




Article

Nutrient Release from Vermicompost under Anaerobic Conditions in Two Contrasting Soils of Bangladesh and Its Effect on Wetland Rice Crop

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Abstract: Although its mechanism of action, particularly under wetland condition, is not clearly understood, vermicompost, a good source of humus and plant nutrients, has been used as organic manure in many parts of the world in order to increase crop production. Here, an anaerobic incubation study and a field study were conducted to observe the nutrient release pattern from vermicompost and its influence on performance and nutrient uptake in wetland rice. Two contrasting soils, viz. highly weathered terrace soil and very young floodplain soil, were subjected to anaerobic incubation, while the field trial was conducted in the terrace soil with control (no amendments), mineral fertilizer, vermicompost (10 t ha⁻¹) + mineral fertilizer, cow dung (10 t ha⁻¹) + mineral fertilizer, vermicompost (20 t ha⁻¹) + mineral fertilizer and vermicompost (local farmer's practice) + mineral fertilizer treatments. Results showed that there were significant increases in nitrogen (N) and phosphorous (P) release in floodplain soil but not in terrace soil, suggesting that nutrient release from vermicompost is soil-dependent. The performance of Boro rice in terms of yield and yield attributes improved significantly in the case of the integrated application of vermicompost with mineral fertilizer. Specifically, combined application of mineral nutrients and vermicompost (10 t ha⁻¹) significantly increased grain yield by 25% compared to the control treatment. We believe that this occurred due to an improvement in supply and subsequent uptake of nutrients, especially N and P. Altogether, our results suggest that vermicompost could increase crop performance under field conditions, and, although these effects may not be significant in short-term incubation studies, they may be even larger in floodplain soil.

Keywords: vermicompost; anaerobic incubation; nitrogen mineralization; rice; nutrient release; nitrogen use efficiency

1. Introduction

Modern agricultural production systems include sustainable management practices that aim to balance the supply and the uptake of nutrients in the soil. Chemical fertilizers usually supply a large amount of nutrients into the soil in a relatively short period of

time and, thus, crop responses (i.e., yield) are often evident. However, large negative effects of chemical fertilizers have been reported on soil, water and the environment [1]. For instance, imbalanced use of inorganic fertilizers alone (i.e., without organic manure addition) degrades soil's physical, chemical and biological properties and causes nutrient leaching, decline of microbial activity and pollution of the surrounding environment [2,3]. Moreover, the monetary price of chemical fertilizers is increasing.

Soil organic matter is considered as the life of soil, as it contains nutrients for plant growth in the form of food for soil microorganisms [4]; therefore, it is considered the most important index of soil fertility [5]. Soil organic matter is usually supplemented with organic manure. Although organic manures are a cheap and ecofriendly substitute for chemical fertilizers, their use is being restricted due to higher transport cost, high application rate and environmental concerns related to their application [6]. Moreover, the amount of organic manure addition is often low in many developing countries, including Bangladesh, due to a change farming practices (absent or minimum livestock rearing) and use of agricultural waste as fuel. Therefore, it is essential to search for suitable alternatives to solve this issue.

Organic manure preparation involves composting of organic or biowaste. Composting is a controlled bio-oxidation process of biomass that converts it into a safer and more stable product and thereby lessens the environmental risk for soil application [7]. Moreover, it decreases transportation costs due to a significant reduction in the moisture level of the raw materials. Recently, composting using earthworms (e.g., *Eisenia foetida*) has been receiving increased attention since it is both ecofriendly and cost-effective [8]. Vermicompost is efficient in maintaining adequate soil fertility and productivity as it carries nutrients and stabilized, fine, peat-like organic manure having a low C:N ratio [9,10]. Moreover, it has high porosity and moisture-holding capacity [11] and increased microbial activity that rejuvenate soils. Since vermicompost contains readily available plant nutrients, such as nitrates, exchangeable phosphate, soluble potassium, calcium and magnesium, growth hormones and beneficial enzymes [12–15], it is considered a good soil amendment [16].

Rice (*Oryza sativa* L.) is a major strategic crop with regard to national food security for more than 3.5 billion people, [17] supplying 20% of global dietary energy [18]. In Bangladesh, rice is the principal food for more than 150 million people and provides almost 48% of rural employment, two-thirds of total calorie supply and one-half of the total protein intake of an average person and provides one-half of the agricultural GDP and one-sixth of the national income [19]. Rice occupies more than 96% of the land area under cereal agriculture [20]. Increase of rice production in Bangladesh is urgently required to fulfill the growing demand of an ever-increasing population that is predicted to extend to about 201.3–218.1 million by 2051 [21] while simultaneously minimizing the environmental impacts that are often associated with increased rice production.

The wetland-rice-based cropping system is a major cropping system practiced in Bangladesh. Traditionally, farmers only use a few nutrient elements (N, P and K) from chemical fertilizers for multiple years with no or minimum organic fertilizer amendment. Therefore, the continuous mining of nutrients while limiting nutrient addition reduces the yield of rice. Moreover, the soil physicochemical properties get degraded. Thus, it is important to replace inorganic fertilizers to some extent with organic fertilizer in a scientific way in order to restore the soil quality. Additionally, an integrated approach for supplying nutrients (i.e., supplying nutrients from organic and inorganic sources) can further enhance these benefits in the rice cultivation system since it could provide synergistic benefits of soil quality improvement and plant nutrient supply [22,23].

Given that, vermicompost technology is getting popular in farming communities throughout southeast Asia, particularly in the rural regions mostly used for vegetable cultivation. Nowadays, with the rise of the availability of feed stocks for vermicomposting, vermicompost application show promise to partially replace chemical fertilizers in the production of cereal crops such as rice. In the last few decades, a number of studies have been performed by many researchers to investigate the performance of vermicompost mainly on

agronomic parameters of rice, i.e., improvement of growth and yield [17,24–48]. Although the latter is examined in many studies, there are few reports on the mineralization pattern of nutrients from vermicompost under anaerobic wetland situations and its use in wetland rice farming [49]. Since the mineralization of nutrients under anaerobic conditions is quite different from that of aerobic conditions, and soil properties could change mineralization, it is necessary to examine these for optimizing the rate of organic and inorganic fertilizer use [50,51]. Considering these facts, the present study was carried out to assess the nutrient release pattern from vermicompost in two contrasting soils (floodplain and terrace) under anaerobic conditions and to explore the performance of the compost on growth and yield improvement of wetland rice.

2. Materials and Methods

Methodology of this study from soil and vermicompost sample collection to field experimentation is outline with a flow-diagram in Figure 1.

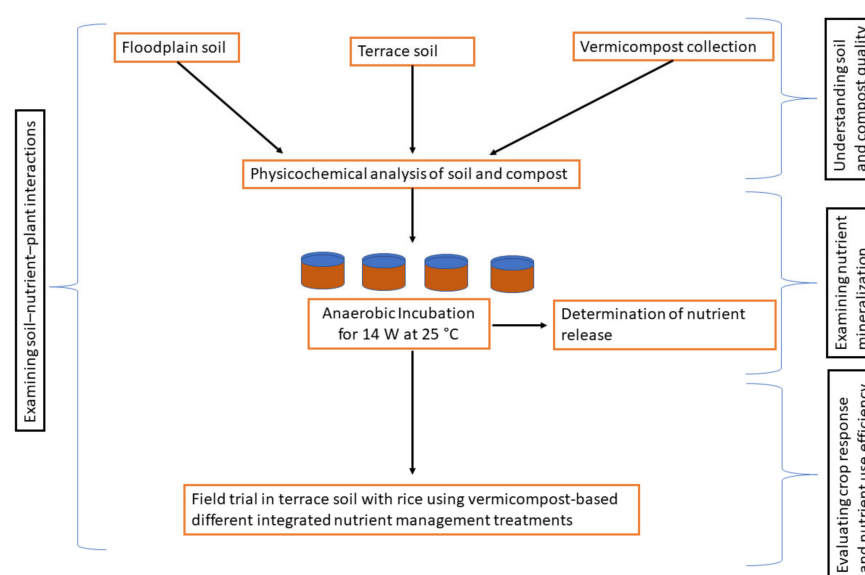


Figure 1. Flow-diagram of experimental methodology from soil and vermicompost sample collection to field experimentation.

2.1. Soil Sample Collection and Preparation

Two contrasting soil samples, namely very young floodplain soil and highly weathered terrace soil, were collected from the surface at a depth of 0–15 cm in selected areas in the Bangladesh Agricultural University (BAU) soil science farm and Fulbaria, Mymensingh, respectively. These samples were air-dried, ground, sieved through a 2 mm sieve and put in polyethylene bags for storage in a cool and dry place before the onset of the incubation trial. The two contrasting soils differed in their physical and chemical characteristics, as presented in Table 1.

Table 1. Physicochemical properties of the two soils studied.

Soil Characteristics	Floodplain Soil	Terrace Soil
AEZ	Old Brahmaputra Floodplain (9)	Madhupur tract (28)
Parent material	Brahmaputra alluvium	Madhupur clay
Soil series	Sonatola series	Kalma series
General soil type	Noncalcareous Grey Floodplain Soil	Grey Valley Soil
USDA taxonomy	Aeric Haplaquepts	Cumulic Humaquepts
% Sand (0.2–0.05 mm)	11.6	20.0
% Silt (0.05–0.002 mm)	75.8	64.0
% Clay (<0.002 mm)	12.6	16.0
Textural class	Silt loam	Silt loam

Table 1. Cont.

Soil Characteristics	Floodplain Soil	Terrace Soil
pH	6.9	5.6
Organic carbon (%)	1.18	0.84
Total nitrogen (%)	0.14	0.12
Available phosphorus (ppm)	6.2	5.3
Exchangeable potassium (me%)	0.07	0.13
Available sulfur (ppm)	2.4	1.5
Approximate mineralogical composition [52]	Mica (31%); vermiculite (6%); chlorite (27%); kaolinite (13%); mica-chlorite interstratified minerals (6%); quartz (8%); feldspar (9%)	mica (45%); vermiculite (10%); chlorite (12%); kaolinite (15%); quartz (14%); goethite (1%); feldspar (3%)

2.2. Analysis of Initial Soil Samples

Mechanical analysis of soil was performed by the hydrometer method [53], and soil textural class was determined by plotting percent sand, silt and clay values to the Marshall's Triangular Coordinate (USDA) system. Soil pH was determined in water (1:5, *w/v*) using a glass-electrode pH meter (HI11310, Hanna Instruments, Carrollton, TX, USA) [54]. Soil organic C was estimated by the Walkley and Black method [55]. Semimicro Kjeldahl [56] and Olsen [57] methods were followed to measure total N and available P. Exchangeable K was determined by flame photometer after extraction of soil with 1 N NH₄OAc at pH 7 [58], while available S content was assessed with CaCl₂ (0.15%) extraction followed by turbidity measurement using a spectrophotometer (PerkinElmer, Waltham, MA, USA) [59].

2.3. Collection of Vermicompost and Determination of Its Chemical Composition

Various vermicompost samples were collected from farmers of different locations of Fulbaria Upazila in Mymensingh District. Cow dung was collected from the dairy farm of Bangladesh Agricultural University, Mymensingh. Collected manure samples were air dried for several days under shaded condition, cleaned to remove extraneous materials, ground and mixed thoroughly. The processed vermicompost was used for chemical analysis and for the incubation experiment. The gravimetric technique [60] and loss on ignition were followed to determine moisture status and total C content of the manures, respectively. To assess total N content in the manures, the Kjeldahl method [56] was employed, while total P and S contents were determined after digestion with HNO₃-HClO₄ (3:1) [61]. The chemical composition of the organic manures is shown in Table 2.

Table 2. Nutrient composition of organic manures.

Organic Manures	Moisture (%)	Organic C (%)	N (%)	P (%)	K (%)	S (%)
Vermicompost (<i>n</i> = 8)	68.0 ± 3.1	34.0 ± 2.1	1.68 ± 0.16	0.41 ± 0.06	1.3 ± 0.12	0.5 ± 0.06
Cow dung (<i>n</i> = 3)	78.3 ± 3.5	45 ± 2.6	1.63 ± 0.19	0.39 ± 0.09	0.94 ± 0.15	0.63 ± 0.07

2.4. Incubation Study

To determine the release of nutrients from vermicompost in two contrasting soils (floodplain and terrace soils) under waterlogged conditions, an incubation study was conducted under controlled conditions with disturbed soil samples for a period of 14 weeks at 25 °C temperature. Two agroecological zones (AEZs) considered in this study were AEZ-9 (a representative of the floodplain soil that covers 80% of Bangladesh's land area) and AEZ-28 (a representative of the terrace soil that covers 8% of Bangladesh's land area). Plastic cups of 5.5 cm internal diameter and 15 cm height were used as incubation containers. Two hundred grams of soil was weighed in each glass and amended with vermicompost at a rate of 2 g 100 g⁻¹ soil (oven dry basis). Soils were incubated under oversaturated conditions during the incubation time by adding water at 2-week intervals in order to maintain a water level of around 4–5 cm above the soil level. This experiment was laid out in a completely randomized design (CRD) with three replications. Locations of the plastic

incubation boxes receiving different treatments were exchanged among the treatments throughout the incubation at one-month intervals for homogenization. Selected nutrients were extracted from incubated samples destructively at 0, 14, 28, 42, 56 and 98 days after incubation (six sampling occasions). The nutrients determined were the mineral N (NH_4^+), S (SO_4^{2-}) and P (phosphate P).

2.5. Nutrient Analysis

After collection of soil samples, gravimetric soil water content was determined for each container with oven drying of 30 g soil at 105 °C temperature. Soil NH_4^+ -N concentration was measured to determine net N mineralization of inherent soil organic matter and applied vermicompost. Soil NO_3^- -N concentration was not measured due to the assumption that the nitrification was very negligible as the soil was incubated under waterlogged condition [62]. Extraction of NH_4^+ -N from soil was done using 0.05 M CaCl_2 extractant, and analysis was performed colorimetrically by the indophenols blue technique [63] with a UV-vis spectrophotometer (Model LT-31) at 636 nm wavelength as adapted by Kader et al. [50]. Available P was extracted from soil using 0.5 M NaHCO_3 extractant (pH 8.5) according to the Olsen method [57], and the NaHCO_3 extracts were analyzed for P concentration by developing the blue color of the $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ reductant and phosphomolybdate complex using the spectrophotometer at 890 nm wavelength. Extraction of available S from soil was performed by CaCl_2 extractant (0.15%), and determination was done by the turbidimetric procedure with the help of the spectrophotometer at 420 nm wavelength [59,64].

2.6. Field Study

The field study was undertaken at farmers' plots in floodplain soil located at Fulbaria Upazila of Mymensingh to evaluate the response of Boro rice (cv. BRRI dhan28) to vermicompost and the release of nutrients from vermicompost under field condition. The treatments were T_0 (control), T_1 (mineral fertilizer only (STB)), T_2 (vermicompost 10 t ha⁻¹ (IPNS) + mineral fertilizer), T_3 (cow dung 10 t ha⁻¹ (IPNS) + mineral fertilizer (IPNS)), T_4 (vermicompost 20 t ha⁻¹ (IPNS) + mineral fertilizer (IPNS)) and T_5 (vermicompost (farmer's practice) + mineral fertilizer). Nutrient content in vermicompost and cow dung was calculated based on N content during integration with mineral fertilizer for IPNS. Randomized complete block design (RCBD) with three replications was followed for this experiment. The unit plot size was 4 m × 4 m, and there were 15 plots which were divided into three blocks where the treatments were randomly distributed. Thirty-five-day-old rice seedlings were transplanted in the fields at 20 cm × 20 cm spacing. The recommended rates of N, P, K, S and zinc (Zn) were 130, 24, 60, 18 and 2 kg ha⁻¹ according to FRG [65] and were supplied from urea, triple super phosphate (TSP), muriate of potash (MoP), gypsum and zinc oxide, respectively. The full amount of inorganic fertilizers (except urea) were applied as basal prior to seedling transplanting, while organic manures were applied during final land preparation. Three equal splits of urea were provided as top dressing at 15, 30 and 50 days after transplanting (DAT). Various intercultural practices, such as irrigation, weeding and pest control were done as per requirement. Rice crop was harvested at the fully matured stage, and the data on various yield parameters were recorded at the time of harvesting. The yields (grain, straw and biological) were measured plot-wise, and the harvest indexes were calculated. The grain and straw samples were collected, oven-dried and prepared by grinding, sieving and storing in paper bags for chemical analyses. The contents of N, P, K and S in grain and straw samples were measured using the semimicro Kjeldahl method [56], modified Olsen method [57], NH_4OAc extraction method [58] and CaCl_2 extraction method [59], respectively, after HNO_3 - HClO_4 (3:1) di-acid digestion [61]. The nutrient uptakes were estimated from the data of yield (kg ha⁻¹) and nutrient concentration (%).

2.7. Nitrogen Use Efficiency

Nitrogen use efficiency (NUE) was calculated in terms of agronomic, physiological and recovery efficiency following Paul et al. [66] as follows:

Agronomic efficiency—yield increase of crop in relation to its nutrient input:

$$AE \text{ (kg kg}^{-1}\text{)} = (Gf - Gu)/Na \quad (1)$$

where

Gf = grain yield of the fertilized plot (kg ha^{−1});

Gu = grain yield of the unfertilized plot (kg ha^{−1});

Na = rate of nutrient applied (kg ha^{−1}).

Physiological efficiency (PE)—transformation of nutrients obtained from the source application into economical yield:

$$PE \text{ (kg kg}^{-1}\text{)} = (GYf - GYu)/(Nf - Nu) \quad (2)$$

where

GYf = grain yield of the fertilized plot (kg ha^{−1});

GYu = grain yield of the unfertilized plot (kg ha^{−1});

Nf = nutrient uptake (grain and straw) of the fertilized plot (kg ha^{−1});

Nu = nutrient uptake (grain and straw) of the unfertilized plot (kg ha^{−1});

Apparent recovery efficiency (ARE)—recovery of applied nutrient by plants from soil when fertilizer is applied:

$$RE \text{ (%) } = ((Nf - Nu)/Na) \times 100 \quad (3)$$

where

Nf = Nutrient uptake (grain and straw) of the fertilized plot (kg ha^{−1});

Nu = Nutrient uptake (grain and straw) of the unfertilized plot (kg ha^{−1});

Na = Rate of nutrient applied (kg ha^{−1}).

2.8. Statistical Analysis

All the data regarding mineralized/released nutrients were fitted to a first-order kinetics model to estimate mineralization and/or nutrient release rate using IBM SPSS version 22 (Chicago, IL, USA). The model is: $N(t) = NA (1 - \exp(-kt))$, where t is the time (in week), $N(t)$ is the amount of mineralized/released nutrients, NA is the potentially mineralizable/releasable nutrients in mg kg^{−1} soil and k is the first-order rate parameter (mg kg^{−1} soil wk^{−1}) as adopted by Kader et al. [50,62] and Suruban et al. [67]. All the collected plant growth parameters and yield data were subjected to statistical analysis using the computer package program of MSTAT-C [68]. The mean differences were adjudged by Duncan's new multiple range test (DMRT) at a 1% level of probability [69].

3. Results

3.1. Nutrient Availability from Vermicompost under Anaerobic Condition

3.1.1. Nitrogen Availability

The evolution of NH₄⁺-N increased with the advancement of the incubation period in the amended and control soil and reached its peak within 4–6 weeks of incubation, as shown in Figure 2A. Thereafter, the NH₄⁺-N evolution mostly remained stable. N mineralization was higher in terrace soil compared to floodplain soil both under the control condition (19.62 and 26.45 mg, respectively, N kg^{−1} soil cropping season^{−1} after 120 days) as well as the vermicompost-amended condition (24.67 and 28.13 mg, respectively, N kg^{−1} soil cropping season^{−1}) (Figure 2B). However, when amended with vermicompost, floodplain soil performed better in mineralization of exogenous vermicompost, with the release of about 25% more N compared to the unamended, while it was only a 6% increase for the terrace soil.

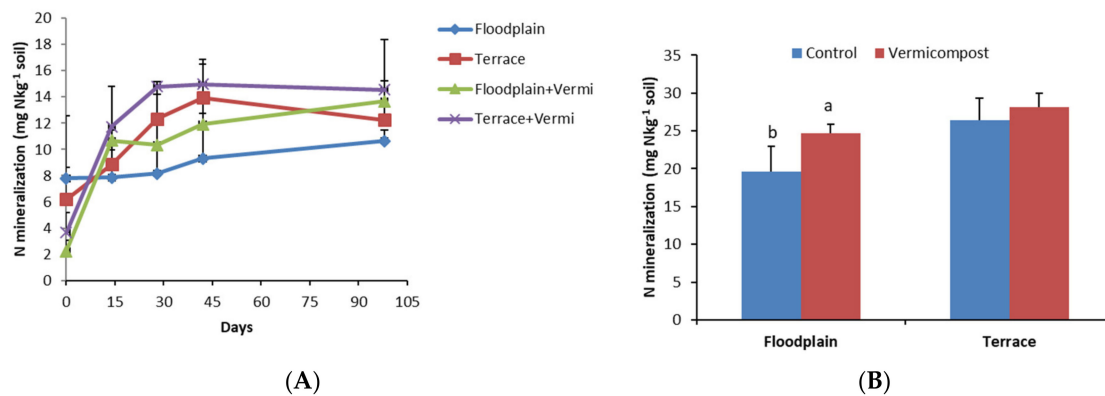


Figure 2. Trend of NH_4^+ -N release pattern from vermicompost-amended soils during incubation study for a period of 14 weeks (A); N mineralization in two contrasting soils after 98 days (B) as influenced by vermicompost amendment.

3.1.2. Phosphorous Availability

Evolution of phosphate P (PO_4^{3-} , HPO_4^{2-} and H_2PO_4^-) in soil was not as straightforward as NH_4^+ -N evolution either in amended or unamended soil (Figure 3A). However, the evolution of phosphate P increased in all the treatments during the whole course of the incubation period. It was a bit rapid at the beginning of incubation, and it slowed down after 6 weeks. In all the treatments, the evolution of mineral P was substantially higher in all the sampling dates than control soil, particularly for floodplain soil. The release or accumulation of mineral P was the highest at 15 days in vermicompost-amended floodplain soil (15.1 mg P kg⁻¹ soil) and the lowest at 15 days in control floodplain soil (5.4 mg P kg⁻¹ soil). P mineralization was highest in terrace soil compared to floodplain soil under the control condition (7.96 and 9.18 mg P kg⁻¹ soil cropping season⁻¹ in floodplain and terrace soil, respectively) (Figure 3B). However, the opposite scenario was observed in P mineralization when the soils were amended with vermicompost (13.45 and 9.56 mg P kg⁻¹ soil cropping season⁻¹ in floodplain and terrace soil, respectively). P mineralization increased by 68% in floodplain soil due to vermicompost amendment, while it only increased by 4% in terrace soil.

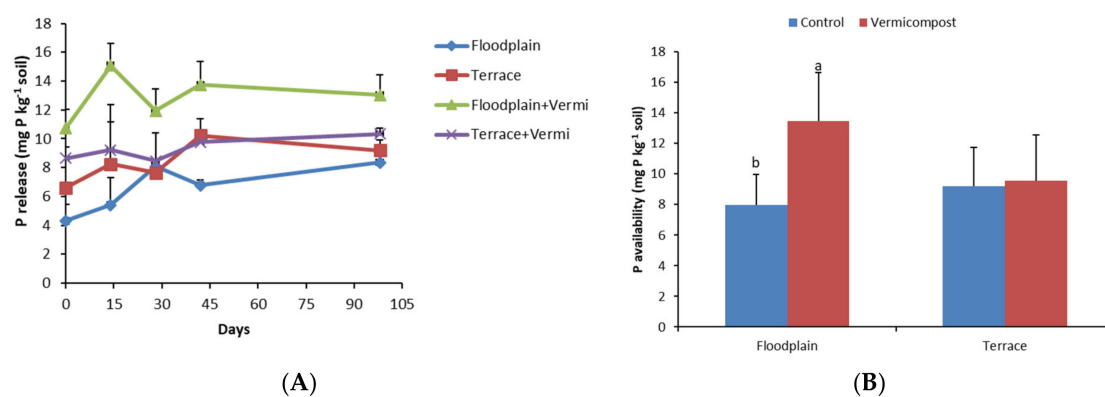


Figure 3. Trend of phosphate P (PO_4^{3-} , HPO_4^{2-} and/ H_2PO_4^-) release pattern from vermicompost-amended soils during incubation study for a period of 14 weeks (A); P release in two contrasting soils after 98 days (B) as influenced by vermicompost amendment.

3.1.3. Sulphur Availability

Generally, the mineralization of S increased with the advancement of the incubation period in all amended treatments, including control soil (Figure 4A). The release of S was highest at 30 days after incubation in vermicompost-amended floodplain soil (29.9 mg S kg⁻¹ soil) and the lowest at 15 days after incubation in control terrace soil

(13.4 mg S kg⁻¹ soil). S mineralization was much higher in floodplain soil compared to terrace soil both in control and vermicompost-amended conditions. Soil amendment with vermicompost showed an increase in S mineralization in terrace soil but a slight decrease in floodplain soil (Figure 4B). S mineralization was higher in floodplain soil compared to terrace soil both in control (25.31 vs. 20.51 mg S kg⁻¹ soil cropping season⁻¹) as well as vermicompost-amended conditions (24.74 vs. 23.29 mg S kg⁻¹ soil cropping season⁻¹).

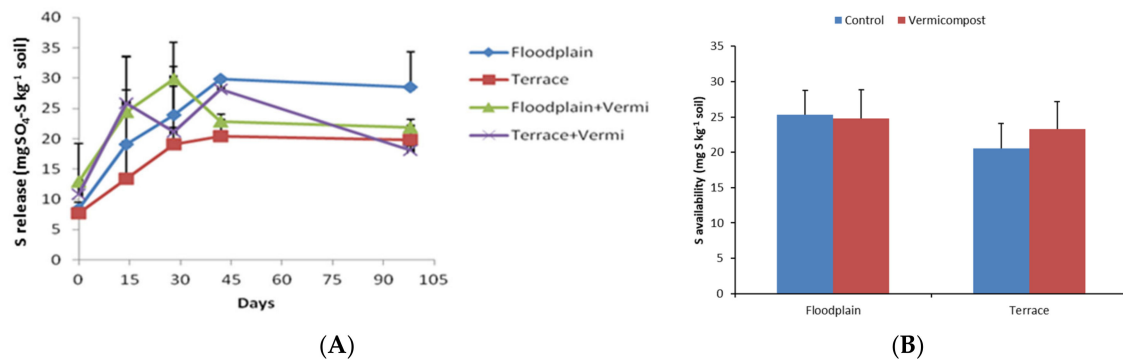


Figure 4. Trend of SO₄²⁻-S release pattern from vermicompost-amended soils during incubation study for a period of 14 weeks (A); S release in two contrasting soils after 98 days (B) as influenced by vermicompost amendment.

3.2. Response of Wetland Rice to Vermicompost

3.2.1. Yield-Contributing Characteristics

Yield parameters of plant height, number of effective tillers hill⁻¹, panicle length and number of grains panicle⁻¹ rice were significantly affected due to the treatments; the only exception was thousand-grain weight (Table 3). The maximum values of some of the yield parameters, viz. plant height (85.9 cm), number of effective tillers hill⁻¹ (14.75), number of grains panicle⁻¹ (170.8), 1000-grain weight (22.01 g) and biological yield (11.11 t ha⁻¹), were observed in T₂ treatment where 10 t ha⁻¹ vermicompost was applied with mineral fertilizers, whereas the minimum values of plant height (77.2 cm), number of effective tillers hill⁻¹ (9.02), number of grains panicle⁻¹ (132.4), 1000-grain weight (20.38 g) and biological yield (7.11 t ha⁻¹) were noted in the control. Again, treatment T₄ produced the highest harvest index of 39.58% where vermicompost was applied at 20 t ha⁻¹ with chemical fertilizers, and treatment T₀ (control) showed the lowest harvest index of 35.22%.

Table 3. Yield parameters and yield of rice (BRRI dhan28) as influenced by vermicompost-based organic and inorganic fertilizers.

Treatments	Plant Height (cm)	Effective Tillers Hill ⁻¹ (No.)	Panicle Length (cm)	No of Grains Panicle ⁻¹	1000-Grain Weight (g)	Grain Yield (t ha ⁻¹)	Biological Yield (t ha ⁻¹)	Harvest Index (%)
T ₀	77.2c	9.02c	21.05b	132.4d	20.38	2.51d	7.11d	35.22c
T ₁	83.2ab	12.12b	23.55a	157.2ab	21.27	4.05a	10.77a	37.59b
T ₂	85.9a	14.75a	25.12a	170.8a	22.01	4.28a	11.11a	38.52a
T ₃	83.1ab	13.23ab	24.56a	164.0a	21.44	3.95ab	10.08b	39.19a
T ₄	83.1ab	12.14b	23.11ab	158.3ab	21.67	3.80b	9.60b	39.58a
T ₅	81.1b	10.47c	21.19b	144.4c	21.17	3.39c	8.94c	37.86b

Per column, same letter(s) indicate statistically similar, and dissimilar letter(s) indicate significant difference at 0.05 level of probability: T₀, control; T₁, mineral fertilizers only (STB); T₂, vermicompost (10 t ha⁻¹) (IPNS) + mineral fertilizer; T₃, cow dung (10 t ha⁻¹) (IPNS) + mineral fertilizer; T₄, vermicompost (20 t ha⁻¹) (IPNS) + mineral fertilizer; T₅, vermicompost (farmer's practice) + mineral fertilizer.

3.2.2. Yield of Wetland Rice

Application of different rates of vermicompost significantly increased the yields of rice grain and straw over control (Figure 4). The study revealed that T_1 , T_2 , T_3 and T_4 treatments enhanced grain yield of rice by 20, 26, 17 and 12%, respectively, over control (Figure 5). The highest grain yield of 4.28 t ha^{-1} was found in the treatment with combined application of vermicompost (10 t ha^{-1}) and mineral fertilizer (T_2), followed by the recommended dose of mineral fertilizer only (T_2), which produced 4.05 t ha^{-1} grain yield. Straw yield of rice also followed a similar trend.

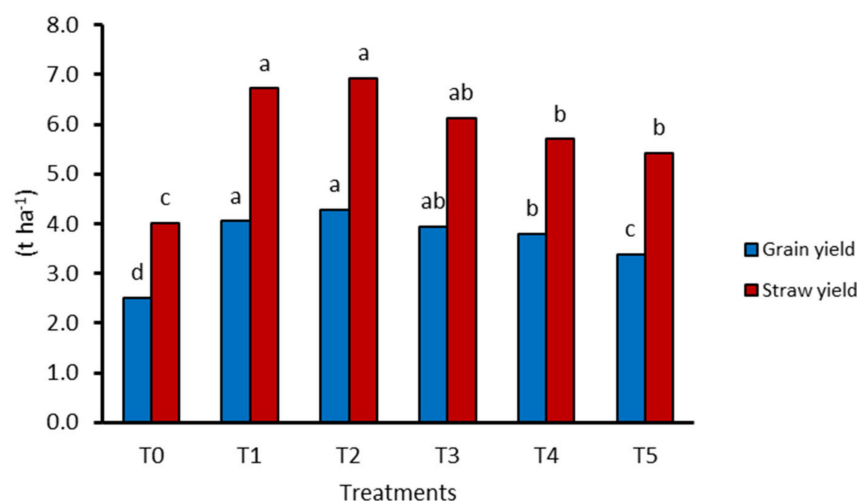


Figure 5. Effect of treatments on grain yield and straw yield of BRRI dhan28 (bars having the same letter(s) are statistically similar, and those having dissimilar letter(s) differ significantly at 0.05 level of probability: T_0 , control; T_1 , mineral fertilizers only (STB); T_2 , vermicompost (10 t ha^{-1}) (IPNS) + mineral fertilizer; T_3 , cow dung (10 t ha^{-1}) (IPNS) + mineral fertilizer; T_4 , vermicompost (20 t ha^{-1}) (IPNS) + mineral fertilizer; T_5 , vermicompost (farmer's practice) + mineral fertilizer.

The rank was mineral fertilizer + vermicompost 10 t ha^{-1} (T_2) > mineral fertilizer (STB) (T_1) > mineral fertilizer + cow dung 10 t ha^{-1} (T_3) > mineral fertilizer + vermicompost 20 t ha^{-1} (T_4) > vermicompost farmer's practice (T_5) > no fertilizer (T_0) (Figure 4). The differences in grain yield between mineral fertilizer + vermicompost 10 t ha^{-1} (T_2) and vermicompost farmer's practice (T_5) was about 26%, which is a very crucial finding for our farmers to optimize their yield. Straw yield for different treatments also trended similar to grain yield.

3.2.3. Nutrient Uptake by Wetland Rice

There was a significant influence of vermicompost treatments on the uptake of nutrients (N, P and S) by rice (grain + straw) during the Boro season (Figure 6). Nitrogen and P uptake ranged between 52.1 and 110.6 kg ha^{-1} and 9.6 and 28.7 kg ha^{-1} , respectively, with the lowest in the control (T_0) and highest in the mineral fertilizer + vermicompost at 10 t ha^{-1} (T_2) treatment (Figure 5). Nitrogen and P uptake in the combination of mineral fertilizer + vermicompost at 10 t ha^{-1} treatment (T_2) was statistically identical only to the mineral fertilizer treatment (T_1). N and P uptake in all three other treatments (T_3 , T_4 and T_5) were statistically identical and inferior to T_1 and T_2 but superior to T_0 treatment.

On the other hand, S uptake varied between 3.9 kg ha^{-1} in the control (T_0) and 11.89 kg ha^{-1} in the mineral fertilizer + vermicompost at 20 t ha^{-1} treatment (T_4). No statistical difference was found between treatments T_4 and T_3 (cow dung 10 t ha^{-1} + mineral fertilizer) for S uptake, while only mineral fertilizer treatment (T_1), mineral fertilizer combined with vermicompost at 10 t ha^{-1} (T_2) and vermicompost plus mineral fertilizer (T_3) were statistically similar.

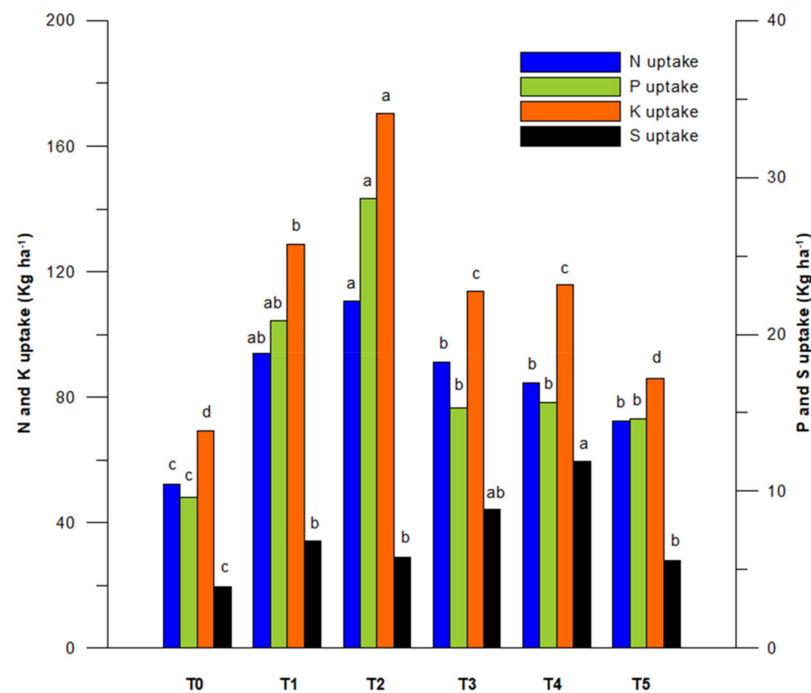


Figure 6. Effect of vermicompost on N, P, K and S uptake by BRRI dhan28 (bars having similar letter(s) are statistically similar, and those having dissimilar letter(s) differ significantly at 0.05 level of probability: T₀, control; T₁, mineral fertilizers only (STB); T₂, vermicompost (10 t ha⁻¹) (IPNS) + mineral fertilizer; T₃, cow dung (10 t ha⁻¹) (IPNS) + mineral fertilizer; T₄, vermicompost (20 t ha⁻¹) (IPNS) + mineral fertilizer; T₅, vermicompost (farmer's practice) + mineral fertilizer.

3.2.4. Nitrogen Use Efficiency

Significant differences in agronomic, physiological and recovery efficiency of N were observed among the treatments (Table 4). The highest agronomic-N-use efficiency was observed in T₂ (vermicompost (10 t ha⁻¹) (IPNS) + mineral fertilizer), which is statistically identical to T₁ (mineral fertilizers only), T₃ (cow dung (10 t ha⁻¹) (IPNS) + mineral fertilizer) and T₅ (vermicompost (farmer's practice) + mineral fertilizer) treatments but superior to T₄ (vermicompost (20 t ha⁻¹) (IPNS) + mineral fertilizer) treatment. Apparent recovery efficiency also showed a similar pattern, with the highest recovery efficiency of 45.3% in T₂ (vermicompost (10 t ha⁻¹) (IPNS) + mineral fertilizer) treatment. Next to this, the recovery efficiency of N in T₁ (mineral fertilizers only) and T₃ (cow dung (10 t ha⁻¹) (IPNS) + mineral fertilizer) treatments were statistically similar but higher than the other two fertilized treatments (T₄ and T₅). However, physiological-N-use efficiency showed the opposite trend, with the lowest in T₂ (vermicompost (10 t ha⁻¹) (IPNS) + mineral fertilizer) treatment.

Table 4. Agronomic efficiency (AE), physiological efficiency (PE) and apparent recovery efficiency (ARE) of rice (BRRI dhan28) as influenced by vermicompost-based organic and inorganic fertilizers.

Treatments	Agronomic Efficiency (AE)	Physiological Efficiency (PE)	Apparent Recovery Efficiency (ARE)
	(kg Grain kg ⁻¹ N Applied)	(kg Grain kg ⁻¹ N Uptake)	(%)
T ₁	12.0ab	36.8b	32.5b
T ₂	13.8a	30.3c	45.3a
T ₃	11.2ab	37.2b	30.2b
T ₄	10.0b	40.1ab	25.1c
T ₅	11.4ab	43.3a	26.4c

Per column, same letter(s) indicate statistically similar, and dissimilar letter(s) indicate significant difference at 0.05 level of probability: T₀, control; T₁, mineral fertilizers only (STB); T₂, vermicompost (10 t ha⁻¹) (IPNS) + mineral fertilizer; T₃, cow dung (10 t ha⁻¹) (IPNS) + mineral fertilizer; T₄, vermicompost (20 t ha⁻¹) (IPNS) + mineral fertilizer; T₅, vermicompost (farmer's practice) + mineral fertilizer.

4. Discussion

4.1. Nutrient Release from Vermicompost under Anaerobic Soil Environment

Vermicompost obtained from animal manure (namely cow dung) is considered to be a good soil amendment with readily available nutrients [13,70–72]. However, the use of vermicompost in rice production has been restricted so far, possibly due to its low availability and higher cost [73]. Historically, cow dung has been widely used as manure in Bangladesh. On the other hand, cow dung samples contain a higher amount of water than vermicompost, as during the vermicomposting process the water content is gradually reduced and finally stabilized. Organic carbon content is an important parameter for assessing the quality of a manure, as mineralization or immobilization of nutrients largely depends on it. Any raw material initially contains a high level of organic carbon, which becomes stabilized upon decomposition over time. The average value of organic carbon content in the cow dung sample was much higher than in the vermicompost samples (Table 2). The labile part of cow dung was decomposed during the vermicomposting process, rendering stable material in the vermicompost. Thus, the amount of organic C in vermicompost was reduced due to biological decomposition and oxidation of C to CO₂. The contents of N, P and K in vermicompost were a bit higher in comparison to those of cow dung, with S content being the exception. In accordance with our study, Agarwal [74] and Singh and Kulbaivab [75] also noted that vermicompost processed by earthworms possessed higher amounts of important plant nutrients, such as N, P and S, by several times in comparison to those available in compost (cattle dung) prepared from the same feed stock.

In our incubation study, mineralization of N, P and S increased with the advancement of the incubation period in all the amended treatments, including the control (Figures 2–4). For all the treatments, the amount of NH₄⁺-N evolution increased with the progress of the incubation period and attained the maximum values within 30 to 45 days, which is supported by Fu et al. [76], who demonstrated a significantly greater NH₄⁺-N accumulation at the early stage of the incubation time with the application of organic residues. In case of N mineralization, both terrace and floodplain soils amended with vermicompost exerted higher NH₄⁺-N content compared to the unamended soils, which is logical (Figure 2). Surprisingly, a higher N mineralization was observed in terrace soil compared to floodplain soil in both control and amended conditions, though organic carbon and total N content of terrace soil is lower than the floodplain soil. Similarly, a higher N mineralization in terrace soils under anaerobic incubation has been reported by Kader et al. [50]. Vermicompost amendment significantly increased N mineralization in floodplain soil but was not significant for terrace soil. It might be due to higher inherent organic C and total N content in floodplain soil compared to terrace soil. Probably, vermicompost created a large positive priming effect on N mineralization in floodplain soil due to higher inherent organic C and total N content, which was not the case for terrace soil [77]. Floodplain soil might have a higher number of microbes due to higher inherent soil C. These microbes re-mineralize soil N and concurrently co-metabolize inherent soil organic C in floodplain soil when amended with vermicompost [78].

Phosphorus release was higher in terrace soil compared to floodplain soil in the control condition. This might be due to release of fixed P resulting from an increase in soil pH from acidic to neutral under anaerobic incubation [79]. However, the opposite scenario was observed in P release while the soils were amended with vermicompost. This might be the result of a positive priming effect of vermicompost amendment on P mineralization in floodplain soil similar to N mineralization due to higher inherent organic C content. The release or accumulation of phosphate-P (PO₄³⁻, HPO₄²⁻ and H₂PO₄⁻) was the highest at 15 days in vermicompost-amended floodplain soil and the lowest at 15 days in control floodplain soil. Vermicompost is a rich source of P, and the faster release pattern of P at the early stage of incubation might be due to minimal exposure of the released P to the different fixation mechanisms at the early stage [80]. Our result is in accordance with the findings of Naher et al. [81], who showed that P mineralization from manure occurs after

15 days of application and steadily increased with the passage of time. Availability of P from animal manure is high (>70%), and the majority of the manure P is inorganic and becomes available to plants after application [82].

The release of SO_4^{2-} -S was highest at 30 days after incubation in vermicompost-amended floodplain soil and the lowest at 15 days after incubation in control terrace soil. S release initially increased due to vermicompost amendment, but with the advancement of time S release decreased compared to control soil. This might be due to a decrease in redox potential for prolonged soil inundation [83]. Vermicompost amendment also further decreased the redox potential of soil due to having a lot of labile organic matter in vermicompost [84]. Under this reduced soil environmental condition, available S (SO_4^{2-} -S) was reduced to sulfide and reacted with Fe, Mn and Zn and formed insoluble FeS, MnS and ZnS [79] in vermicompost-amended soil, thus exhibiting lower available S. This finding is partially similar with Reddy et al. [85], who reported that the S release was maximum in the first week, followed by a constant decline in manure-amended and unamended soils. Soils amended with vermicompost showed an increase in S release in terrace soil but a slight decrease in floodplain soil. There was little difference in S release among the treatments. This might be due to the influence of redox potential as a result of anaerobic incubation and anaerobic decomposition of vermicompost and native soil organic C [86,87]. In this study, mineralization of N, P and S varied between floodplain and terrace soils, which might be due to variation in their parent material and soil properties such as pH, organic matter content, etc. It should be mentioned that soil pH regulates nutrient mineralization in soil as it has a direct influence on microbial population and activities and influences the extracellular enzymatic activities which participate in the microbial transformation of organic matter [88]. According to Moharana et al. [49], the rate of nutrient mineralization also depends on levels of native soil organic matter.

4.2. Response of Wetland Rice to Vermicompost

Considering the significance of sustainable rice production, the field study was performed to delineate the influence of vermicompost on yield-contributing parameters, yields (grain and straw) and nutrient uptake in rice. The highest yield-contributing characteristics and yields (grain, straw and biological) were obtained from the combination of mineral fertilizer + vermicompost at 10 t ha^{-1} treatment. Our results are more-or-less similar to the findings of some researchers [17,30–34,40–43,46–48,89,90] who reported higher rice yields and yield parameters using vermicompost plus chemical fertilizers. The greater yield may have occurred due to an increased supply of nutrients (as found in the mineralization study) and its subsequent plant uptake (discussed in the next section). Nutrient availability may have increased due to enhanced mineralization of organic matter (especially with the impulse of inorganic fertilizer addition) and addition of intrinsic nutrients of the compost and their retention in the enhanced reactive sites created by vermicompost amendment. This availability may have also enhanced with changes in soil properties, including soil pH since it was an acidic soil. However, a similar increment was not obtained when vermicompost was applied at a higher rate (20 t ha^{-1}), suggesting that a higher rate of compost application may reduce yield. This was possibly due to the immobilization of N at the higher compost application rate.

Importantly, vermicompost is a unique organic amendment, with higher activities of microbes and enriched with nutrients such as N, P, K, Ca, Mg, Fe, Mn, Zn and Cu in a readily available and adsorbable manner [91–94]. Thus, both vermicompost and inorganic fertilizers provide the nutrients essential for plant. The positive aspects of vermicompost when applied in combination with inorganic fertilizers may be attributed to the enrichment of readily available plant nutrients due to the interactions between the earthworms and microbes that help improve crop productivity and restore soil fertility. According to Raha [93], better performance of vermicompost may be due to the biological effects of the compost viz. enhanced activities of useful enzymes and beneficial microbial populations and the existence of plant-growth-promoting substances such as hormones or growth

regulators. In the early developmental stage, inorganic fertilizers provide readily available nutrients, while vermicompost liberates nutrients through mineralization that requires time for utilization by plants. Therefore, rice yields did not increase much in T₄ (mineral fertilizer combined with vermicompost at 20 t ha⁻¹) compared to T₂ (mineral fertilizer combined with vermicompost at 10 t ha⁻¹). This is also indicated by the lower nutrient use efficiency in T₄ (mineral fertilizer combined with vermicompost at 20 t ha⁻¹) compared to T₂ (mineral fertilizer combined with vermicompost at 10 t ha⁻¹) (Table 4).

4.3. Effect of Vermicompost on Nutrient Uptake by Wetland Rice

In the present study we observed that the maximum N and P uptake, agronomic and recovery efficiency of N in rice was found in the combination of mineral fertilizers plus vermicompost at 10 t ha⁻¹. Since nutrient uptake is a function of yield and percent nutrient content, nutrient uptake data followed a similar pattern to that observed with grain yield and straw yield (Figure 5), with the highest N and P uptake in T₂ (110.6 and 28.7 kg ha⁻¹). The highest S uptake was noted in T₄ treatment where mineral fertilizers were applied with 20 t ha⁻¹ vermicompost. In fact, vermicompost offers favorable conditions for soil microbes that are involved in nutrient transformation and, as a consequence, availability and retention capacity of nutrients are enhanced, which results in higher nutrient uptake and use efficiency in rice. The impact of vermicompost on the improvement of nutrient uptake was reported by some researchers [90,95,96]. The organic acids released from vermicompost solubilize nutrients from complexes during decomposition, decrease adsorption capacity and increase desorption of nutrients in soil, supporting higher nutrient uptake in vermicompost treatment [97,98]. As suggested by Thirunavukkarasu and Vinoth [90], the higher nutrient uptake in rice may be due to higher nutrient availability in soil through vermicompost and chemical fertilizer addition.

5. Conclusions

In conclusion, it should be stated that the response of vermicompost in releasing plant nutrients is soil-dependent and largely influenced by the inherent characteristic of the soil. Generally, it was observed from the study that vermicompost in the floodplain soil mineralizes the nutrients more rapidly than the terrace soil. A significant difference among the treatments was found in N and P mineralization and/or release, but not much difference was observed in S release. Rice yield responded significantly to the application of vermicompost in the farmer's Boro rice field. Vermicompost at 10 t ha⁻¹ was the best treatment considering its performance on yield parameters, grain yield, nutrient uptake (except S uptake) and N use efficiency compared to the other treatments. Yield improvement of rice through the use of vermicompost will benefit rice farmers and will play a significant role in the development of the southeast Asian countries where rice is inextricably linked with the socioeconomic life of people. However, this is the result of experimentation over the course of one season, and, to draw a valid conclusion, multiple years of experimentation under different agro-climatic zones and soils are needed. In addition to soil, there might also be variations in performance among different varieties of rice in response to vermicompost application, which was not tested in this study. Therefore, it is recommended to further repeat this study in different locations of the country with different rice varieties.

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