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ORIGINAL RESEARCH

Role of electron acceptors in soil resource circulation for organic waste composting

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Abstract

Purpose Soil is an important accelerator for biodegradable processes. Soil resource circulation concept by using the compost from the previous crop as cover materials for the recent composting mass was evaluated as it contained soil and amorphous Fe as an energy source. Therefore, this research was focused on the possibility and the changes in the electron acceptors in the organic waste composting process.

Method The 2 experiments using different covering materials: paddy soil as a control (T1) and compost (T2) in a completely randomized design. An amount (670 g) of organic wastes was altered with 210 g of materials covered in 3 layers with 60 mL of water added every 7 days during a period of 30 days. The physico-chemical parameters, redox potential (Eh), and electrical conductivity (EC) were studied beside the basic soil parameters including electron acceptors such as, NO_3^-, Fe_2O_3, MnO_2 and SO_4^{2-}.

Results The changes in physical and chemical properties during the degradation process were not different. The Eh reacted intensely and continuously in the same direction. The T2 compost product contained the highest level compared to T1 but there were no significant differences in the organic carbon and C/N ratio, though the quality of T1 was better.

Conclusion Covering the organic waste with compost improved the nutrient content in the compost products. Therefore, compost can be used as a cover material instead of soil in the composting process. However, to increase the number of electron acceptors, cover materials should be mixture of soil with compost for greater efficiency.

Keywords Compost, Organic waste, Electron acceptors, Redox potential (Eh)

Abbreviations

Eh	Redox potential
EC	Electrical Conductivity
ORP	Oxidation-Reduction Potential
MC	Moisture Content
mg/kg	Milligram per kilogram
OM	Organic Matter
OC	Organic Carbon
CEC	Cation Exchange Capacity
C/N	Carbon per Nitrogen

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Introduction

Municipal solid waste management has long been considered a severe environmental problem. The mismanagement of solid waste could increase the toxicity of ecosystems and impact adversely on human health. Thailand has given a priority to this problem and has promoted appropriate technology for solid waste management at local-level point sources such as food waste is used to feed animals or composting for soil improvement and crop production, as well as for biogas production to reduce the amount of waste disposal in landfills. Similar to other Asian countries, most waste in Thailand has a high organic composition comprising about 64% of all wastes (food waste, organic materials, and agricultural waste) by weight with high moisture content and higher degradability (Pollution control department 2021).

Therefore, composting technology is suitable for sorted organic waste while sanitary landfill is suitable for unsorted waste. Composting is the natural process of degradation and recycling of organic material into humus and inorganic matter. There are various methods of composting technology that enhances degradation performance. The composting technology using soils as electron acceptors is widely popular in Thailand because it can be applied locally, is cheap, reduces the leachate problem, and can be implemented on done in small areas. Furthermore, soil can be efficient in scrubbing gases to reduce unpleasant odors during the biodegradation process as organic waste has the potential to produce hydrogen sulfide (strong, rotten-egg smell), ammonia (pungent smell), methane, and air toxins including some volatile organic carbons are generated.

The composting technology process involves covering the organic waste with soil and using amorphous Fe or active Fe (III) as an oxide compound (Fe_2O_3) which play a vital role as an electron acceptor. Other electron acceptors such as nitrate NO_3^-, amorphous Mn (MnO_2) and sulfate SO_4^{2-} also contribute to continue degradation, even under the anaerobic conditions. Natural facultative anaerobes can also use oxides, organic matter, or inorganic compounds. Both organic waste and inorganic compounds in soil can act as electron acceptors. Consequently, the soil is an important factor to promote microbial activity during the composting process (Chueawong et al. 2019). However, in different areas, especially in towns or cities, it is difficult to find suitable soil for this purpose. The soil resource circulation concept involves using the compost from the previous crop as a covering material to replace the soil as the compost already containing amorphous Fe soil as an ingredient to influence the redox properties of organic substances and to facilitate the important redox-active functional groups. (He et al. 2019). Accordingly, the current research focused on the effect of using compost as a covering material and to examine quality of the compost product through this process. The results of this study can be used as guidelines for soil resource circulation, reducing soil excavation for composting purpose, and can be adopted in areas of soil shortage. This study was carried out in The King's Royally Initiated Laem Phak Bia Environmental Research and Development Project (LPB project), Chaipattana Foundation in Thailand in November, 2020.

Materials and methods

The experiments were conducted by modifying the traditional use and procedure of the LPB project's concrete box technology which was simulated at a reduced scale of 1: 1,000. There were 2 experiments in the randomized block design. The ratio of organic wastes-to-soils was 2:1 (1 kg of soil covered the organic material in 3 layers and 2 kg of organic wastes consisting of rice, boneless breast chicken, cabbage, and banana peel.

The experiments were done in square plastic boxes (length 15.5 cm, width 25 cm, and height 17 cm), as shown in Fig. 1. The bottom was perforated and some pieces of charcoal were placed over the holes for the release of leachate into a plastic bottle. A basal layer of sand (approximately 1–2 cm thickness) was spread over the unit. The simulation used the organic waste and cover materials for 3 layers. The organic waste consisted of 670 g per layer and the cover materials were placed in 3 different layers from bottom to top of 210, 210, and 630 g, respectively. Water (60 ml) was added to the compost boxes at the interval of every 7th day and composting was carried out for 30 days, as shown in Fig. 1. The treatments varied the materials used for cover in the composting process: 1), paddy soil (T1, the control) and 2) compost from the previous crop (T2). This experiment was set up using a completely randomized block design with 5 replications.

Parameters such as temperature and moisture content (MC) were monitored at the center of each unit every day. The pH, oxidation-reduction potential (redox potential; Eh), and electrical conductivity (EC) parameters were collected and analyzed in the laboratory every 7th day. The soil, compost, and organic waste characteristics measured were: soil texture, pH, EC, organic matter (OM), organic carbon (OC), cation exchange capacity (CEC), total nitrogen, total phosphorus, and total potassium. The measured electron acceptors parameters were: nitrate, active Mn (MnO_2), active Fe (Fe_2O_3), and sulfate which were sampled from each unit. The data were analyzed using one-way analysis of variance (ANOVA) and Tukey's test in the SPSS 17 version software package and significance was tested at the 5% probability level.

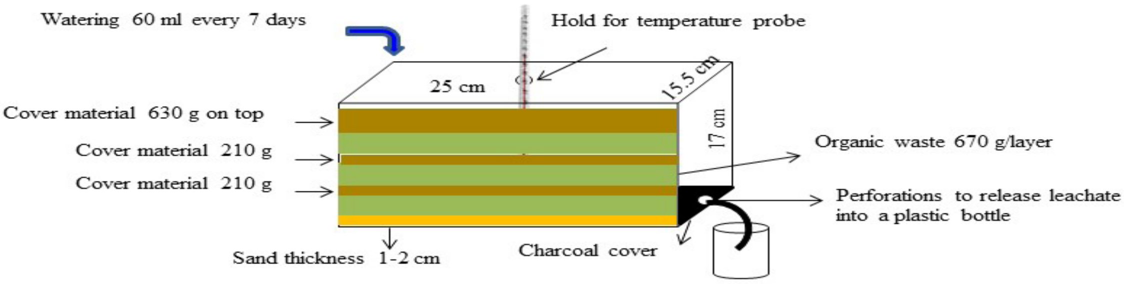

Fig. 1 Organic waste composting in plastic boxes instead of concrete boxes by scaling down 1,000 times

Results and discussion

Characteristics of paddy soil, compost, and organic waste

The characteristics of paddy soil, compost material, and organic waste used in the experiment had different physical and chemical properties (Table 1). The paddy soil had clay texture, neutral pH, and low organic matter and organic carbon. There were electron acceptors in the paddy soil, such as (NO_3^-), (MnO_2), (Fe_2O_3), and SO_4^{2-} especially, the oxides of iron or the amorphous Fe forms have been reported to have a role in anaerobic respiration (Ponnamperuma 1972). The amounts of active Fe in the paddy soil and compost were 6,700 and 6,500 mg/kg, respectively. These constituents were redox-active and capable of mediating biogeochemical redox reactions (Nurmi and Tratnyek 2002; Huang et al. 2010).

Table 1 the characteristics of paddy soil, compost material, and organic waste before the experiment

Parameters	Paddy Soil	Compost	Organic waste
pH (1:10)	6.8	7.2	5.7
EC (dS/m)	0.31	1.83	1.93
OM (%)	1.08	3.73	84.06
OC (%)	0.62	2.16	48.76
Total N (%)	0.03	0.22	2.21
Total P (%)	0.02	0.05	0.10
Total K (%)	0.005	0.78	0.78
C/N ratio	17.87	10.82	22.06
SO_4^{2-} - S (mg/kg)	22.85	31.95	54.92
NO_3^- - N (mg/kg)	151.25	109.8	
MnO_2- Mn (mg/kg)	1,400	1,200	
Fe_2O_3- Fe (mg/kg)	6,700	6,500	
CEC (cmol/kg)	15.64	24.15	
Texture	Clay		
Sand (%)	14		
Silt (%)	33		
Clay (%)	53		

Other studies have also reported on their redox properties (Bauer et al. 2007; Huang et al. 2010; Yuan et al. 2011). For T2, the compost (cover material) came from the previous crop, consisted of paddy soil which had neutral pH and higher EC, sulfate, OM, OC, and CEC values than the paddy soils. These values were related to the nutrient contents in the compost which had low levels of nitrate and electron acceptors. In paddy soil, CEC decreased through soil degradation, and buffering altered when the pH was not stable (Ratneetoo and Wongkrachang 2013; Jacoby et al. 2017). The C/N ratio in the compost was 10.82, indicating high-quality compost (Eiland et al. 2001).Otherwise, the organic waste had a pH of 5.7 (moderately acidic reaction), OC of 48.76 percent and a high total nitrogen loading (22.06 C/N ratio).

Physical parameters

Temperature

During the composting process the temperature increased in both treatments. Temperature is an indicator of microbial activity during the composting process (Liang et al. 2003). The temperature changes during the various stages of composting were similar to those reported by Bustamante et al. (2008) and Zahrim et al. (2016). The initial temperature in both treatments was 33.30 °C in the mesophilic stage and reached the maximum temperatures on day 2 when the values for T1 and T2 treatments were 41.60 and 43.60 °C, respectively (Fig. 2a). The temperature in the compost box increased rapidly from the 2nd to the 4th day due to the release of heat energy during the organic degradation process. The rise in temperature during the process confirmed exothermic degradation of the organic materials, which increased the microbial population and the rate of degradation of the organic matter (Pattanaik et al. 2020). The highest temperature in the initial stage with a short duration is essential for the composting process to encourage rapid microbial growth activity (Tang et al. 2007; Rich et al. 2018). Later on the temperature reduced continuously which could be related to a decrease in microbial growth due to the exhaustion of a microbial energy source. During the rapid growth stage, facultative anaerobes require rich organic substances and environmental factors to maintain their activity, if these are insufficient then unstable temperature and moisture content result.

Moisture content (MC)

In the early stages of the decomposition process, the moisture content was 40-60%.The higher temperature suppressed ammonification and the growth, and activity of the nitrifying bacteria (Li et al. 2013). Likewise, by-products had high MC levels which tended to increase in 4-8 days (Fig. 2a). MCwas related to the elevated temperature during the active phase of composting and decreased again after 7 days (Yuan et al. 2012). Then, the MC continuously decreased until maturity with some minor increases on some days depending on the temperature and weight loss rate. The MC remained stable at a high level since the 3rd week which resulted in the coagulation of compost under anaerobic conditions (Riddech 2013). Humic acid has a tendency to catch many metallic ions such as Mn^{2+}, Zn^{2+}, Cu^{2+}, Fe^{3+}, and Al^{+} (Khan 1969). The MC at 50-70% significantly influenced the microbial activity of the composting process.

Weight loss rate

The organic degradation process can be divided into two phases: the initial phase (rapid degradation) and the later phase (slower degradation) (Pattanaik et al. 2020). During the composting process, both conditions had an abundance of microorganisms that were diverse and changed with time. The highest weight loss rate started in the 2nd week (Fig. 2b), which was related to the temperature increase and the associated microbial activity during the composting process and then was stable during the active phase before decreasing again after 7 days until the end of the experiment. At the end of the process, the compost product had a high amount of organic matter and a high organic carbon concentration. The experiment ended when the C/N ratio was less than 20:1, indicating that the composting process was complete and the compost was mature. (Said-Pullicino et al. 2007).Similarly, the degradation of cellulose and hemicellulose at mesophilic temperatures was reported to reduce the composting volume due to higher decomposition from microbial activity (Paradelo et al. 2013), as shown in Fig. 2.

pH

Neutral pH values are suitable for composting with 6.0 being recommended at the start and 6.5–7.5 at the end

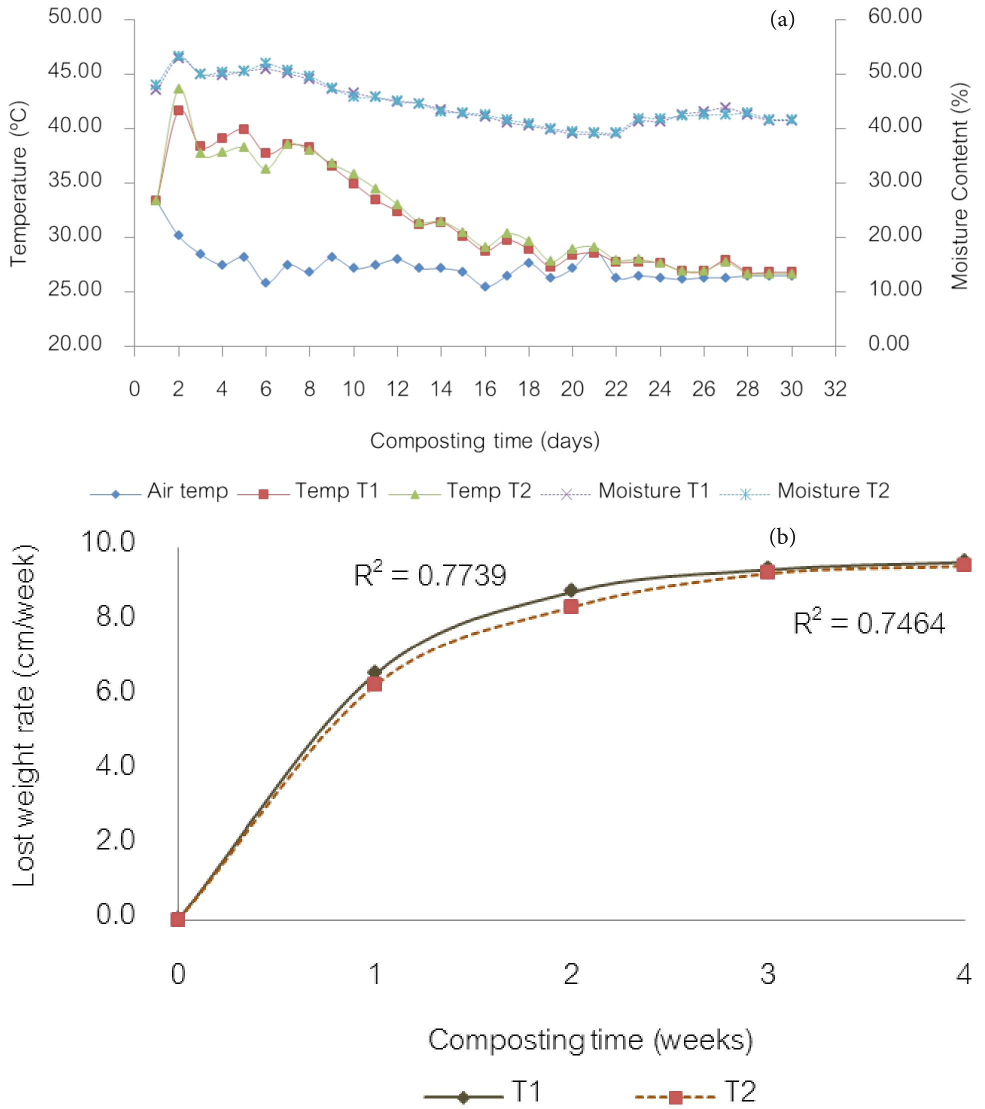

Fig. 2 Physical changes during degradation process for treatments T1 and T2: (a) Relationship between temperature and moisture content, (b) Weight loss rate of compost

(Wang et al. 2013). The pH increased in the initial phase due to the accumulation of ammonia in the process followed by ammonification of organic N into NH_3NH or $NH^{+}_{4}NH$. The pH value increased with $NH^{+}_{4}NH$ which came from the ammonification process of organic nitrogen (Zhang et al. 2018), then the pH decreased in the 2nd week during the mesophilic stage. The results showed that T1 had a more pronounced reduction in pH than T2. As the growth of nitrifying bacteria is inhibited by an acidic pH, the nitrification process is suggested to have a pH of 7.5–8.0 to mineralize to (Wong et al. 2017; Cáceres et al. 2018; Yu et al. 2019). The number of electron acceptors was affected, with a rapid reduction reaction producing compounds as electron donors. In addition, the Eh values were highly negative under acidic conditions (Fig. 3a and 3b).

Electrical conductivity (EC)

During the composting process, the EC increased by release of soluble salts and the deposition of mineral salts containing phosphate, potassium, and ammonium ions (Awasthi et al. 2014; Sharma et al. 2018). Finally, the EC values of the compost product were lower than 1 dS/m, as shown in Fig. 3c and Table 3. The correlation between electron acceptors and the Eh was encouraged by an elevated pH value, as not only did the salinity increase, but the compost materials expanded and blocked macropores which caused the EC and pH to reduce and a rapid reduction in the bio-oxidation state (Diacono and Montemurro 2015) and this increased again in the maturation phase following an EC increase that may have been attributable to the saturation of sites and the association of all protons. There was an immediate decrease in the EC curves that could be largely explained by the reaction between the salt and the functional groups of humic acids. However, the major functional groups that could be involved in the salt reaction in the present experiment were carboxylic groups (El-Hasini et al. 2020).

Redox potential (Eh)

The Eh value changed and tended to decrease with the formation of humic acids in the compost (Kappler et al. 2001) with an increase in the humic acid concentration in the soil (Khalil et al. 2008; Yuan et al. 2012; Yuan et al. 2019). The results showed that the Eh values for both treatments were -345.43 and -257.86 mV in the first week and tended to increase in terms of negative millivolts until the 2nd week due to each treatment having a high moisture content which affected the oxidation-reduction reaction of the organic and inorganic compounds, resulting in electron release with high energy compounds. The reduction reaction was intense in the 3rd week, likewise the pH and electric conductivity had the same trend through the composting process period. According to theory, the increase in pH in the 2nd week could be attributed to the production of ammonia associated with protein degradation in the samples and the decomposition of organic acids (Liu et al. 2011). Rich organic matter could be used as an energy source and carbon source for microbial activity. The change in Eh during the composting process corresponded to the biodegradation of organic matter. Consequently, Eh was linked to temperature, EC, and pH and positively correlated with organic matter. The treatment (T1) had a stronger reduction effect than the T2 treatment as T2 had a high organic loading the cellulose content in the compost. At the end of the composting process, there was no significant difference in the reduction reaction associated with the moisture content, weight loss rate, and the organic compounds. There was gradual shift towards less reduced state by the 3rd week (Samudro and Hewmana 2007; Chueawong et al. 2019) as shown in Table 2.

Table 2 Change in redox potential (mV) during 28 days

Treatment	Redox potential (mV)				
	Initial day	7 days	14 days	21 days	28 days
T1	188.83	-346.43	-346.57	-167.40	-85.77
T2	144.60	-257.86	-344.17	-305.20	-77.70
F – test	*	*	ns	*	ns
CV (%)	16.13	20.73	0.49	41.24	6.98

Remark: ns = not significant, * = significant at $p \geq 0.05$

Changes in electron acceptors

The facultative anaerobe decomposers took NO_3^- and MnO_2 as electron acceptors in anaerobic respiration. On the other side of the equation, or $Fe(OH)_3$ and were reduced by obligate anaerobes through the electron transport system. The organic compounds were changed to carbon dioxide, ammonia, or sulfide and ferrous compounds by the biochemical reaction. In the first and third weeks of the experiment, the Eh values were significantly different since oxygen was rapidly depleted and then the facultative anaerobes had to trap oxygen from other inorganic compounds in the cover material. Generally, Eh was reduced and became negative following the activity of the microorganisms in the thermodynamic sequence which again depended on many factors such as OM, temperature, pH, and the kinds of electron acceptors (Ponnamperuma 1972). The data showed that a number of organic compounds affected the MC; T2 had a higher MC than T1, due to the rich organic matter which had higher water holding capacity. During the mesophilic-thermophilic composting period, microorganisms required more soluble phosphorus for rapid organic matter degradation (Wang et al. 2019). Some of the electron acceptors could be recycled in the electron transfer process within the 3rd week which was related to the change in redox potential (Eh) in the decomposition process by utilizing active Fe or the other electron acceptors such as NO_3^-, MnO_2, and SO_4^{2-} from the covered material.

Consequently, the carbon oxidation and sulfate formation of compost were influenced by Eh. Indeed, the low values of Eh in the beginning of the process were due to unstable intermediate compounds. Monitoring the Eh

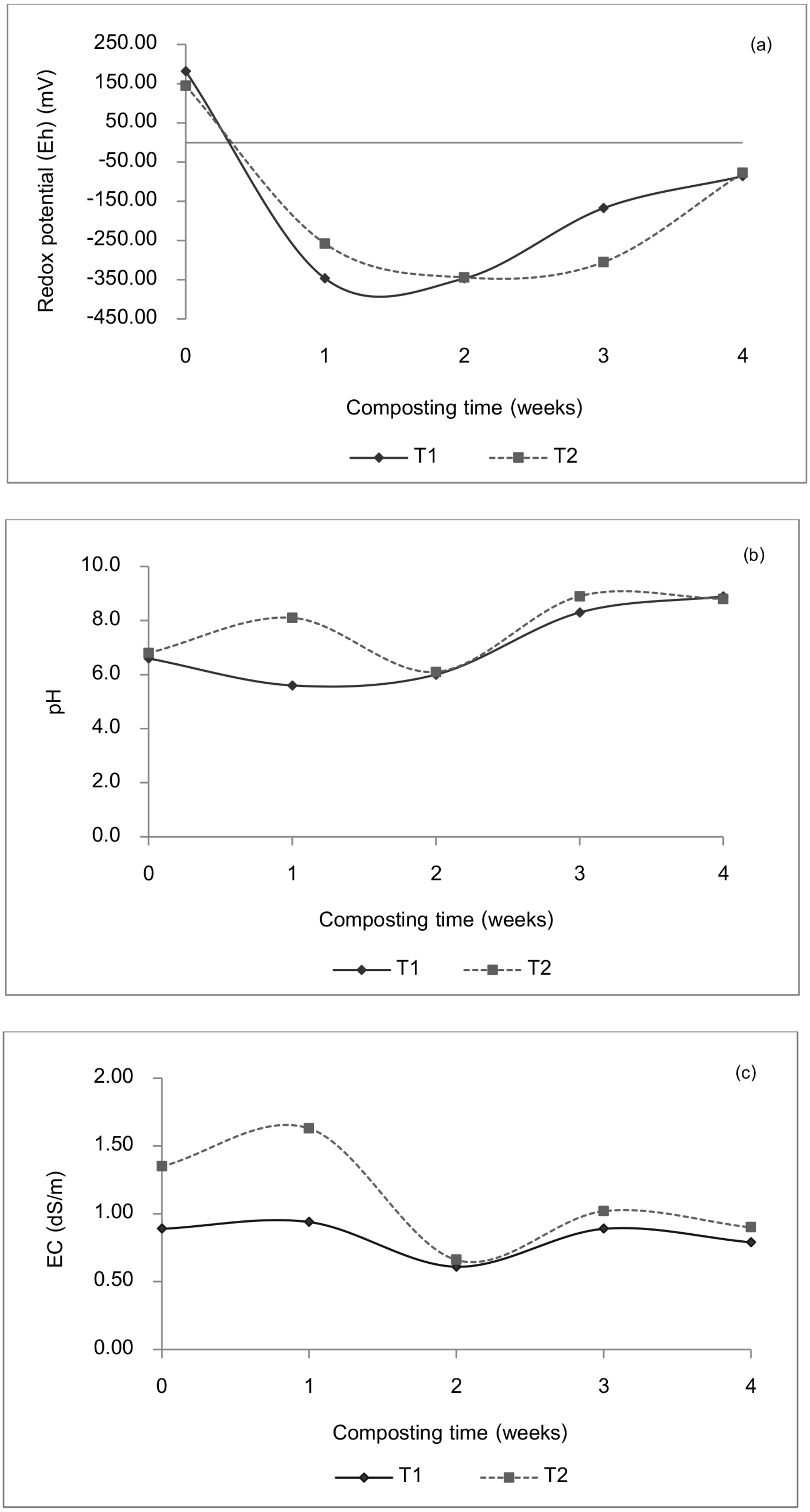

Fig. 3 Changes in chemical characteristics during degradation process: (a) Redox potential (Eh), (b) pH, and (c) Electrical conductivity (EC)

trend was useful for monitoring the composting process, when Eh value was stable that indicated that compost had entered the maturation phase and was rich in humic substances (Khalil et al. 2008). Humic acids were able to chelate metals on their carboxylic sites (Zingaretti et al. 2018; El-Hasini et al. 2020). Humic acids have proved their ability to take part in complex formations, ionic exchange, and oxidation-reduction reactions (Davies et al. 1997).

Qualities of by-product from composting

The results showed that MC, pH, EC, C/N ratio, and the nutrients were within the prescribed organic composting standards of the Department of Agriculture, Thailand. The quantity of required bulking agents to provide an optimum environment for microorganisms during composting can be treated to enhance degradation (Wu et al. 2017). The C/N ratio, in the initial stage, was slightly higher due to ammonification but in the later phase N gradually decreased due to N immobilization by microbes (Cai et al. 2013; Chan et al. 2016). Thus, it was possible that the polyphosphate accumulator, which utilized the external carbon source in the metabolism of the microbial cell, may help in the removal of nitrogen and phosphorus, while the pH was higher than 8 (Li et al. 2011; Rout et al. 2017).

Table 3 Qualities of compost product

Treatment	Moisture (%)	pH	EC (dS/m)	OC (%)	OM (%)	Total N (%)	Total P (%)	Total K (%)	C/N ratio
T1	14.23	7.77	0.89	5.51	9.49	0.70	0.05	0.76	7.92
T2	21.60	7.83	0.99	5.39	9.29	0.73	0.08	0.83	7.58
Paddy Soil	1.89	6.8	0.31	0.62	1.08	0.03	0.02	0.005	17.87
Compost materials	14.2	7.2	1.83	2.16	3.73	0.22	0.05	0.78	10.82
F - test	*	ns	*	ns	ns	ns	*	ns	ns
CV (%)	29.09	0.54	7.52	1.56	1.51	2.97	32.64	6.23	3.10

Remark: ns = not significant, * = significant at $p \geq 0.05$

C/N ratio and TOC

The study showed that the C/N ratio decreased due to the organic carbon being consumed by microorganisms as an energy source for their growth and propagation, releasing which affected the degradation of organic matter and was related to the pH and EC values (Awasthi et al. 2014; Sharma et al. 2018). The ratio of C:N:P directly controls the microbial population to degrade phospholipids, DNA, and simple phosphate monoesters, by providing energy for the metabolic process (Khan and Joergensen 2009). On the other hand, paddy soil has an instant energy source that can impact the microbial community structures and regulate moisture, aeration, nutrient conditions, and the pH of the compost (Barthod et al. 2018; Rastogi et al. 2020). The percentage of clay particles showed another side effect of using compost as a cover material because some cellulose remained as a complex structure which was difficult to decompose by microorganisms. Consequently, there was a significantly longer period for adapting. However, when the C/N ratio was over 20, N immobilization occurs continuously. Initially, the nitrogen content in the organic waste materials was affected by the cover material and decreased in the initial phase with an increase in the inoculum (Pattanaik et al. 2020). In the final state, total nitrogen increased but the weight of the compost product reduced. This same trend occurred with other factors, except for total phosphorus and sulfate as shown in Table 4. The production of organic and inorganic acids from the decomposition of organic wastes can increase the number of bacterial populations, which is affected by carbon and nitrogen cycling in the ecosystem (Guo et al. 2020). When electrons were released, the anaerobes provided the electron transport system, and affected the pH that changed from slightly acidic to neutral. A high percentage of clay in the soil could absorb nutrients and cations as well utilizing capillary force.

The number of electron acceptors in the compost product such as and were lower compared to the raw materials. The recovery efficiencies of T1 and T2 remained at 92.5 and 88.5 percent, respectively, and the recovery efficiencies were 76.1 and 76.4 percent, respectively. The and structures have a rough surface area, solubility, and can flocculate to clay particles. The anaerobes used electron acceptors and transformed to ferrous (Fe^{2+}) and to manganese (Mn^{2+}) (Ponnamperuma 1972; Saenjan et al. 2004; Yuan et al. 2019). Therefore, the compost properties indicated that T2 had a longer period of entirely anaerobic respiration than T1.The amount of nitrate in the compost product was higher than in the raw materials due to the nitrification process (Scherer and Zhang 2002). There was a highly significant difference in sulfate between T1 and the T2 compost product as the organic waste contained S in amino acids. Thus, electron acceptors such as NO_3^-, Fe_2O_3, MnO_2 and SO_4^{2-} were transformed in the decomposition process under anaerobic respiration conditions, which was related to a decrease in the compost product mass due to weight loss rate through humus formation. Dissolved organic matter and humic substances could be reversibly oxidized and reduced during the electron transferring process when the redox potential was continuously increasing...

Table 4 Amounts of electron accepters in compost product

Items	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
T1	387.32	1065.55	6196.00	56.81
T2	314.31	916.90	5755.41	157.63
Paddy soil	151.25	1,400	6,700	22.85
Compost materials	109.8	1,200	6,500	31.95
F - test	ns	ns	*	*
CV (%)	14.71	10.60	104.96	66.49

Remark: ns = not significant, * = significant at $p \geq 0.05$

Conclusion

The paddy soil was rich in electron acceptors such as NO_3^-, Fe_2O_3, MnO_2 and SO_4^{2-} that enhanced anaerobic respiration in the organic waste degradation process. Therefore, the soil was an influential material in the composting process. Compost products from organic waste degradation contained electron acceptors and clay texture. Consequently, it was possible to use compost as a cover material instead of paddy soil for the organic waste composting process in the second crop, which would help to reduce paddy soil utilization in areas where there was a soil shortage. The biochemical mechanism of organic waste degradation into inorganic substances (called mineralization) occurred through the utilization of the active electron acceptors. The results of the soil circulation process for organic waste composting based on the modified concrete box technology showed that the electron acceptors affected physical indicators such as temperature, moisture content, and weight loss rate. The changes in the pH, EC, and Eh, which were different in the initial week, but stable in the third week until composting had finished. It can be concluded that the compost material can be used as an electron acceptor to maintain microbial activity and the degradation process, with the bulk materials functioning as substrate. The nutrient composition was increased by the decomposition of the organic carbon and the C/N ratio was also less than 20. The highest nutrient level was that of total potassium. Use of compost as a cover material in the organic waste composting process, would promote more complete anaerobic degradation compared to use of paddy soil only. Therefore, organic waste compost can be used as a cover material but should be mixed with paddy soil as a co-compost to increase energy sources from NO_3^-, Fe_2O_3, MnO_2 and SO_4^{2-}. This would be a positive factor in cellular respiration, reducing the need for paddy soil in the composting process, as the compost product had high nutrient levels. This would also improve agricultural performance as a soil amendment, especially in areas where there is a shortage of soil.

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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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