhan & Singh, 2015; Sinha & Rajiv, 2008). However, Edwards, 1995 and Edwards et al., 2004 emphasized that the growth-promoting effects of vermicompost are influenced by its biological characteristics, the plant species involved, and the cultivation conditions under which plants are grown. Vermicompost has been shown to significantly enhance vegetative growth, particularly during germination and early seedling stages, by stimulating shoot and root development, promoting flowering, and increasing flower number and biomass (Arancon et al., 2004; Atiyeh, Lee, et al., 2002; Ievinsh, 2011). In addition, vermicompost has been reported to improve fruit yield (Atiyeh et al., 2001; Atiyeh, Lee, et al., 2002; Tian et al., 2024), Compared with conventional compost, vermicompost exhibits distinct advantages, including lower levels of actinomycetes, increased fungal abundance, and reduced total microbial biomass (Lazcano et al., 2008), although both compost and vermicompost contain plant growth–promoting hormones (Hameeda et al., 2006). Moreover, when applied in fields, vermicompost enriches soil quality by augmenting microbial activity and biomass. These microbes play a pivotal role in nutrient cycling, synthesis of plant growth regulators, and defense against soil-borne diseases and arthropod pests (Ansari et al., 2011, 2016; Chauhan & Singh, 2013).

Recent studies have highlighted the beneficial effects of vermicompost derived from plant residues on plant growth and phytochemical attributes. Bohlouli et al., 2024 reported that vermicompost produced from pistachio and madder wastes significantly enhanced biomass production, essential oil yield, and antioxidant activity in *Dracocephalum kotschyi*. Their findings demonstrate that plant materials rich in phenolic compounds can be effectively recycled into vermicompost to improve phytochemical traits while supporting sustainable biomass management. Similarly, Oliveira et al., 2024 showed that vermicompost derived from corn residues markedly improved the growth and development of cherry tomato seedlings under semiarid conditions, with higher application rates leading to increased plant biomass and nutrient uptake, underscoring its potential as a sustainable organic fertilizer for horticultural crops. Furthermore, Iraji et al., 2025 and Syarifinnur et al., 2024 emphasized composting and vermicomposting as effective approaches for sustainable waste management and resource recovery, demonstrating improvements in soil structure, nutrient availability, and plant productivity, alongside reduced dependence on chemical fertilizers and mitigation of environmental impacts. Nevertheless, the application of vermicompost must be carefully managed in agricultural and horticultural systems (Ievinsh, 2011), highlighting the importance of determining optimal and cost-effective application rates (Moghadam et al., 2012). In this context, the present study aims to evaluate the effects of varying vermicompost concentrations on seed germination, morphological growth parameters of *Oryza sativa* (rice), and the physicochemical properties of the soil system.

## 2. Materials and methods

### 2.1. Collection of rice seeds and soil

The experiment was conducted during the rice seedling season of 2021 (March to May) in the campus of Sambalpur University, Burla, Odisha, India. Healthy rice seeds of the Hardil variety were collected from a farmer in Bargarh District, Odisha, India. The soil sample was collected from a fallow land near Sambalpur University, Burla, Odisha. The initial characteristics of the soil sample are given in Table 1.

**Table 1.** Initial characteristics of soil.

| Sl. No. | Parameters | Mean ± SD |
|---|---|---|
| 1 | pH | 6.56 ± 0.02 |
| 2 | EC (dS/m) | 0.62 ± 0.05 |
| 3 | Organic Carbon (%) | 4.12 ± 0.05 |
| 4 | Organic Matter (%) | 7.10 ± 0.08 |
| 5 | Water Holding Capacity (%) | 526.67 ± 66.58 |
| 6 | Phosphate (mg/Kg) | 5.36 ± 0.04 |
| 7 | Nitrate (mg/Kg) | 6.15 ± 1.91 |
| 8 | Zn (mg/Kg) | 124 ± 0.02 |
| 9 | Mn (mg/Kg) | 152.12 ± 0.04 |
| 10 | Cd (mg/Kg) | 0.2 ± 0.001 |
| 11 | Pb (mg/Kg) | 0.6 ± 0.005 |
| 12 | Cr (mg/Kg) | 3.2 ± 0.02 |

All the values are in Mean ± SD, where n = 3

### 2.2. Collection and preparation of Water Hyacinth manure

Water Hyacinth was collected from an aquatic body near Sambalpur, Odisha, India (Figure 1). Vermicompost was prepared by mixing Water hyacinth and fly (WH + FA) ash in different proportions (Table 2) along with an epigeic earthworm i.e., *Eisenia foetida* (Figure 2). The substrate material (WH + FA) was shredded into pieces of 1-2cm before feeding into the reactors. The treatments were left for 20 days before inoculating earthworms for thermal stabilization, initiation of microbial degradation, and softening of substrate material in a shady area. 20 earthworms were inoculated into each reactor. The whole setup was carried out at room temperature and moisture. The mixtures were turned manually every 24 hours for 20 days to eliminate the volatile gases that may have potentially toxic effects on earthworms. These treatments were maintained for about 70 days and the chemical and elemental composition for each was determined. As reported in our previous study (Mishra et al., 2025), R5 yielded the best quality vermicompost (Table 3), therefore, this material was selected and incorporated into soil at different proportions for subsequent investigation. Subsequently, compost was prepared in the same proportion as that of R5 to compare the effect of both compost and vermicompost on the growth of Rice plants and soil physicochemical properties.


**Figure 1.** Sampling site of water hyacinth near Sambalpur University (Power Channel of Hirakud Reservoir, Burla, Odisha).

**Table 2.** Mixing proportion of Fly Ash and Water Hyacinth during vermicomposting.

| Reactor | Substrate material(g) | Fly ash(g) |
|---|---|---|
| $R_1$ | 0 | 1000 |
| $R_2$ | 1000 | 0 |

| | | |
|---|---|---|
| $R_3$ | 250 | 750 |
| $R_4$ | 500 | 500 |
| $R_5$ | 750 | 250 |

**Table 3.** Characteristics of compost and vermicompost used for sowing of rice seeds.

| Sl. No. | Parameters | Vermicompost | Compost |
|---|---|---|---|
| 1 | pH | 7.35 ± 0.12 | 6.82 ± 0.21 |
| 2 | EC (dS/m) | 6.6 ± 1.15 | 1.55 ± 0.41 |
| 3 | TOC (%) | 32.7 ± 1.97 | 16.6 ± 1.08 |
| 4 | OM (%) | 56.37 ± 3.39 | 28.61 ± 1.82 |
| 5 | TKN (%) | 1.34 ± 0.018 | 1.08 ± 0.02 |
| 6 | C/N | 19.94 ± 0.05 | 15.37 ± 0.08 |
| 7 | TAP (ppm) | 7.01 ± 0.1 | 6.21 ± 0.61 |
| 8 | Zn (mg/Kg) | 98.87 ± 0.01 | 110.3 ± 0.025 |
| 9 | Cd (mg/Kg) | 5 ± 0.01 | 6.21 ± 0.02 |
| 10 | Cr (mg/Kg) | 18.52 ± 0.02 | 28.13 ± 0.005 |
| 11 | Pb (mg/Kg) | 12.26 ± 0.01 | 30.02 ± 0.002 |
| 12 | Mn (mg/Kg) | 72 ± 0.02 | 92.32 ± 0.005 |

All the values are in mean ± SD, where n = 3

**2.3. Experimental set up**

One kg of soil was mixed with different combinations of vermicompost (Table 4) and compost of Water Hyacinth (WH) + Fly Ash (FA) i.e., 0% (control), 5%, 10%, 20%, 30%, 40%, and 50%. Experiments were conducted in triplicate, and average values were recorded. Plastic pots were used for sowing the rice seeds. twenty healthy rice seeds were soaked overnight and sown in the pots the next day. Figure 2 illustrates the detailed workflow of vermicomposting and composting of Water Hyacinth (WH) and Fly Ash (FA), along with their applications in rice plants.

**Table 4.** Details of different treatment combinations used for growing Rice seedlings.

| Treatments | Compost/Vermicompost (in g) | Soil (in g) |
|---|---|---|
| Control | - | 1000 |
| $T_{1c}/T_{1vc}$ | 50 | 950 |
| $T_{2c}/T_{2vc}$ | 100 | 900 |
| $T_{3c}/T_{3vc}$ | 200 | 800 |
| $T_{4c}/T_{4vc}$ | 300 | 700 |
| $T_{5c}/T_{5vc}$ | 400 | 600 |
| $T_{6c}/T_{6vc}$ | 500 | 500 |

**2.4. Analysis of plant and soil sample**

After 60 days of growing rice seedlings, growth parameters like germination percentage, root, and shoot length, number of leaves, root-to-shoot ratio, and fresh weights of the seedlings were investigated. Total chlorophyll content and protein content of leaves were analyzed according to standard protocol of Arnon, 1949 and Lowry et al., 1951 respectively. Soil samples were analyzed for pH and EC by substrate to water extract ratio of 1:5 (w/v) by electrometric method, Water holding capacity (WHC) by approximation method, Nitrate by phenol disulphonic method, and phosphate content by stannous chloride method, organic carbon (OC) and organic matter (OM) content by Walkley and Black rapid titration method (Walkley & Black, 1934). Digestion for heavy metals was done in a microwave digester (ETTHOS EASY microwave digestion system, make the milestone, Italy), and SK-14 rotors were used. Then the digested samples were determined by Inductively coupled plasma mass spectroscopy (Agilent's 7900, ICP-MS).

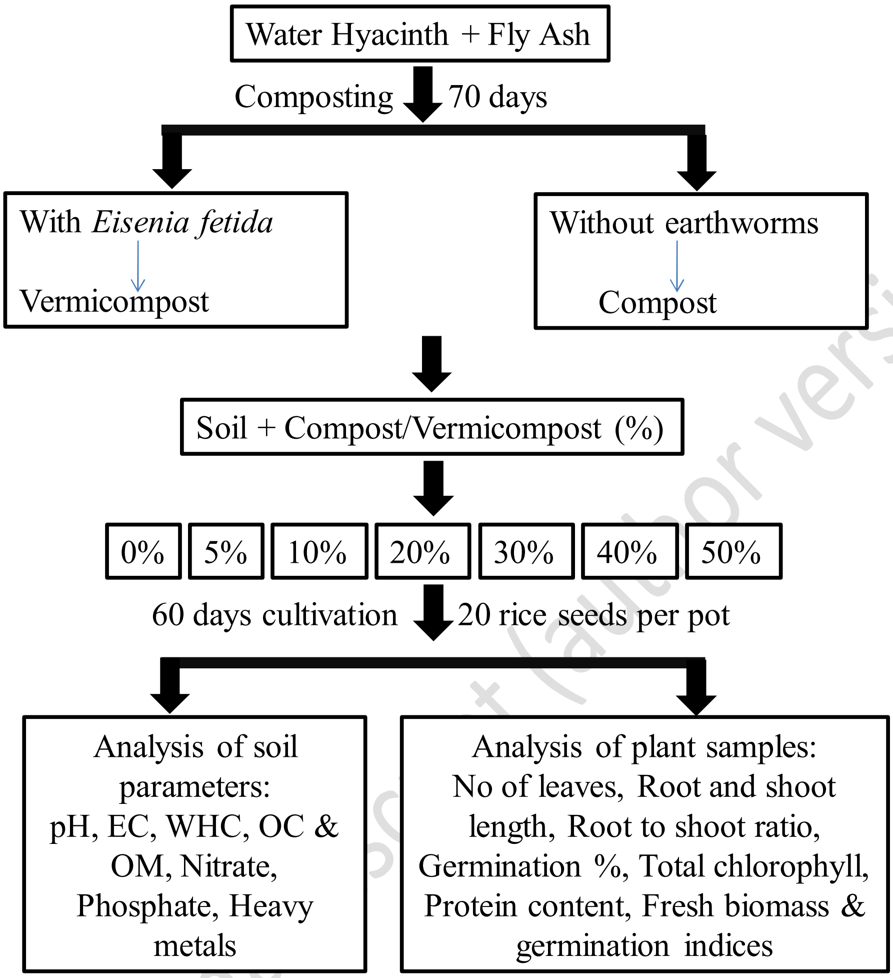



**Figure 2.** Work flow of vermicomposting and composting of Water Hyacinth (WH) and Fly Ash (FA)and its applications in rice plants.

### 2.5. Germination indices

Germination potential, Germination index, and Vigor index (Gupta, 1993) were calculated by the following formula:

$$\text{Germination potential (\%)} = \frac{\text{Number of rice seeds germinated within 3 days}}{\text{Total number of seeds tested (20 grains)}} \times 100$$

$$\text{Germination Index} = \frac{\text{Number of seeds germinated on day (1 − 7 days)}}{\text{The number of germination days (1 − 7 days)}}$$

$$\text{Vigor Index} = \text{Germination percentage} \times \text{Seedling length}$$

### 2.6. Statistical analysis

Statistical analysis of physicochemical parameters of soil was conducted using two-way analysis of variance (ANOVA). The mean and standard deviation for each reactor were calculated from triplicate measurements using MS Excel. Principal component analysis (PCA) and cluster analysis were carried out using Origin Pro 2024b.

## 3. Results and Discussion

### 3.1. Vermicompost significantly improved physicochemical properties of the soil compared to only compost treatment.

The physicochemical properties, such as, pH, EC, OC, OM, nitrate, phosphate content, and WHC, of all the treatments were analyzed after 60 days of sowing rice seeds (Table 5). Initially, the soil pH was slightly acidic (6.56± 0.02). However, the application of compost and vermicompost increased the soil pH significantly ($F_{(1,6)} = 22.5$; $p \geq 0.001$), with vermicompost-amended soil showing higher alkalinity (7.3 ± 0.08 to 7.8 ± 0.1) compared to compost (7.2 ± 0.05 to 7.3 ± 0.04). This observation is consistent with the findings of Fernández-Bayo et al. (2009) and Padmavathiamma et al. (2008), who reported that vermicompost can increase soil pH owing to its buffering capacity. This effect is particularly beneficial in acidic soils, where vermicompost helps suppress the release of labile aluminium. Electrical conductivity (EC) increased significantly ($F_{(1,6)} = 106$; $p \geq 0.001$) in all the treatments, with vermicompost showing the highest rise (T6vc: 4.77± 0.63 dS/m) compared to the control (0.88 ± 0.02 dS/m). This increase can be attributed to the high ion content in the composting materials, WH and FA, both of which are known to have high EC. The electrical conductivity of vermicompost relies on the raw materials utilized in the vermicomposting process and is correlated with their ion concentrations (Gutiérrez-Miceli et al., 2007). An increasing trend in organic carbon percentage (OC%) was also observed with higher doses of compost/vermicompost, with vermicompost-treated soils consistently showing higher values. The highest OC% was found in T6vc (11.8 ± 1.7%), and the lowest in the control (4.18 ± 0.11%). This trend is consistent with the findings of Chaoui et al., 2003, who highlighted the low C/N ratio of vermicompost as a favourable property for enhancing soil fertility. Soil nitrate content initially increased with compost/vermicompost application, but a significant decrease ($F (1,6) = 7$; $p \geq 0.01$) in nitrate was observed with higher vermicompost concentrations. This could be due to rapid nitrate uptake by growing rice plants, as suggested by Masciandaro et al., 2010, who reported nitrate depletion from vermicompost due to plant absorption, which also reduces the risk of leaching.

Phosphate content and Water-holding capacity (WHC) also improved significantly ($F_{(1,6)} = 42.19$; $p \geq 0.001$). The enhancement in WHC can be attributed to improved porosity and structure due to the organic matter in vermicompost, which is consistent with the findings of Kumar, 2005. The added organic matter helps retain moisture, thereby improving in better root absorption and plant hydration. Vermicompost is rich in plant-available nutrients, such as nitrate, phosphate, potassium, calcium, and magnesium (Atiyeh et al., 2000; Prabha, 2009), which likely contributed to these improvements. Furthermore, vermicompost can act as a slow-release fertilizer with readily available nutrients (Atiyeh et al., 2001), unlike many chemical fertilizers which may be more nutrient-dense but less plant-accessible. Furthermore, several species of phosphate-solubilizing bacteria have been reported in earthworm casts, which could play a crucial role in mobilizing the phosphate reserves in fly ash (Biswas et al., 2018). Depending on the parent material, vermicompost can serve as an exceptionally nutrient-rich medium, providing not only an immediate supply of plant nutrients but also augmenting reserves for future crops.

**Table 5.** Effect of Compost/Vermicompost on soil physico-chemical properties.

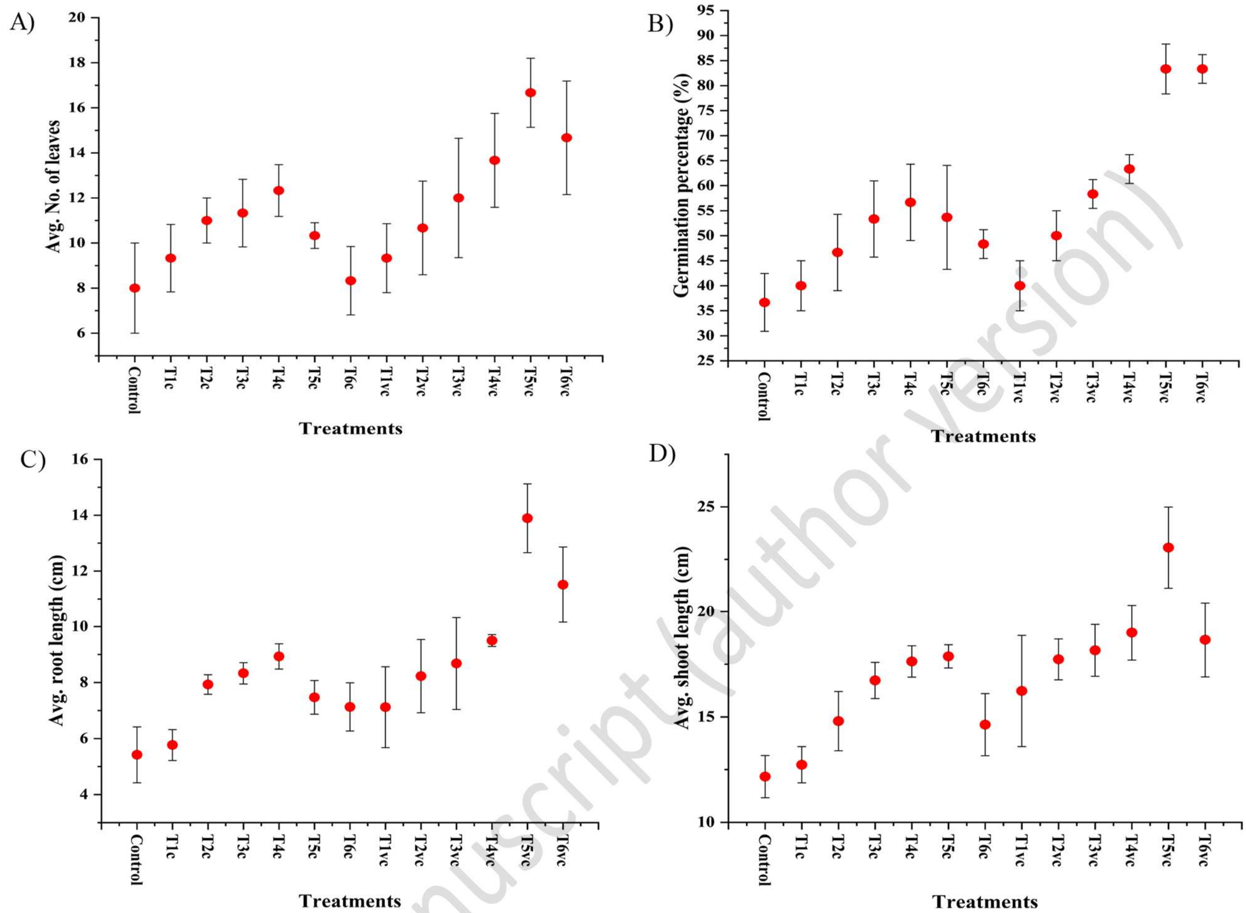
| Treatments | pH | EC (dS/m) | WHC (%) | OC (%) | OM (%) | Phosphate (ppm) | Nitrate (ppm) |
|---|---|---|---|---|---|---|---|
| Control | 6.5 ± 0.09 | 0.88 ± 0.64 | 543.33 ± 55.08 | 4.18 ± 0.11 | 7.21 ± 0.18 | 5.36 ± 0.35 | 6.31 ± 0.6 |
| $T_{1c}$ | 7.26 ± 0.05 | 1.12 ± 1.24 | 546.67 ± 30.55 | 4.58 ± 0.22 | 7.51 ± 0.45 | 5.55 ± 0.73 | 10.09 ± 0.54 |
| $T_{2c}$ | 7.27 ± 0.13 | 1.34 ± 0.96 | 596.67 ± 25.17 | 4.85 ± 0.09 | 8.37 ± 0.16 | 5.95 ± 0.83 | 9.36 ± 0.88 |
| $T_{3c}$ | 7.32 ± 0.11 | 1.37 ± 1.11 | 616.67 ± 30.55 | 5.31 ± 0.34 | 8.64 ± 0.4 | 6.67 ± 0.53 | 9.92 ± 0.84 |
| $T_{4c}$ | 7.34 ± 0.08 | 2.17 ± 0.95 | 656.67 ± 20.82 | 6.22 ± 0.39 | 10.59 ± 0.85 | 6.79 ± 0.83 | 9.11 ± 1.82 |
| $T_{5c}$ | 7.35 ± 0.08 | 2.38 ± 0.59 | 720 ± 26.46 | 7.17 ± 0.15 | 12.33 ± 1.34 | 7.52 ± 0.67 | 8.77 ± 1.88 |
| $T_{6c}$ | 7.38 ± 0.04 | 3.73 ± 0.39 | 743.33 ± 15.28 | 7.06 ± 0.16 | 12.16 ± 0.2 | 7.46 ± 1.18 | 8.05 ± 1.36 |
| $T_{1vc}$ | 7.31 ± 0.08 | 1.94 ± 0.55 | 583.33 ± 55.08 | 8.74 ± 1.61 | 15.04 ± 2.78 | 6.35 ± 0.88 | 11.93 ± 2.77 |
| $T_{2vc}$ | 7.5 ± 0.04 | 2.37 ± 0.81 | 656.66 ± 45.09 | 8.91 ± 1.53 | 15.32 ± 2.64 | 6.64 ± 0.73 | 11.79 ± 0.56 |
| $T_{3vc}$ | 7.56 ± 0.08 | 2.42 ± 0.71 | 700 ± 20 | 9.61 ± 1.51 | 16.53 ± 2.59 | 7.13 ± 0.82 | 11.37 ± 0.82 |
| $T_{4vc}$ | 7.62 ± 0.05 | 2.86 ± 0.46 | 753.33 ± 30.55 | 11.21 ± 1.76 | 19.28 ± 3.03 | 7.57 ± 0.77 | 11.03 ± 0.23 |
| $T_{5vc}$ | 7.69 ± 0.06 | 3.16 ± 0.55 | 780 ± 40 | 11.83 ± 1.65 | 20.35 ± 2.84 | 8.35 ± 1.36 | 9.07 ± 1.3 |
| $T_{6vc}$ | 7.81 ± 0.1 | 4.77 ± 0.63 | 793.33 ± 23.09 | 11.87 ± 1.7 | 20.46 ± 2.93 | 8.06 ± 1.42 | 8.49 ± 0.86 |
| p- value | 0.001 | 0.001 | 0.001 | 0.035 | 0.046 | 0.001 | 0.016 |

All the values are in mean ± SD, where n = 3

### 3.2. Vermicompost application enhanced rice seedling growth and physiological performance, with optimal effects at moderate concentrations.

Application of compost and vermicompost both significantly improved the growth and physiological parameters of rice seedlings compared to control after 60 days, with vermicompost showing a stronger positive effect (Figure 3).The variation in plant growth between compost and vermicompost amendments is primarily due to differences in their nitrogen mineralization rates (Ievinsh, 2020). Among compost treatments, T4c showed the highest germination percentage (56.66 ± 7.63), while T5c had the highest root and shoot length and fresh weight. According to Vuković et al., 2022, the increased root and shoot length observed in T5c may be attributed to higher levels of plant pigments, such as chlorophyll, which enhance photosynthetic activity and thereby promote plant growth. The number of leaves was also highest in T4c (12.33 ± 1.15). However, vermicompost outperformed compost in all treatments. T5vc (40% vermicompost) yielded the maximum values for germination (83.33%), shoot length (23.06 ± 1.93 cm), root length (13.89 ± 1.23 cm), fresh weight (15.72 ± 1.61 g), and number of leaves (16.67). This corroborates findings from Majid, 1986; Majid et al., 1980, who reported increased crop yields with water hyacinth-based composts. The enhanced growth can also be attributed to the presence of plant hormone-like compounds in vermicompost. Studies by Bachman and Metzger , 2008, and Atiyeh, Arancon, et al., 2002; Atiyeh, Lee, et al., 2002 have shown that vermicompost contains auxins, gibberellins, and cytokinins synthesized by microbial action during composting, promoting root initiation, elongation, and shoot development effects clearly observed in our T5vc treatment. Additionally, vermicompost's beneficial effect on rice growth supports previous findings from Gunnarsson & Petersen , 2007 and Kayum et al. , 2008, who demonstrated improved fertility and yield from water hyacinth manure. These improvements in our study also align with Doan et al. , 2013 and Pramanik et al. , 2009, who observed increased mineralizable nitrogen and phosphorus due to vermicompost application.

However, at higher concentrations of compost and vermicompost, growth of rice plant declined. Supporting our findings, Ievinsh et al. (2020) reported a gradual decline in the growth of *T. vulgaris* at 30% and 40% compost, and 40% vermicompost, possibly due to certain chemical constituents in the amendments exerting negative effects on the plant. The dose-dependent response, where lower vermicompost levels are more effective than higher ones, indicates the existence of an optimal application rate for maximizing plant growth. Excessive application can result in nutrient imbalances or other adverse effects that hinder development. Meta-analysis carried out by Blouin et al., 2019 indicates that the beneficial impact of vermicompost peaks when it constitutes 30%–50% of the soil volume. While vermicompost is known to promote root branching, surpassing this optimal range may cause stunted root growth or reduced branching due to nutrient toxicity, imbalance, or competition among soil microorganisms (Makkar et al., 2017).


A)
Avg. No. of leaves
Treatments
B)
Germination percentage (%)
Treatments
C)
Avg. root length (cm)
Treatments
D)
Avg. shoot length (cm)
Treatments
Control
T1c
T2c
T3c
T4c
T5c
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T4vc
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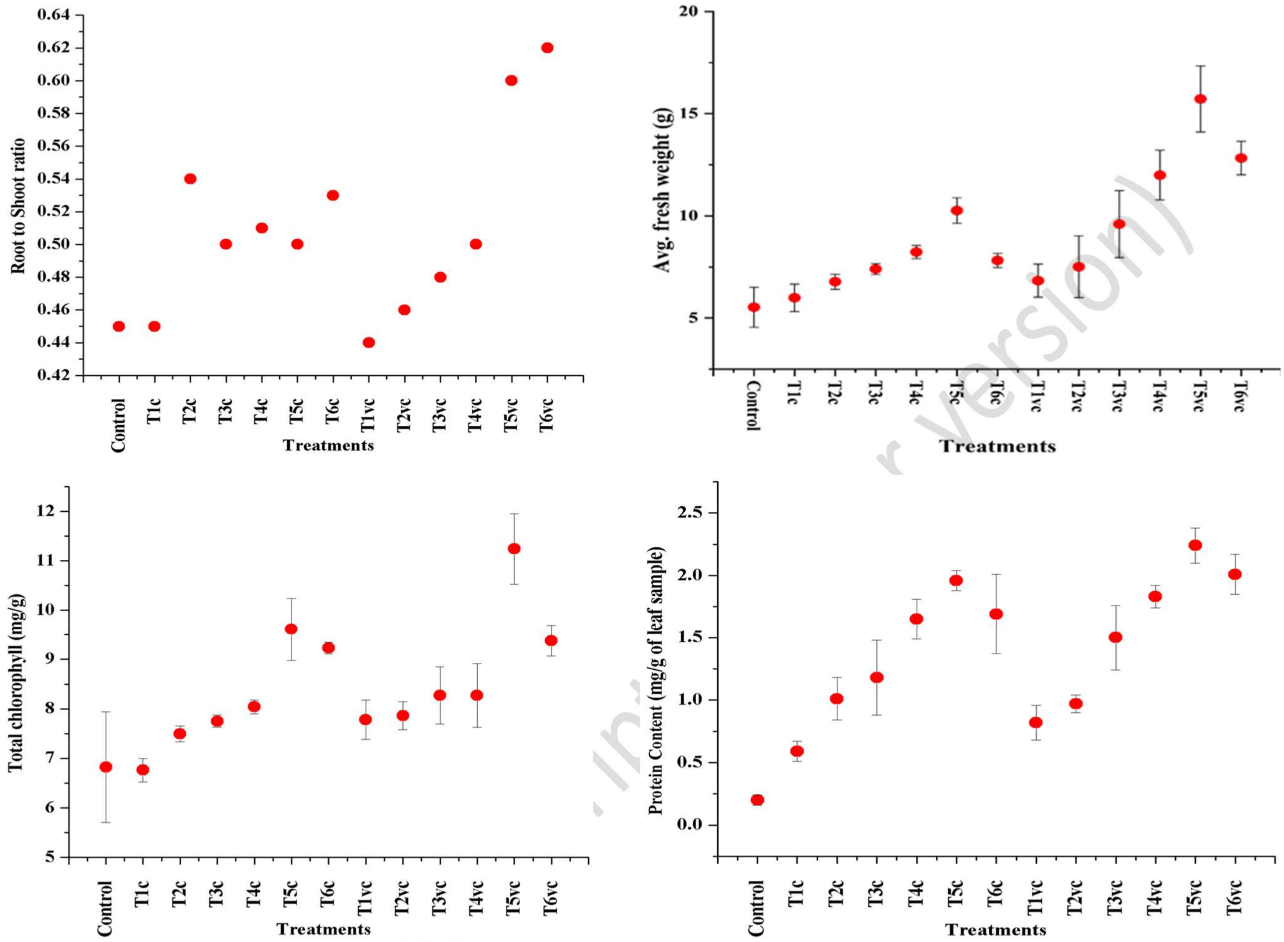


**Figure 3.** Variation in growth and biochemical parameters of Rice seedlings followed by application of compost/vermicompost **A.** Average No. of leaves, **B**. Germination Percentage, **C**. Average Root length, **D**. Average Shoot length, **E.** Average Fresh Weight**, F.** Root to Shoot Ratio, **G.** Total Chlorophyll Content, **H**. Protein Content (Vertical bars indicate standard errors)

**3.3. Optimal 40% vermicompost application maximizes chlorophyll and protein content in rice leaves**

Chlorophyll content of leaves increased with increasing compost/vermicompost concentration up to 40%, after which it declined which may be due to toxicity or other adverse effects at higher doses as supported by Sari et al. , 2025. The maximum chlorophyll content was found in T5vc (11.24 ± 0.71 mg/g), followed by T5c (9.61 ± 0.63 mg/g), while control showed the least. The decline at 50% concentration could be due to salt stress or reduced oxygen availability from excessive organic matter. This trend reflects the balance between nutrient enrichment and potential phytotoxicity at higher concentrations. The optimal 40% application highlights the efficiency of vermicompost in enhancing photosynthetic activity through improved nutrient uptake and possibly hormonal stimulation. In addition to chlorophyll content, the results also indicate that increasing compost/vermicompost supplementation leads to a significant and linear enhancement in protein content. This suggests that organic amendment whether compost or vermicompost positively influence nutrient availability and microbial activity in the soil, which may contribute to improved protein synthesis in plants. In summary, the total chlorophyll and protein content results from this study further validate the beneficial role of compost and vermicompost as soil amendments, supporting their use in sustainable agriculture practices aimed at boosting crop nutritional value.

**3.4. Vermicompost application reduced heavy metal concentrations in amended soil**

Initial compost/vermicompost application increased concentrations of Zn, Mn, Pb, Cd, and Cr due to the nature of raw materials (e.g., fly ash), but their levels decreased over time (Table 6). T6vc showed the highest reduction in Zn (12.12%) and Mn (9.61%), while T5vc had the highest reductions in Pb (11.31%), Cd (8.91%), and Cr (9.20%). In contrast, compost treatments showed comparatively lesser reductions. These reductions suggest a bioremediation potential of vermicompost, possibly due to the formation of stable organic-metal complexes and enhanced microbial activity that facilitates metal immobilization or uptake by plants.

**3.5. Forty percent vermicompost maximized seed germination and seedling vigor, indicating an optimal application threshold**

The germination potential, germination index, and vigor index were highest in T5vc (40% vermicompost). Compost treatments peaked at 20–30% (T3c and T4c), after which performance declined (Table 7). This again supports the idea of an optimal threshold beyond which compost/vermicompost addition may be counterproductive due to excess salts or organic loading. The superior performance of T5vc across all germination metrics reinforces the positive role of vermicompost in improving seedling establishment through better nutrient availability, improved substrate texture, and presence of growth-promoting substances.

**Table 6**. Initial and Final concentration of heavy metals (ppm) with percent reduction ($\%_{red}$) in soil following application of compost/vermicompost.

| | Zn (ppm) | | | Mn (ppm) | | | Cd (ppm) | | | Pb (ppm) | | | Cr (ppm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Initial** | **Final** | $\%_{red}$ | **Initial** | **Final** | $\%_{red}$ | **Initial** | **Final** | $\%_{red}$ | **Initial** | **Final** | $\%_{red}$ | **Initial** | **Final** | $\%_{red}$ |
| **Control** | 124 | 123.32 | 0.55 | 152.12 | 150.08 | 1.34 | 0.21 | 0.20 | 4.76 | 0.60 | 0.58 | 3.33 | 3.20 | 3.08 | 3.75 |
| $T_{1c}$ | 132.08 | 130.35 | 1.31 | 154.09 | 152.10 | 1.29 | 0.32 | 0.31 | 3.13 | 12.28 | 12.13 | 1.22 | 13.40 | 12.83 | 4.25 |
| $T_{2c}$ | 133.10 | 129.01 | 3.07 | 154.72 | 152.04 | 1.73 | 0.62 | 0.59 | 4.84 | 12.56 | 12.36 | 1.59 | 14.02 | 13.52 | 3.57 |
| $T_{3c}$ | 134.36 | 128.85 | 4.10 | 155.38 | 151.24 | 2.66 | 0.85 | 0.82 | 3.53 | 14.02 | 13.84 | 1.28 | 14.98 | 13.85 | 7.54 |
| $T_{4c}$ | 136.60 | 128.01 | 6.29 | 157.28 | 152.61 | 2.97 | 1.02 | 0.98 | 3.92 | 15.1 | 14.04 | 7.02 | 15.35 | 13.98 | 8.93 |
| $T_{5c}$ | 138.81 | 129.82 | 6.48 | 157.87 | 150.42 | 4.72 | 1.32 | 1.28 | 3.03 | 15.38 | 14.12 | 8.19 | 16.31 | 15.31 | 6.13 |
| $T_{6c}$ | 141.81 | 132.35 | 6.67 | 159.04 | 151.16 | 4.95 | 1.69 | 1.65 | 2.37 | 16.53 | 15.18 | 8.17 | 16.78 | 15.98 | 4.77 |
| $T_{1vc}$ | 131.30 | 129.01 | 1.74 | 153.12 | 149.08 | 2.64 | 0.28 | 0.26 | 7.14 | 10.4 | 9.82 | 5.58 | 10.65 | 10.18 | 4.41 |
| $T_{2vc}$ | 132.02 | 128.18 | 2.91 | 153.86 | 147.4 | 4.20 | 0.32 | 0.3 | 6.25 | 10.51 | 9.84 | 6.37 | 10.98 | 10.31 | 6.10 |
| $T_{3vc}$ | 133.50 | 127.02 | 4.85 | 154.01 | 146.12 | 5.12 | 0.51 | 0.48 | 5.88 | 11.24 | 10.48 | 6.76 | 11.72 | 10.72 | 8.53 |
| $T_{4vc}$ | 134.90 | 122.86 | 8.93 | 155.31 | 144.18 | 7.17 | 0.73 | 0.68 | 6.85 | 11.68 | 10.78 | 7.71 | 12.51 | 11.43 | 8.63 |
| $T_{5vc}$ | 136.52 | 120.32 | 11.87 | 155.78 | 143.61 | 7.81 | 1.01 | 0.92 | 8.91 | 13 | 11.53 | 11.31 | 12.83 | 11.65 | 9.20 |
| $T_{6vc}$ | 138.39 | 121.62 | 12.12 | 157.10 | 142 | 9.61 | 1.24 | 1.16 | 6.45 | 13.34 | 12.33 | 7.57 | 13.69 | 12.68 | 7.38 |

**Table 7.** Effects of Compost/ Vermicompost on Germination potential (%), Germination Index and Vigour Index of Rice seedlings (Mean ± SD) where n = 3.

| Treatments | Germination Potential (%) | Germination Index | Vigour Index |
|---|---|---|---|
| Control | 16.66 ± 2.88 | 1.84 ± 0.02 | 644.85 ± 7.32 |
| $T_{1c}$ | 20 ± 5 | 2.09 ± 0.12 | 740 ± 8.92 |
| $T_{2c}$ | 23.33 ± 5.77 | 3.07 ± 0.21 | 1060.58 ± 5.77 |
| $T_{3c}$ | 26.66 ± 2.88 | 3.43 ± 0.05 | 1336.45 ± 7.82 |
| $T_{4c}$ | 23.33 ± 7.63 | 3.34 ± 0.14 | 1504.89 ± 10.02 |
| $T_{5c}$ | 21.66 ± 7.63 | 2.23 ± 0.12 | 1359.74 ± 9.21 |
| $T_{6c}$ | 16.66 ± 7.63 | 2.01 ± 0.12 | 1051.66 ± 8.32 |
| $T_{1vc}$ | 28.33 ± 2.88 | 2.65 ± 0.08 | 934 ± 9.51 |
| $T_{2vc}$ | 33.33 ± 2.88 | 3.12 ± 0.32 | 1298 ± 5.82 |
| $T_{3vc}$ | 38.33 ± 5.77 | 3.83 ± 0.23 | 1565.58 ± 8.24 |
| $T_{4vc}$ | 36.66 ± 2.88 | 3.85 ± 0.18 | 1804.91 ± 10.24 |
| $T_{5vc}$ | 43.33 ± 7.63 | 4.03 ± 0.14 | 3079.04 ± 10.78 |
| $T_{6vc}$ | 41.66 ± 7.63 | 3.32 ± 0.21 | 2514.07 ± 9.88 |

### 3.6. Principal component analysis revealed stronger positive influence of vermicompost over compost on rice seedling growth and soil properties

PCA biplot was performed to visualize the effect of different treatments of compost/vermicompost on Rice seedlings. The PCA resulted in 2 principal components i.e., PC1 and PC2 with loading values of 62.3% and 12.6% and eigen values of 10.82 and 1.55 respectively. The biplot shows a clear separation between compost and vermicompost treatments, while vermicompost shows a more significant and positive impact on Rice seedlings (Figure 4).

PC1 was positively loaded with almost all the parameters measured. This can be attributed to the fact that both vermicompost and compost had an enhanced effect on soil and the growth of Rice seedlings. Vermicompost treatments such as T2vc, T3vc, T4vc, T5vc, and T6vc are mainly clustered towards the right side of the biplot, whereas compost treatments such as T1c, T2c, T3c, T4c, T5c, and T6c are spread towards the left and lower part of the biplot. It implies that vermicompost treatments have a stronger and more prominent effect on the growth of Rice seedlings as well as soil quality as compared to compost treatments.

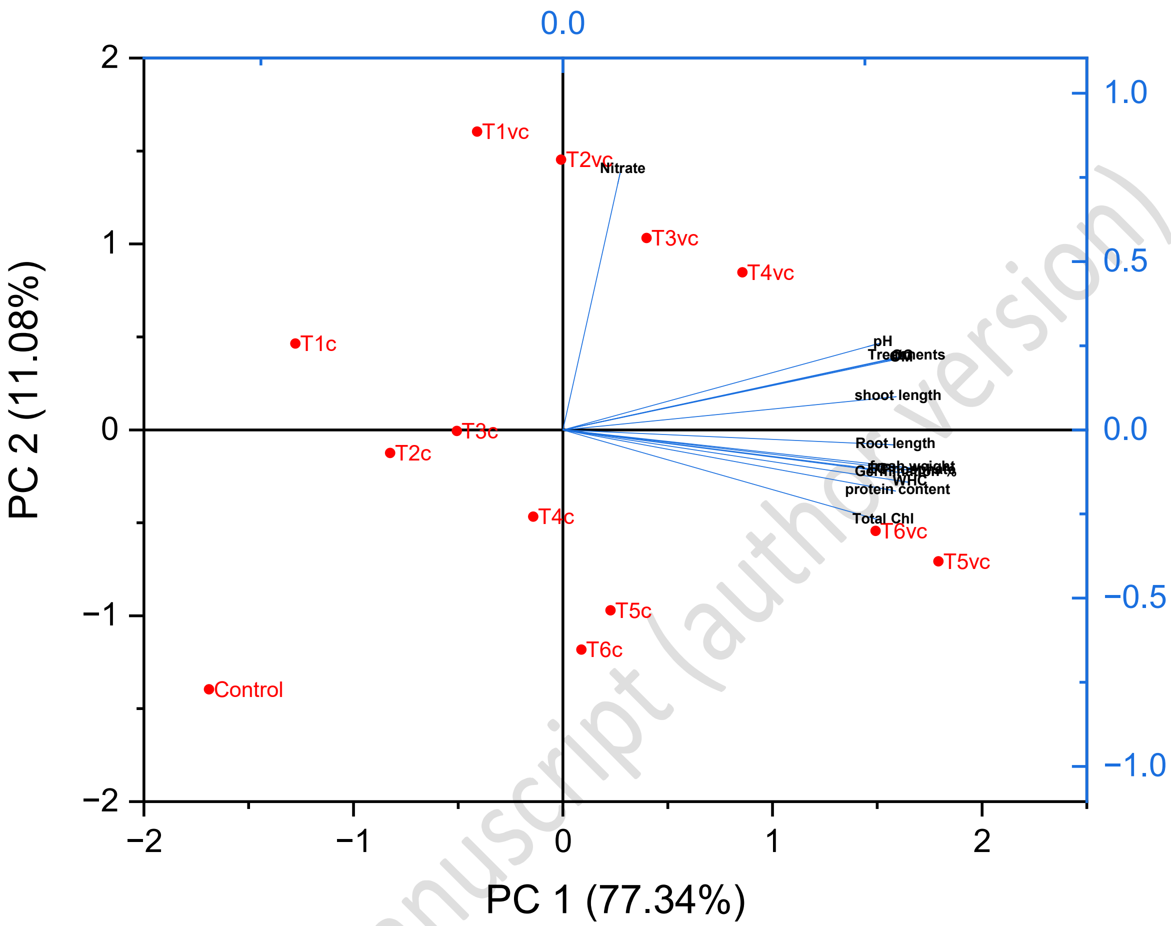


**Figure 4.** Biplot of Principal Component Analysis showing effect of compost/vermicompost on soil physicochemical properties and growth of rice seedlings (EC = Electrical Conductivity, WHC = Water Holding Capacity, OC = Organic Carbon, OM = Organic Matter, Total Chl = Total Chlorophyll, C: N = Carbon to Nitrogen ratio)

PC2 was positively loaded with nitrate content along with some influence from pH, OC, OM, and shoot length. Nitrate may respond differently to different concentrations of compost and vermicompost compared to other parameters e.g., parameters like pH or organic carbon increase steadily with increasing concentration of compost/vermicompost whereas, nitrate content showed an early rise followed by a drop at higher treatment levels, which may be due to nutrient uptake by rice seedlings or leaching.



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### 3.7. Hierarchical cluster analysis grouped soil and plant parameters, highlighting key factors influencing rice seedling growth and soil quality

HCA was used to classify the soil quality parameters and plant morphological indices into different, similar groups. The Dendrogram of the HCA of soil and plant samples are shown in Figure 5. Five primary clusters were identified namely: cluster 1 (pH & EC), cluster 2 (WHC, phosphate, protein content & total chlorophyll), cluster 3 (germination percentage, root length, shoot length and fresh weight), cluster 4 (EC) and cluster 5 (nitrate). The values for pH and OC in cluster 1 suggest their regulating effect in this cluster, as pH affects nutrient availability and OC is vital for soil fertility and microbial degradation. Cluster 2 are variable that exerts a major influence on the WHC and phosphate content of the soil. Soil with better water-holding capacity can enhance the supply of nutrients like phosphate because nutrients are taken up in solution (Goodwin & Burrow, 2006; Pitman, 2006; Santalla et al., 2011). Supply of nutrients in turn contributes to an increase in photosynthetic activity consequently leading to an increase in the chlorophyll content of leaves. EC in cluster 4 did not show any significant relation with other parameters, hence existing as a cluster of its own, while nitrate in cluster 5 showed a negative relation with most of the parameters measured hence forming a cluster at the top of the dendrogram.

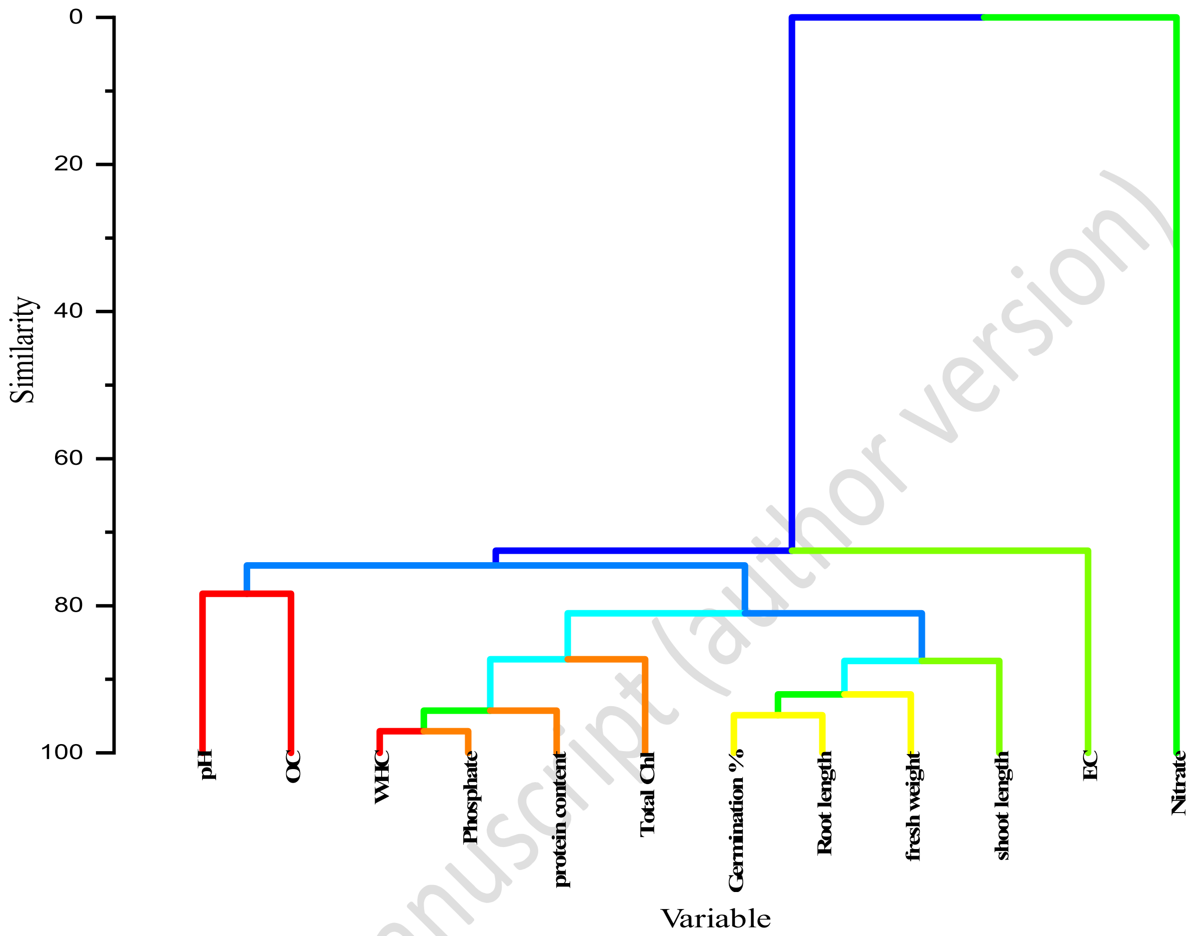


**Figure 5.** Dendrogram showing classification of soil quality parameters and plant morphological indices (OC = Organic Carbon, WHC = Water Holding Capacity, Total Chl. = Total Chlorophyll, EC = Electrical Conductivity)

## 4. Conclusion

The study demonstrates that vermicompost derived from water hyacinth and fly ash significantly enhances soil quality, plant growth, and seedling vigor compared with conventional compost. Vermicompost-amended soils exhibited improved physicochemical properties, including higher pH electrical conductivity, organic carbon, organic matter, phosphate content, and water-holding capacity, highlighting its nutrient-rich and buffering capabilities. Rice seedlings grown with vermicompost showed superior growth and physiological performance, with optimal effects observed at a 40% application rate. This indicates an ideal threshold for maximizing benefits while avoiding potential phytotoxicity at higher concentrations. Chlorophyll and protein content in leaves were markedly higher in vermicompost treatments, indicating enhanced photosynthetic activity and nutrient assimilation. Moreover, vermicompost reduced heavy metal concentrations over time likely through microbially mediated stabilization and organo-metallic complex formation. Seed germination, germination index, and vigor index were highest at 40% vermicompost, emphasizing its role in promoting seedling establishment and overall plant health. Multivariate analysis, including principal component analysis and cluster analysis further confirmed that vermicompost treatment exerted a stronger and more consistent influence on soil properties and rice seedling growth than compost alone. These findings validate the dual benefits of vermicompost as a sustainable soil amendment that enhances soil fertility and crop productivity while mitigating environmental risks, thereby supporting its application in sustainable agricultural practices.

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**Data Availability:** All data generated or analyzed during this study are included in this article.

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