Nitrogen, phosphorus and sulphur mineralization in soil treated with amended municipal solid waste compost under aerobic and anaerobic conditions

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Abstract

Purpose Our study had considered some organic amendments to enhance nutrient level of marketed municipal solid waste (MSW) compost for its potential use as fertilizer for growing crops in alluvial soils.

Method We prepared three types of amended compost by mixing 20% mustard oil cake (MOC), and 30% poultry manure (PM) or cowdung (CD) or sugarcane press mud (SPM) with 50% MSW compost. The nitrogen (N), phosphorus (P) and sulphur (S) mineralization study was done in soil treated with three amended and one unamended composites with three replications through an incubation experiment at a temperature of 25 ± 1°C for 82 days under aerobic (field capacity) and anaerobic (submerged) conditions. The mineralization data were fitted to the first-order kinetic model.

Results The soil NO$_3^-$-N content was 2-3 times higher in aerobic condition than in anaerobic condition, while the NH$_4^+$-N was higher in anaerobic soils. The kinetic model reveals that poultry manure and sugarcane press mud had higher capability to supply N for use by the crops. The P release was the highest at day 15 with three-time higher availability in anaerobic condition. The S mineralization in soil was higher in field capacity than in submerged condition.

Conclusion The compost mixture comprising MSW, MOC and SPM in a ratio of 5:2:3 demonstrated the highest cumulative N, P and S mineralization in both aerobic and anaerobic conditions. The N and S availability decreased while the P availability increased in submerged soils which result has fertilizer management implications for wet land rice crop.

Keywords Kinetic model, N mineralization, P mineralization, S mineralization, MSW compost, Submerged soils

Introduction

Composting of municipal solid waste (MSW) is a good option of solid waste management to protect the environment and to serve as a good source of organic fertilizers. The MSW includes the residential, commercial, and institutional solid waste generated daily in a city. The benefits of using MSW compost include its impact on soil chemical, physical and biological properties that will eventually improve soil productivity. However, marketed MSW compost is reported generally poor in essential plant nutrients and the crops do not respond to its exclusive addition. Many studies are done to combine chemical fertilizers with MSW compost to obtain better crop response; the approach is called integrated nutrient management (Aktar et al. 2018; Jahiruddin et al. 2012; Kavitha and Subramanian 2007).

A good opportunity exists to improve the nutrient status of MSW compost through addition of some organic materials; literature pertaining to this type of work is highly limited. Torkashvand (2010) used molasses, office paper, sulfuric acid and paper mill sludge as mixing materials with municipal wastes
for increasing the agronomic value of the compost. Wang et al. (2014) reported that the combined green waste compost, sedge peat and furfural residue (GSF treatment) had substantially ameliorated the saline soils in northern China, compared to individual amendment. As observed by Abideen et al. (2020), the biochar-compost mixture (1.5% biochar + 1.5% compost) better promoted nutrient uptake, water balance, and photosynthetic system efficiency compared to biochar (1.5%). Houot et al. (2012) compared four composts such as biowaste compost (BioW), municipal solid waste compost (MSW), green waste compost (GW) and co-compost of green waste and sludge (GW+S). They found no clear difference in the degrading capacity of the different composts, and the major difference was lying with the higher mineralizing capacity of the maturation microflora compared with the thermophilic microflora (e.g. bacteria).

Sustainable agriculture requires the use of organic fertilizers for steady nutrients supply and improving soil organic matter, soil physical & chemical properties and crop productivity (Hati et al. 2007; Khan et al. 2007; Liu et al. 2009).

Mineralization of nutrients from soil organic matter (SOM) is a biochemical process that is governed by many factors, such as chemical composition of SOM (Sano et al. 2006), environmental conditions (Rui et al. 2011; Pinto et al. 2020), soil properties (Xiao et al. 2013), soil microbial communities (Roth et al. 2011) and agricultural practices (Chang et al. 2014). Organic matter contains N, P and S which are present mostly in organic forms. During decomposition process, these nutrients are released as plant available forms such as NH$_4^+$, NO$_3^-$, orthophosphate ions (H$_2$PO$_4^-$, HPO$_4^{2-}$and PO$_4^{3-}$) and SO$_4^{2-}$. Understanding the dynamics of soil N, P and S mineralization is a prerequisite for optimizing fertilizer management and decreasing environmental risk (Rahn et al. 2003; Yin et al. 2007).

Most N assimilated by plants is derived from inorganic-N pools (mainly NH$_4^+$ and NO$_3^-$). Thus, the rate of organic-N decomposed and mineralized to inorganic-N is a key factor controlling the N supply for crops (Zhang et al. 2015). The N mineralization is also influenced by the fertilizer type (such as chemical or organic fertilizer), soil moisture content, and Temperature (Hossain et al. 2017). Using a $^{15}$N tracing model, it was shown that mineral fertilizer enhanced mineralization of recalcitrant organic N, whereas the application of organic fertilizers stimulated the mineralization of labile organic N in the soil (Zhang et al. 2012). Temperature is recognized as an important factor for organic matter decomposition in soil. Klimek et al. (2020) studied the temperature sensitivity of SOM decomposition in different types of forest and concluded that the metabolic abilities of the soil microbial communities and the soil nutrient content were important controls of temperature sensitivity in taiga soils. However, mineralization of organic matter and release pattern of nutrients (N, P and S) from compost amendment is little known in alluvial soils.

The present study had considered locally available and low cost organic materials for mixing with MSW compost that the farmers commonly use as a source of organic matter in crop production. These materials were cowdung (CD), poultry manure (PM), sugarcane press mud (SPM) and mustard oil cake (MOC). It was hypothesized that MSW compost amended with organic manure such as mustard oil cake, poultry manure and cowdung would supply higher amount of nutrients to the crops. Thus, objective of the study was to examine the N, P & S mineralization behavior in soil mixed with some amended MSW composts. The expected outputs were that magnitude of nutrient availability from amended compost would be known which would help reduce the fertilizer requirement for crops.

Materials and methods

Preparation of nutrient enriched MSW compost

MSW compost was procured from the organization ‘GRAMAUS’ (Grameen Manobic Unnayan Sangstha) which produces and markets compost with solid wastes collected from Mymensingh City, Bangladesh. They separate plastics, glasses and metals at source point of collection. Mustard oil cake (MOC), poultry manure (PM), cowdung (CD) and sugarcane press mud (SPM) were used as amended materials in a suitable proportion to enrich the MSW nutrient level. Table 1 shows the N, P, K & S contents of the organic materials used in this study. The N, P, K & S levels in four different types of amended compost are displayed in Table 2.

Nutrient analysis

The procedure for determining nutrient contents of different organic materials and amended MSW composts was the same, as outlined below. For N
Table 1 Nutrient status of MSW compost, mustard oil cake, cowdung, poultry manure and sugarcane press mud

<table>
<thead>
<tr>
<th>Organic material</th>
<th>N content (%)</th>
<th>P content (%)</th>
<th>K content (%)</th>
<th>S content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSW compost</td>
<td>1.14</td>
<td>0.23</td>
<td>0.87</td>
<td>0.27</td>
</tr>
<tr>
<td>Mustard oil cake</td>
<td>4.70</td>
<td>1.06</td>
<td>0.91</td>
<td>0.93</td>
</tr>
<tr>
<td>Cowdung</td>
<td>1.07</td>
<td>0.57</td>
<td>0.54</td>
<td>0.32</td>
</tr>
<tr>
<td>Poultry manure</td>
<td>1.33</td>
<td>0.80</td>
<td>0.89</td>
<td>0.42</td>
</tr>
<tr>
<td>Sugarcane press mud</td>
<td>1.59</td>
<td>0.091</td>
<td>0.64</td>
<td>0.51</td>
</tr>
</tbody>
</table>

MSW compost (mature) had 7.2 pH and 17.3 C:N ratio.

Table 2 Nutrient level of different types of compost

<table>
<thead>
<tr>
<th>Types compost</th>
<th>N content (%)</th>
<th>P content (%)</th>
<th>K content (%)</th>
<th>S content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compost 1</td>
<td>1.41</td>
<td>0.33</td>
<td>1.01</td>
<td>0.41</td>
</tr>
<tr>
<td>Compost 2</td>
<td>3.14</td>
<td>0.84</td>
<td>0.84</td>
<td>0.52</td>
</tr>
<tr>
<td>Compost 3</td>
<td>2.91</td>
<td>0.62</td>
<td>0.77</td>
<td>0.45</td>
</tr>
<tr>
<td>Compost 4</td>
<td>3.22</td>
<td>0.40</td>
<td>0.81</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Compost 1 = MSW 100%; Compost 2 = MSW 50% + MOC 20% + PM 30%; Compost 3 = MSW 50% + MOC 20% + CD 30%; Compost 4 = MSW 50% + MOC 20% + SPM 30%.

determination, \( \text{H}_2\text{SO}_4 \) digestion (Kjeldahl method) and for P, K \& S determination \( \text{HNO}_3\cdot\text{H}_2\text{O}_2 \) digestion procedures were followed (Page et al. 1982). The amount of N, P, K and S in the acid digest was measured by the same methods used for soil analysis. Nitrogen in the digest was estimated by distillation with 10N NaOH followed by titration of the distillate trapped in \( \text{H}_3\text{BO}_3 \) indicator solution with 0.01N \( \text{H}_2\text{SO}_4 \) (Bremner and Mulvaney 1982). The K concentration in the acid digest was determined by flame photometer (Knudsen et al. 1982). The amount of P in the digest was determined by colorimetric method and the S was determined by turbid method, as described in the section 2.5 (quantification of N, P and S mineralization).

Set up of incubation experiment

An incubation experiment was performed in the laboratory to examine the nutrient release pattern for N, P and S from mineralization of different types of amended MSW compost. Each compost at a rate of 10 g kg\(^{-1}\) (equivalent to 20 t ha\(^{-1}\), recommended dose for crop cultivation) was mixed with 100g soil in PVC pipes for aerobic (field capacity, 25% soil moisture) condition and plastic cup for anaerobic (1 cm standing water above soil) environment. A control soil (without compost) was run along with each set of incubation. They were incubated in the laboratory at room temperature (25 ± 1°C) for 82 days. The soil moisture level was checked weekly by weight loss and adjusted.

Destructive samplings were done in this study, i.e., there was a separate set of pipe/cup for each sampling time. The first sampling was done just on the next day of incubation and this analysis was considered as initial moisture content of soil. The second measurement was done at 7 days after incubation (DAI), and thereafter measurement was done at 15-day intervals. So, there were four treatments (3 amended and 1 unamended) with three replications of each treatment, arranged in a completely randomized (CRD) design.

Basic characteristics of soil

The soil (0-15 cm) was silt loam (14% sand, 70% silt &16% clay) having 6.7 pH (water), 2.79% organic matter (Nelson and Sommer 1982), 0.17% Kjeldahl N (Bremner and Mulvaney 1982), 4.1 mg kg\(^{-1}\) Olsen P (Olsen and Sommer 1982), 0.089 cmol (+) kg\(^{-1}\) \( \text{NH}_4\text{OAc} \) extractable K (Knudsen et al. 1982) and 17.1mg kg\(^{-1}\) \( \text{CaCl}_2 \) extractable S (Fox et al. 1964).

Quantification of N, P and S mineralization

The available N (\( \text{NH}_4^+\cdot\text{N} \) and \( \text{NO}_3^-\cdot\text{N} \)) content of soil was extracted by 2M KCl solution, with a 1:10 soil-extractant ratio (Keeney and Nelson 1982). The aliquot was steam distilled with MgO and Devarda alloy followed by titration of the distillate trapped in \( \text{H}_3\text{BO}_3 \) indicator solution with 0.01N \( \text{H}_2\text{SO}_4 \). The available P (\( \text{H}_3\text{PO}_4^-; \text{HPO}_4^{2-} \) and \( \text{PO}_4^{3-} \)) was extracted by 0.5M NaHCO\(_3\) solution, pH 8.5 and then determined.
colorimetrically by developing blue colour with reduction of phosphomolydate complex using NH$_4^+$-molybdate and ascorbic acid reagent (Olsen and Sommer 1982). Available S (SO$_4^{2-}$-S) was extracted from soil by 500 ppm P solution from Ca(H$_2$PO$_4$)$_2$. H$_2$O and was determined by turbidity method using BaCl$_2$ (Fox et al. 1964).

**Fitting of mineralization data to the first order kinetic model**

The N, P and S mineralization data were fitted to the first-order kinetic model (Stanford and Smith 1972):

\[ M_t = M_0 (1-e^{-kt}) \]

where \( M_t \) is the net N, P and S mineralized (mg kg$^{-1}$ soil) at time \( t \), \( M_0 \) is the potentially mineralizable N, P and S (mg kg$^{-1}$ soil), \( k \) is the rate constant (day$^{-1}$).

**Results and discussion**

The concentrations of N & P in the amended MSW composts had appreciably increased compared to original MSW compost.

**Nitrogen mineralization**

The available N content refers to the sum of NH$_4^+$-N and NO$_3^-$-N contents. These inorganic forms of N are the forms that plants and microorganisms can use.

The amount of NH$_4^+$-N formation at day 52 became level off, the highest level being recorded at day 22. Walpola and Arunakumara (2010) reported that the NH$_4^+$-N content reached to the peak at day 15 followed by gradual reductions in all treatments. Unlike NH$_4^+$-N, the NO$_3^-$-N concentration for all types of compost treatments was 2-3 times higher in aerobic condition compared to anaerobic condition. Aguilera et al. (2012) observed the similar result that the concentration of NH$_4^+$-N in flooded soils was higher than in dry soils and the reverse was true for the concentration of NO$_3^-$-N. The NO$_3^-$-N content under aerobic condition went to its peak at day 15; then, it decreased and finally it leveled off after 82 days for all amended soils. Ling-ling and Shu-tian (2014) found the rapid N mineralization in manure treated soil during 56-84 days of incubation.

**NH$_4^+$-N release pattern**

The release of NH$_4^+$-N from nutrient enriched MSW composts was significantly influenced by the added materials (cowdung, poultry manure, mustard oil cake and sugarcane press mud), soil moistures (aerobic and anaerobic conditions) and incubation days. Fig. 1 shows the extent of NH$_4^+$-N mineralization of different types of enriched compost under aerobic and anaerobic conditions over the period of 82 days. The soil amended with composts showed an increase in NH$_4^+$-N content initially presumable due to mineralization of organic matter. The amount of NH$_4^+$-N production reached its peak at day 22 in all the treatments and then decreased to a minimum at day 52 when it became almost stable for the rest period in aerobic condition, and under anaerobic condition, it attained the peak at day 15. Walpola and Arunakumara (2010) reported that the NH$_4^+$-N content reached to the peak at day 15 followed by gradual reductions in all treatments. The NH$_4^+$-N concentration was almost two times higher for every treatment in anaerobic condition than in aerobic condition. At the start (day 1) of the experiment, the NH$_4^+$-N concentration ranged from 2.80 mg kg$^{-1}$ (T$_0$) to 7.47 mg kg$^{-1}$ (T$_6$ & T$_7$) and it became level off on day 67 for both aerobic and anaerobic conditions. Treatment MSW compost + MOC + PM (T$_4$) had the highest release of NH$_4^+$-N showing a rate of 31.76 mg kg$^{-1}$ soil under aerobic condition at day 22 and 62.74 mg kg$^{-1}$ soil under anaerobic condition at day 15. It appeared that all compost amended soils in anaerobic condition demonstrated higher NH$_4^+$-N mineralization compared to aerobic condition. It appeared that the NH$_4^+$-N concentration became almost zero on day 67 and onwards under aerobic and anaerobic conditions (Fig. 1).

**NO$_3^-$-N release pattern**

The trend of NO$_3^-$-N release under aerobic and anaerobic conditions is presented in Fig. 2. The soils amended with different types of MSW compost showed an increase of NO$_3^-$-N content that was presumably due to mineralization of organic matter. As opposite to NH$_4^+$-N concentration, the NO$_3^-$-N concentration for all types of compost was found 2-3 times higher in aerobic environment compared to anaerobic over the treatments. With the passage of time, the NO$_3^-$-N content under aerobic condition increased progressively up to 15 days, then it sharply decreased within 37 days and thereafter it decreased slowly and finally leveled...
Fig. 1 Trend of NH$_4^+$-N release from different types of amended MSW compost under aerobic and anaerobic conditions

T$_1$: Only soil; T$_2$: MSW; T$_3$: MSW + MOC + PM; T$_4$: MSW + MOC + CD; T$_5$: MSW + MOC + SPM.

Fig. 2 Trend of NO$_3^-$-N release from different types of amended MSW compost under aerobic and anaerobic conditions

T$_1$: Only soil; T$_2$: MSW; T$_3$: MSW + MOC + PM; T$_4$: MSW + MOC + CD; T$_5$: MSW + MOC + SPM.
Cumulative N ($NH_4^+ + NO_3^-$) mineralization

The cumulative N mineralization due to different treatments and soil moisture levels across the incubation period is displayed in Fig. 3. The cumulative values of mineralization increased with incubation days, showing higher values for aerobic condition than for anaerobic condition. At the end of incubation time, the cumulative available N at field capacity soil moisture (aerobic) was found 178, 317, 442, 321 and 336 mg kg$^{-1}$ for $T_1$-$T_5$ treatments, respectively. These values for submerged soil condition (anaerobic) were chronologically 142, 210, 326, 202 and 250 mg kg$^{-1}$. Then, the cumulative KCl extractable (available) soil N under both soil conditions clearly followed the order: $T_3 > T_5 > T_4 \approx T_2 > T_1$.

The labile SOM fraction can play a dominant role in N mineralization since it serves as an easily accessible energy source for microorganisms and results in greater soil N mineralization (Ros et al. 2011; Whalen et al. 2000). On the contrary, Ros (2012) reported that labile SOM fractions acted as the source of soil mineralizable N. Decreases in the soil N mineralization potential occurred when dissolved organic matter was removed (Li et al. 2010). As observed by Bu et al. (2015), POM (particulate organic matter) could have a vital role in soil N mineralization under different crop rotation systems. However, in the present study the OM fractionation was not done, thus scope is limited to compare the present results.

Fig. 3 Trend of cumulative N mineralization from different types of amended MSW compost under aerobic and anaerobic conditions

$T_1$: Only soil; $T_2$: MSW; $T_3$: MSW + MOC + PM; $T_4$: MSW + MOC + CD; $T_5$: MSW + MOC + SPM.

N mineralization kinetics

The N mineralization data for all types of compost at two soil moisture levels over the 82 days’ incubation period were fitted to the first order kinetic model, $N_t = N_0 (1 - e^{-kt})$, where $N_t$ is the net N mineralization (mg kg$^{-1}$ soil) at time t, $N_0$ is the potentially mineralizable N (mg kg$^{-1}$ soil) and k is the rate constant (day$^{-1}$). The data weakly to moderately fitted to the kinetic model, as shown in Table 3. The kinetic data reveal that the potential mineralization ($N_0$) was the maximum for $T_3$ treatment (poultry manure- based treatment), the values being 92.41 and 74.15 mg kg$^{-1}$ under aerobic and anaerobic conditions, respectively. A different result was noted for ‘k’ value (mineralization constant), showing the highest value 1.667 for $T_3$ for aerobic case and 1.847 for $T_4$ for anaerobic case. This model analysis indicates that poultry manure and sugar press mud had higher capability to supply N for use by the crops.

Cheng and Wen (1993) from a 10-year decomposition experiment concluded that the annual mineralization rate of organic N in newly-formed humus varied with the type of original plant materials and the water regimes for decomposition. Wu et al. (2017) reported on the effect of 20-year long fertilizer application on soil N transformation in paddy soils in China that higher N nitrification was induced by manure application, which might lead to increased N losses.
Table 3  Estimated parameters of the first order kinetic model for N mineralization in soil treated with amended MSW composts

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Aerobic</th>
<th>Anaerobic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N₀</td>
<td>k</td>
</tr>
<tr>
<td>T₁: Only soil</td>
<td>35.21</td>
<td>0.014</td>
</tr>
<tr>
<td>T₂: MSW</td>
<td>62.74</td>
<td>1.451</td>
</tr>
<tr>
<td>T₃: MSW + MOC + PM</td>
<td>92.41</td>
<td>1.616</td>
</tr>
<tr>
<td>T₄: MSW + MOC + CD</td>
<td>66.21</td>
<td>1.631</td>
</tr>
<tr>
<td>T₅: MSW + MOC + SPM</td>
<td>70.89</td>
<td>1.667</td>
</tr>
</tbody>
</table>

MSW = Municipal solid waste, MOC = Mustard oil cake, PM = Poultry manure, CD = Cowdung, SPM = Sugarcane press mud.

*R² (adjusted) value: 0.0 to 0.2 - very weakly fit, 0.2 to 0.4 - weakly fit, 0.4 to 0.7 - moderately fit, 0.7 to 0.9 - strongly fit, 0.9 to 1.0 - very strongly fit.

N₀ = Potentially mineralizable N (mg kg⁻¹ soil), k = Rate constant (day⁻¹)

Phosphorus mineralization

P release pattern

The trend of P release from different types of amended MSW compost under aerobic and anaerobic conditions over the incubation period is displayed in Fig. 4. The P release was the highest at day 15 due to the T₃ treatment (MSW compost + MOC + PM) at field capacity (aerobic) condition. Next to T₃, the other treatments except control demonstrated similar P availability in soil. The P level went down to about 50% for all treatments after about 12 weeks of incubation. The T₁, i.e., exclusive soil treatment (no addition of manure) showed the lowest P concentration which was 2.28 mg kg⁻¹ at day 1 and 9.52 mg kg⁻¹ after day 82. The P release under submerged soil (1 cm standing water) condition was the maximum at day 7 and thereafter it sharply decreased until day 22; then, it decreased steadily until incubation expiry time. The P release under anaerobic condition was about three times higher compared to aerobic condition. Naher et al. (2004) reported that the P mineralization from organic manure occurred after 15 days of application and then it increased steadily with times. They found higher P mineralization in the cowdung and poultry manure treated soils.

Cumulative P mineralization

The cumulative P mineralization, as expected, increased

![Fig. 4 Trend of P release from different types of amended MSW compost under aerobic and anaerobic conditions](image-url)
progressively with the advancement of incubation time for all treatments. The value of cumulative P mineralization at every sampling date was higher in anaerobic condition than in aerobic condition. This is not the case for N and S mineralization processes where reverse trend was noticed. The values of cumulative P at field capacity soils (aerobic) due to different treatments were as follows: T₁ (88.4 mg kg⁻¹) > T₄ (54.6 mg kg⁻¹) > T₅ (41.5 mg kg⁻¹) > T₂ (32.0 mg kg⁻¹) > T₃ (17.8 mg kg⁻¹). These values for anaerobic condition was in the order of T₅ (259 mg kg⁻¹), T₃ (253 mg kg⁻¹), T₄ (220 mg kg⁻¹), T₂ (189 mg kg⁻¹) and T₁ (96.3 mg kg⁻¹) (Fig. 5).

Ahmad et al. (2019) stated that mineralization and mobilization of biosolids (product of wastewater or MSW) P in soil have beneficial input to both environment and soil nutrient amendment. Microbial P immobilization makes soil P temporarily unavailable to plants; it eventually becomes available upon complete microbial decomposition due to the simultaneous mineralization–immobilization processes (Johnson 2012; Kirkby et al. 2014).

Zhang et al. (2020) observed that P fertilization accelerated the soil dissolved organic matter (DOM) cycle, which potentially benefited soil C sequestration in paddy fields.

### P mineralization kinetics

The P mineralization data were fit to the first order kinetic model, 
P_t = P_0 (1- e^{-kt}), where P_t is the P mineralization at time t (mg kg⁻¹ soil), P_0 is the potentially mineralizable P (mg kg⁻¹ soil) and K is the rate constant (day⁻¹). In aerobic condition, the data fitted moderately for T₁, T₂ and T₅, weakly for T₃ and very weakly for T₄. In anaerobic condition, the data for all treatments fitted weakly to the kinetic equation. Like N mineralization, the T₅ (poultry manure based) treatment showed the highest potential P mineralization (P₀). But for the mineralization constant rate (k), the T₄ treatment (cowdung based) had the highest value under aerobic situation and in anaerobic situation, the T₁ (control, soil only) showed the highest value (Table 4).

### Sulphur mineralization

#### S release pattern

Like N and P, the S mineralization was also significantly influenced by the compost types, soil moisture levels and incubation days. The highest S mineralization was observed with MSW + MOC + SPM (T₅) with the value of 313.48 mg kg⁻¹ in aerobic condition (Fig. 6). In case of anaerobic condition, the maximum S concentration of 217.33 mg kg⁻¹ was noted with the combination of MSW + MOC + CD (T₄). The S concentration ranged from 32.87 mg kg⁻¹ (T₁) - 209.46 mg kg⁻¹ (T₃) under aerobic condition and 21.93 - 179.11 mg kg⁻¹ under anaerobic condition in the same two treatments, respectively. The
Table 4 Estimated parameters of the first order kinetic model for P mineralization in soil treated with amended MSW composts

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Aerobic</th>
<th>Anaerobic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_0$</td>
<td>$k$</td>
</tr>
<tr>
<td>$T_1$: Only soil</td>
<td>2.28</td>
<td>2.684</td>
</tr>
<tr>
<td>$T_2$: MSW</td>
<td>7.72</td>
<td>1.335</td>
</tr>
<tr>
<td>$T_3$: MSW + MOC + PM</td>
<td>14.08</td>
<td>7.217</td>
</tr>
<tr>
<td>$T_4$: MSW + MOC + CD</td>
<td>9.46</td>
<td>8.273</td>
</tr>
<tr>
<td>$T_5$: MSW + MOC + SPM</td>
<td>8.48</td>
<td>1.123</td>
</tr>
</tbody>
</table>

MSW = Municipal solid waste, MOC = Mustard oil cake, PM = Poultry manure, CD = Cowdung, SPM = Sugarcane press mud.

* $R^2$ (adjusted) value: 0.0 to 0.2 - very weakly fit, 0.2 to 0.4 - weakly fit, 0.4 to 0.7 - moderately fit, 0.7 to 0.9 - strongly fit, 0.9 to 1.0 - very strongly fit.

$P_0$ = Potentially mineralizable P (mg kg$^{-1}$ soil), $k$ = Rate constant (day$^{-1}$)

S concentration of different types of compost reached its peak within a week, then came down sharply until week 3, then dropped gently until 7 weeks have passed when the S levels remained almost the same for the rest period.

**Cumulative S mineralization**

The cumulative S mineralization was likely to follow an increasing trend with the incubation days, showing the highest value at day 82 and the lowest at day 1 for all treatments at two moisture levels. In aerobic soil, the $T_3$ treatment demonstrated the highest level (1176 mg kg$^{-1}$), followed by $T_4$ (970 mg kg$^{-1}$), $T_5$ (819 mg kg$^{-1}$), $T_2$ (600 mg kg$^{-1}$) and $T_1$ (412 mg kg$^{-1}$) (Fig. 7). The cumulative S mineralization in anaerobic condition followed the same order, with lower values showing $T_3$ (807 mg kg$^{-1}$), followed by $T_4$ (633 mg kg$^{-1}$), $T_5$ (596 mg kg$^{-1}$), $T_2$ (479 mg kg$^{-1}$) and $T_1$ (330 mg kg$^{-1}$). It is assumed that much SO$_4$-S went into reduction to H$_2$S or S under submerged condition.

**S mineralization kinetics**

Unlike N and P mineralization, the S mineralization data under aerobic condition fitted strongly for all the treatments except $T_1$ which showed weak fit to the first order kinetic model, $S_t = S_0 (1 - e^{-kt})$, where $S_t$ is the S mineralization at time t (mg kg$^{-1}$ soil), $S_0$ is the potentially mineralizable S (mg kg$^{-1}$ soil) and k is the rate constant (day$^{-1}$). In anaerobic condition, the data
Fig. 7 Trend of S mineralization from different types of amended MSW compost under aerobic and anaerobic conditions

from treatments $T_2$ and $T_3$ fitted strongly, $T_4$ moderately and $T_5$ weakly to the kinetic model. Concerning mineralization rate constant that expressed by ‘k’ value, it followed the order $T_1 > T_5 > T_4 > T_2 > T_3$ under aerobic condition, while under anaerobic condition the order is opposite, showing $T_3 > T_4 > T_2 > T_5 \approx T_1$ (Table 5).

**Conclusion**

Use of 20% mustard oil cake and 30% sugarcane press mud or poultry manure or cowdung with 50% MSW compost (in 2:3:5 ratio) greatly increased the nutrient level of MSW compost. The highest $NH_4^+$-N and P release (orthophosphate ions) occurred at day 15 while the $NO_3^-$ and $SO_4^{2-}$ release happened at day 22 and day 7, respectively over the 82 day’s incubation period. The N and S availability was reduced 2-3 times in submerged (1 cm water depth) soil conditions while the P availability much increased in this situation, the result has great implications for sustainable nutrient management in wet land rice culture. The kinetic model analysis indicates that poultry manure and sugarcane press mud had higher nutrient supplying capacity to the crops.

**Table 5** Estimated parameters of the first order kinetic model for S mineralization in soil treated with amended MSW composites

<table>
<thead>
<tr>
<th>Treatments</th>
<th>$S_0$</th>
<th>k</th>
<th>$R^2_{adj*}$</th>
<th>$S_0$</th>
<th>k</th>
<th>$R^2_{adj*}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$: Only soil</td>
<td>65.38</td>
<td>7.134</td>
<td>0.274</td>
<td>65.05</td>
<td>1.436</td>
<td>0.293</td>
</tr>
<tr>
<td>$T_2$: MSW</td>
<td>130.58</td>
<td>1.917</td>
<td>0.777</td>
<td>116.92</td>
<td>2.371</td>
<td>0.799</td>
</tr>
<tr>
<td>$T_3$: MSW + MOC + PM</td>
<td>252.79</td>
<td>1.887</td>
<td>0.769</td>
<td>226.89</td>
<td>3.055</td>
<td>0.867</td>
</tr>
<tr>
<td>$T_4$: MSW + MOC + CD</td>
<td>200.65</td>
<td>2.178</td>
<td>0.703</td>
<td>170.14</td>
<td>3.367</td>
<td>0.689</td>
</tr>
<tr>
<td>$T_5$: MSW + MOC + SPM</td>
<td>250.55</td>
<td>2.730</td>
<td>0.733</td>
<td>65.05</td>
<td>1.436</td>
<td>0.293</td>
</tr>
</tbody>
</table>

MSW = Municipal solid waste, MOC = Mustard oil cake, PM = Poultry manure, CD = Cowdung, SPM = Sugar press mud.

*$R^2$ (adjusted) value: 0.0 to 0.2 - very weakly fit, 0.2 to 0.4 - weakly fit, 0.4 to 0.7 -moderately fit, 0.7 to 0.9 - strongly fit, 0.9 to 1.0 - very strongly fit.

$S_0$ = Potentially mineralizable S (mg kg$^{-1}$ soil), k = Rate constant (day$^{-1}$)
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Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

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