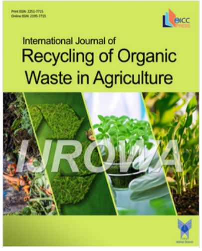

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Feasibility of mango by-products and biogas solid residue aerobic co-composting at different C/N ratios

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Abstract:
Purpose: Co-composting of mango by-products and biogas solid residue eliminates some shortcomings of composting these wastes separately. Specifically, co-composing solves the problem of the low pH values in mango by-products while enhances biodegradable organic matter of biogas solid residues. However, no research report is available on co-composting of mango by-products (MB) and biogas solid residue (BR).
Method: This study established three in-vessel lab-scale composting bins with 3 different C/N ratios, including Bin 1: 27.4/1 (156 kg MB + 144 kg BR); Bin 2: 30.23/1 (193 kg MB + 107 kg BR); and Bin 3: 37.7/1 (224 kg MB + 76 kg BR). The raw compost materials underwent 57 days of incubation, including 36 days of raw incubation and 21 days of mineralization.
Results: Bin 3 containing larger amounts of mango by-products and less amounts of biogas residue showed a higher percentage of remaining carbon in the final products (17.97%), lower nitrogen loss (17%), and showed 0.5% increase in available P_2O_5 content, compared to the other bins. From 300 kg of initial raw material, the final compost mass in Bin 1, Bin 2, and Bin 3 were 26.2 kg, 32.7 kg, and 88.1 kg, respectively.
Conclusion: Resultantly, an initial C/N ratio of 37.7/1 could be suggested in the aerobic co-composting of biogas residue with mango by-products.

Keywords: Biogas solid residue; Co-composting; C/N ratio; Humus; Mango byproducts

1. Introduction

Mango (Mangifera indica) is a member of the cashew family (Anacardiaceae), a widely cultivated fruit in tropical regions. The mango tree is indigenous to Asia, especially Myanmar and the Assam state of India. Vietnam is also the 13th largest mango producer in over the world, with a total production area of 87,000 hectares and an output of 893,200 tonnes in 2020. The majority of Vietnamese mango production is concentrated in the Mekong Delta region, which accounts for 48% of the country's total production area (MARD, 2020). In recent years, there has been a major increase in the number of mango-derived products to fulfil the demand for food, leading to the rapid development of mango processing industry. As a result, a significant quantity of bio-waste of the mango processing industry is produced that can cause considerable environmental issues. These bio-wastes are mainly composed of peels and kernels, accounting for up to approximately 30 – 50% of total solid waste, of which 19 – 38% is peels and 7 – 14% is kernels (Elsheshetawy et al. 2016). There have been many treatment approaches for this type of waste reported, such as animal feeding (Dou et al. 2018)), composting (Cerda et al. 2018; Guidoni et al. 2018; Oviedo-Ocaña et al. 2019), anaerobic/aerobic digestion (Zhu 2007), and landfill disposal (Badgett and Milbrandt 2021).Composting is a potential measure to treat bio-wastes because of its potential benefits. In effect, utilization of bio-wastes of the mango processing industries into compost or organic fertilizer can be seen as among the best resolutions to mitigate environmental issues. This approach can not only increase the profitability of fruit processing industries but also facilitate improved solid waste management (Campos et al. 2020).

Composting technology is beneficial to the environment, which turns biodegradable waste into organic fertilizer, contributing to the sustainable development of agriculture. Thanks to this, mango by-products after processing can be used for composting. Composting is a process facilitating microorganisms to digest organic material under aerobic conditions. The main organic products of waste are fully mineralized during composting process and results into carbon dioxide, water, heat, and humus that are stable and free of pathogens (Sharma and Garg 2018). The evidence from the literature available showed that composting proceeds through three phases, under optimal conditions. The initial mesophilic decomposition phase is performed by mesophilic bacteria, which rapidly break down the soluble and readily degradable compounds. There is a high amount of substrate at this time to ensure that the microorganisms are active in the presence of oxygen (aerobes). The high level of microbial activity generates large quantities of metabolic heat energy, which causes the temperature of the compost pile to increase. Rising temperature to over 45°C leads to less favourable environmental conditions for the mesophilic bacteria, but favours the growth of the thermophilic bacteria in the second decomposition phase (Day and Shaw 2001). Thermophilic bacteria degrade the organic matter (fats, cellulose, hemicellulose and lignin), which causes the temperature in the compost pile to rise further. Once the compost cools down in the final maturation phase, mesophilic bacteria again predominate. The dominant bacterial phyla in the composting process includes Firmicutes, Actinobacteria, Proteobacteria, Bacteroidetes, and Chloroflexi (Li et al. 2019; Aguilar-Paredes et al. 2023). In particular, Firmicutes play an important role in lignocellulose degradation; Proteobacteria are closely related to the mineralization of nitrogenous organic substrate; Bacteroidetes are involved in the degradation of a wide range of complex carbohydrates; Actinobacteria are involved in the breakdown of lignocellulose and recalcitrant cellulose; and Chloroflexi is related to the degradation of hemicellulose under thermophilic conditions of the composting process (Aguilar-Paredes et al. 2023).

However, similar to other biological processes, composting is considerably influenced by characteristics of the initial materials, environmental conditions (e.g., moisture, temperature, particle size, pH) and nutrient availability (e.g., nitrogen, phosphorus, potassium, and other trace elements), and time of maturation (Yasmin et al. 2022; Nguyen et al. 2020). Controlling these factors provides microorganisms with a favourable environment for thriving. Meanwhile, the main composition in mango by-products are fibre, protein, lipids, and lignin difficult to biodegrade (Mandha et al. 2021). Thus, it is necessary to mix mango by-products with other nutrient-dense ingredients to enhance nutrients for compost. Solid residue generated by anaerobic digester of biogas production systems from pig manure is one of the best choices. Biogas solid residue is a well-stabilized material, rich in minerals, nutrients, and microbial communities, which favour the degradation process of mango wastes. Therefore, co-composting of mango by-products and biogas solid residue can contribute to fastening the composting process and reduce the cost for supplements.

In composting, the initial carbon-to-nitrogen (C/N) ratio and the moisture content are the essential parameters contributing to the effectiveness of the process. Meanwhile, bulking agents are effective in maintaining suitable moisture and the C/N ratio. Diverse types of bulking agents are used in co-composting process to achieve high quality, time-efficient and cost-effective compost products. Nguyen et al. (2020) conducted the study of co-composting of food waste and dried leaves, at different C/N ratios (20, 25 and 30) and at different turning frequency (once a day, once per 2 days and once per 3 days) to test the growth of several vegetables (Cucumis sativus, Solanum lycopersicum, Momordica charantia, Ipomoea aquatica). The composting process lasted for 42 days. Their findings showed that the highest plant growth was achieved with compost at the C/N ratio of 30 under turning frequency of once per 2 days. Also, compost products showed better quality compared to chemical fertilizers (Nguyen et al. 2020). Effects of initial C/N ratio on quality of final compost of turkey manure and olive pomace were also determined in a recent research (El-Mrini et al. 2022). The results showed that composting of these two wastes at an initial C/N ratio of 22 combined with turning frequency of twice a week can produce a final compost of better quality. With pilot-scale composting, Soto-Paz et al. conducted a study on the effects of mixing rate of biowaste and sugarcane filter-cake (100:0, 90:10, 80:20, 70:30) at different turning frequency (every 7 days, 14 days and 21 days) (Soto-Paz et al. 2020). The results indicated that the highest quality product and reduced processing time were achieved with turning frequency of 14 days and mixing ratio of 80:20 (Soto-Paz et al. 2020). Another study on the composting of Camellia oleifera shell combined with goat manure, which was conducted by Zhang et al. (2019), showed that the highest nutrient, the longest thermophilic stage and lowest C/N were obtained with turning frequency of every 7 days and the composting process lasted for 76 days. The co-composting horticultural waste with organic wastes, including fruit peels, food waste, and soybean residues, could significantly shorten the composting time to reach the standard C/N ratio (Standard C/N: $12-24$, according to Singapore CUGE Standards) (Choy et al. 2015). Older research conducted on the co-composting of pig manure with sawdust, the results showed that at low initial C/N can reduce the amount of sawdust used, but it would require a composting period of over 63 days (Huang et al. 2004).

Although there has been a considerable number of research papers dealing with the potential of various food or agriculture waste-based composting process, but reports on co-composting of mango by-products and biogas solid

Table 1. Characteristics of mango by-products, biogas solid residue and composted substrate.

Parameter	Initial materials Mango by-products	Initial materials Biogas solid residue	Composted substrate
Moisture content (%)	73.66	86.65	40.2
Dry matter (%)	26.34	13.35	59.8
Bulk density (kg/m^3)	640	1,077	1,000
C (%)	46.58	26.76	53.52
TN (%)	0.94	3.05	3.07
TN (mg/kg)	9,356	30,500	30,700
C/N ratio	49.6/1	8.77/1	17.4/1
P_2O_5 (%)	-	7.72	0.042
P_2O_5 (mg/kg)	-	77,200	-
pH	-	8.08	-

residue are still limited. Given the research gaps stated above, this study was conducted to explore appropriate C/N ratios contributing to improve the effectiveness of composting process using combined mango by-products and biogas solid residue.

2. Material and methods

2.1 Raw materials

Mango by-products (peels and kernels) and biogas residue (solid phase) from pig manure were used as basic raw materials. The fresh mango by-products were obtained from Ba Suong single member limited liability company in Hau Giang Province. After collection, they were chopped into small pieces of about 3 – 5 cm to increase the surface area for microbial action. Biogas residue was collected from a biogas pig family farm in Hau Giang province. After collection, they were left to settle naturally for 2 days to reduce moisture before being mixed with chopped mango by-products.

Composted substrate contains a wide variety of adapted microorganisms that can speed up the breakdown of materials. Since biogas solid residue itself contains microbial communities, preparing substrates from mango by-products with biogas solid residue therefore allows for the self-selection process of composting microbial communities to occur. The substrates therefore contain microorganisms acclimated to the composting environment. In this research, composted substrate was prepared by mixing 150 kg mango waste and 150 kg solid residue (1:1 ratio). These materials were incubated within 21 days before being used for composting. The prepared substrates were added to the mixture to enhance the composting process by accelerating organic matter degradation in the initial activation phase during the composting process.

Characteristics of materials are shown in Table 1. The initial moisture content of mango by-products and biogas solid residue were 73.66% and 86.65%, respectively, which was higher than the recommended moisture content – between 40% and 60% for the composting process (Haug 2018).

The pH value of biogas solid residue was 8.08. The suitable pH is between 7.5 and 8.5 (Ren et al. 2022). This pH favours microbial growth in the composting process. Nevertheless, pH of raw materials might decrease because of the high sugar content in mango peels producing acid through fermentation. Therefore, pH needs to be controlled by adding lime to maintain a proper pH level.

In addition, the C/N ratio of mango was 49.6/1 and biogas solid residue was 8.7/1. Both values were not suitable for composting. C/N ratio can be regulated by selecting the suitable combination of compost materials and bulking agents to achieve a final ratio within the optimum range. It is recommended that the good balance of carbon and nitrogen is in the range from 20 to 40 (Xiao et al. 2017).

Table 2. Initial mass of raw materials under different C/N ratios for the composting system of mango by-products and biogas solid residue.

Bin	C/N ratio	Mango by-products (kg)	Biogas solid residue (kg)	Composted substrate (kg)	Lime (kg/kg material)
1	27.4	156	144	40	0.155
2	30.23	193	107	40	0.158
3	37.7	224	76	40	0.180

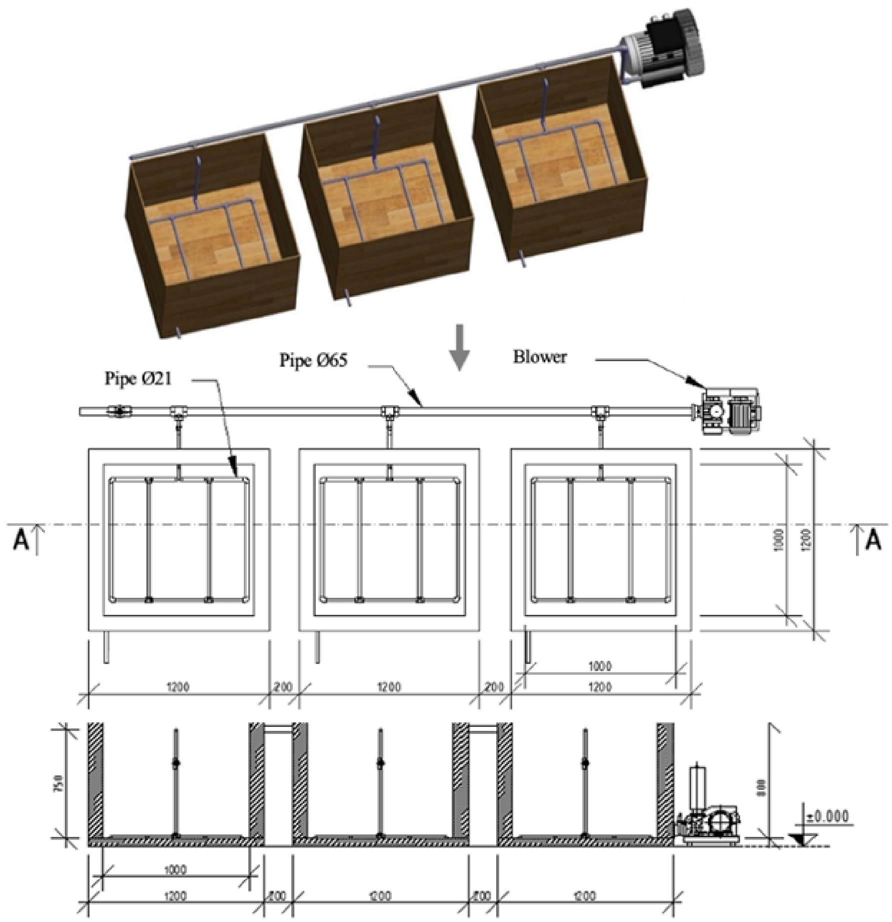

Figure 1. Schematic diagram of the composting system of mango by-products and biogas solid residue.

2.2 Experimental set-up

Three in-vessel laboratory scale composting bins of mango by-products and biogas solid residue were established at Can Tho University, Vietnam. Each composting box had a uniform measurement of 1 m × 1 m × 0.8 m for length, width and height, respectively (Fig. 1). The inside of the box was lined with a waterproof canvas to prevent water from leaking out. Ventilation inside the boxes was performed by GB-1500S air blower, capacity of 1.5 kW, 26 kPa, 220 m^3/h. The ventilation periods in the experiments was adjusted for 15 minutes every 30 minutes. The total height of the incubated layer was about 0.3 m. To reduce the compaction and improve aeration of the composting materials, turning of the compost was performed manually every seven days (i.e., on day 7, 14, 21 and 28 of the composting period).
Three trials were evaluated, including Bin 1: C/N = 27.4/1, Bin 2: C/N = 30.23/1, and Bin 3: C/N = 37.7/1.
These ratios ensured the initial C/N of compost piles was in the ideal range for composting of 20 – 40. The amount of material mixed to obtain the C/N ratios is shown in Table 2.

2.3 Sampling and analytical methods

The temperature of composting materials was measured daily. The sites for temperature measurement are illustrated in Fig. 2. Samples were taken from different parts of the composting and collected samples were analysed for the following analysis (Table 3).
Note:
+ Points 1, 2, 3, 4, 5 on the surface of the bin show 5 of locations for temperature measurement.
+ The points of 10 cm, 20 cm, 30 cm on the cross section show the depth of placing the thermometer: 10 cm - surface of the material layer; 20 cm – midpoint of material; and 30 cm - the bottom point of the material.

3. Results and discussion

3.1 Variation of temperature, settlement, pH, and moisture during composting

Changes in temperature

Temperature is the main factor affecting the activities of microorganisms in composting. It is also a good indicator of the various phases of the composting process (Sharma and Garg 2018). Changes in temperature during composting are shown in Fig. 3. Temperatures in 3 compost bins were much higher than the ambient temperature. The temperatures recorded at 3 different depths (10, 20, and 30 cm) were almost similar. This shows that composting piles were kept at a uniform temperature. The temperatures in all bins, overall, increased throughout the composting period. However, there was a difference between the 3 bins in terms of temperature (Fig. 3). The highest temperature

Table 3. Sampling and analytical methods used in the composting experiment of mango by-products and biogas solid residue.

Parameter	Sampling frequency	Method
pH	one time/ day until reaching a stable pH	pH meter (HANA HI9812-5)
Temperature	twice/ day	Thermometer
Moisture content	three times/ day	Gravimetric method (TCVN 9297:2012)
Total Phosphorus (TP)	one time/ stage	UV-VIS method (TCVN 8563:2010)
P_2O_5	one time/ stage	UV-VIS method (TCVN 8559:2010)
Total Nitrogen (TN)	one time/ stage	Kjeldahl method (TCVN 8557:2010)
$N\text{-}NH_4^+$	one time/ stage	Distillation and titration method (TCVN 5255:2009)
$N\text{-}NO_3^-$	one time/ stage	Distillation and titration method (TCVN 5255:2009)
Carbon	one time/ stage	Walkley method (TCVN 9294:2012)
Salmonella	after mineral process	ISO 6579:2017
Settlement rate	one time/ day	Using tape measure
Leachate	one time/ day	Volumetric analysis

was obtained in Bin 3, reaching to approximately 46°C on day 22nd. Bin 2 was the second highest (roughly 40°C on day 30th), followed by Bin 1 (fairly 38°C on day 28th). After that, the temperature gradually decreased to ambient condition, which showed that the composting process was completed.

The increase in temperature showed that the microbial biological activities generate heat while decomposing organic materials. Previous work showed that the optimum temperature between 32 – 60°C is beneficial for the composting process (Haggar 2005). A high temperature should be reached upto 60°C for good pathogen destruction. Temperatures of bins decreased on days of turning (day 7th, day 14th, day 21th, and day 28th). This is caused by the effects of turning. Composting piles were exposed and transferred heat with ambient air temperature. After turning, the temperature increased significantly again in the following days. Turning the composting piles could help produce high quality compost in the shortest time.

It should be noted that the decomposition process during composting could be only partially completed and would be continued after its application to the soil. Thereafter, this might influence the soil temperature. Soil temperature is an important regulator for nutrient transformation and uptake by roots of crops (Yang et al. 2019). Increased soil temperature influences soil moisture, aeration and availability of plant nutrients, which are necessary for plant growth. Some studies suggested that the application of compost increases the soil temperature. For example, in pot and field experiments on a bare Andosol in a cool climate region, the application of compost increases the soil temperature by decreasing evaporation from the soil surface (Deguchi et al. 2009). Within limits, a higher soil temperature will promote crop growth, particularly in cool climate regions. However, extremely high temperatures can destroy pathogenic organisms and weed seeds, as is done in composting process (Eash et al. 2015).

Changes in settlement

Similar to mass, pile height was also decreased throughout composting time (Fig. 4). The initial height of all bins was 30 cm. After settlement, the pile height declined to 16 cm for Bin 1, 17.6 cm for Bin 2, and 19 cm for Bin 3. During initial days, the materials had high porosity, contributing higher settlement rate than remaining days. The height of piles increased on day 7th, 14th, 21th, 28th, and 36th because of frequency of turning (once/ 7 days).

As mentioned previously, composting underwent the

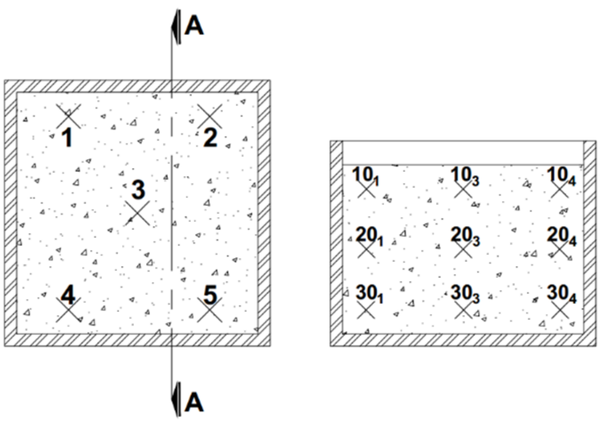

Figure 2. Locations for monitoring temperature in compost bins.

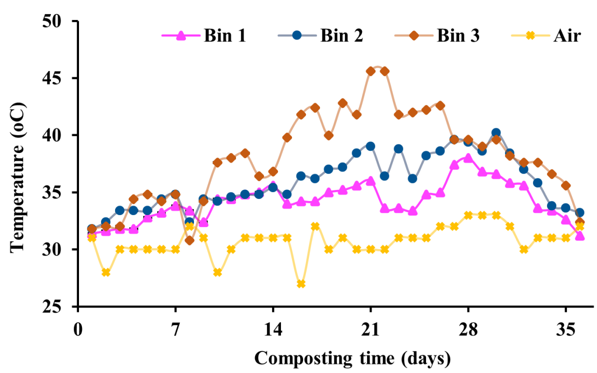

Figure 3. Temperature profiles of compost trials throughout the composting period.

Table 4. Quality parameters of products during composting stages in three bins of composting mango by-products and biogas solid residue.

Parameter	Bin 1			Bin 2			Bin 3		
	Raw material	Raw incubation	Mineralization	Raw material	Raw incubation	Mineralization	Raw material	Raw incubation	Mineralization
Moisture content (%)	81.9	48.23	42.97	79.82	46.85	40.58	77.6	42.64	36.01
Porosity (%)	-	-	47	-	-	50	-	-	48
C (%)	66.45	24.24	14.54	70.14	31.06	15.26	71.24	23.27	17.97
TN (%)	2.43	1.78	1.70	2.32	1.71	1.6	1.89	1.7	1.56
C/N ratio	27.4/1	13.6/1	8.5/1	30.23/1	18.16/1	11.23/1	37.7/1	14/1	9.8/1
TP (%)	1.93	1.64	1.75	1.87	1.06	1.5	1.28	1.29	1.46
P_2O_5 (%)	4.24	3.46	3.66	4.11	2.99	3.25	2.73	2.37	3.26
P_2O_5 (mg/kg)	42,400	34,600	36,600	41,100	29,900	32,500	27,300	23,700	32,600
pH	6.23	7.58	7.81	6.18	7.57	7.76	6.05	7.84	7.85
N-NH_4^+ (mg/100g)	-	-	83.48	-	-	133.39	-	-	82.42
N-NO_3^- (mg/100g)	-	-	1,324	-	-	1,047	-	-	954,64
Salmonella	-	-	not-detected	-	-	not-detected	-	-	not-detected

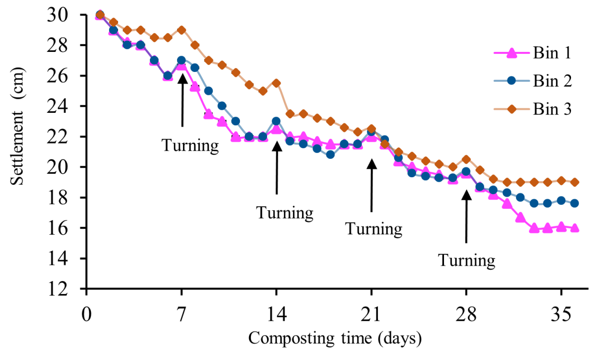

Figure 4. Changes in settlement rates during composting period.

stages of degradation of organic matter (mesophilic phase), stabilization of organic matter (thermophilic phase), and cooling (second mesophilic phase). In this process, the microbial community decomposes organic compounds into gas, leading to the decrease in material size. The settlement of raw materials decreased sharply from day 10th to day 28th. During this period, the temperature in bins increased because of the strong decomposition of microorganisms (thermophilic phase). After this stage, the settlement rate decreased slowly from day 30th to day 36th while the temperature of the compost bins also gradually decreased to nearly the ambient temperature (Fig. 3). Biodegradation was almost completed resulting in stable heights of the piles. It was recognised that settlement in compost could be divided into two stages: the physical compressive settlement and the mass loss settlement (Yue et al. 2008).

Changes in pH

The final pH of the compost mainly depends on the feedstock, the compost process, and the addition of any amendments (Sullivan and Miller 2001). Changes of pH in the compost piles are presented in Fig. 5. Generally, pH level rose gradually compared to the start date. pH values in the initial materials were 6.23, 6.18, and 6.05 in Bin 1, Bin 2, and Bin 3, respectively. At the end of composting, the pH of all treatments were in range of 7.76 – 7.85; these pH values are in range recommended for stable compost products, which is from 6.0 to 8.0 (Epstein 2017). The pH was relatively low in the initial days could be because of the organic acid formation under anaerobic conditions. After this stage, pH increased significantly because of protein breakdown and some NH_3 formation (Hubbe et al. 2010). It has been reported that pH values less than 6.0 can inhibit the transition from the mesophilic to thermophilic phase in composting (Sundberg et al. 2004).

Most mineral nutrients are readily available to plants when soil pH is near neutral. It is well-established that the compost amendment increased pH in a soil with low buffering capacity (Latifah et al. 2018), thus, the applications of composts produced from mango by-products and biogas solid residue to acid soils may be beneficial.

Changes in moisture content

The moisture content of compost is a critical criterion for optimum composting because it has a greater influence on microbial activity (Liang et al. 2003). Moisture in compost mainly comes from two sources, including moisture in the initial feedstock and metabolic water produced by microbial action. Whereas, changes in moisture during composting depend on the feedstock bulking agents and method of composting of being outdoors or indoors (Day and Shaw 2001). In this study, environmental effects such as precipitation and temperature can be eliminated because of the experiments were performed in indoor conditions. The variation of moisture content in this study is shown in Fig. 6, showing that moisture content in the 3 compost bins decreased with time. The same initial feedstocks lead to the moisture content in the three compost bins was not much different. As already noted, the initial moisture content of mango by-products and biogas solid residue were 73.66% and 86.65%, respectively. The supplement of lime solution adds some moisture to the compost piles; thus, the initial moisture content was relatively high in all mixtures (range in 80.85% – 85.89%). At the early composting days, there was a slightly decreased in moisture content, mainly due to evaporation of the feedstock. The following days (from 22nd onwards), moisture content values showed a quick drop. After a 36-day incubation period, the moisture content in Bin 1 ($\sim$ 43%) was higher than that in other bins ($\sim$ 41% for Bin 2 and $\sim$ 36% for Bin 3) as the temperature in Bin 1 was much lower than others (Fig. 3). Overall, such moisture content results in all the bins being within the optimum moisture content for the composting process. Haug recommended that composting piles could maintain a moisture content between 40% and 60%. Low moisture content (below 40%) could limit microbial activity (Haug 2018).

In addition, the amount of leachate recorded on the first 13 days in Bin 1, Bin 2, and Bin 3 were 3 L, 3.1 L, and 3.6 L. These results showed that waste decomposed to produce organic acids, leading to leachate.

3.2 Variation of carbon, nitrogen, phosphorus, and mass during composting

C/N ratio

While the starting C/N ratio is important for efficient composting, the final C/N ratio is also essential to use as an index of maturity for a compost material. Ideally, compost feedstock mixtures have an initial C/N ratio of approximately 30/1, decreasing to less than 20/1 as the composting process proceeds (Sullivan and Miller 2001). A final C/N ratio of 15/1 to 20/1 is usually the range aimed for soil amendment for growing crops (Fang et al. 1999), although a value of 10 has been suggested as ideal (Mathur 1991). Using C:/N ratio of compost is based on the C/N ratio of stable soil organic matter, which usually ranges from 10/1 to 15/1. If cured for an extended period, compost C/N will approach that of soil organic matter C/N (Sullivan and Miller 2001). A mature compost with a C/N ratio greater than 20 should be avoided since it causes the plant to be deprived of nitrogen, because microorganisms need nitrogen to oxidize excess carbon.

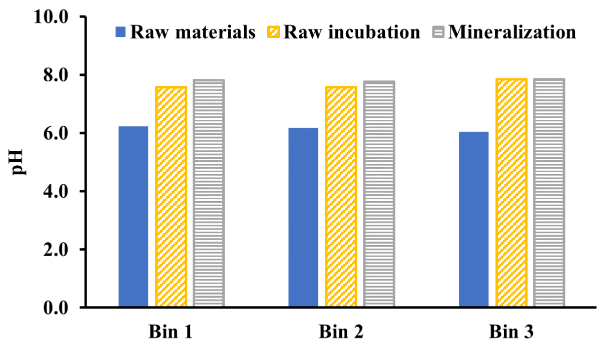

Figure 5. pH profiles of compost trials.

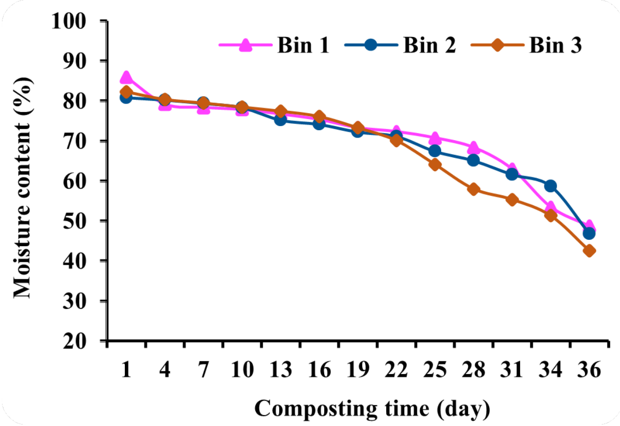

Figure 6. Moisture content profiles of compost trials throughout the composting period.

In order to meet this need, microorganisms compete with plants to consume soil nitrogen, thus immobilizing it (Amlinger et al. 2003). In this research, the three initial C/N ratios in Bin 1, Bin 2, and Bin 3 were 27.4/1, 30.23/1, and 37.7/1, respectively, declining to 8.8/1, 11.23/1, and 9.8/1 in their mature composts (Table 4). These low C/N ratios in mature compost material, upon applied to soil, can prevent competition between growing plants and microorganisms for nitrogen. Also, low C/N ratio in final products are good indicators of nitrogen availability and microbial activity after it is added to the soil, thus impacts positively on plant growth and seed germination.

Carbon loss

A decreasing trend in carbon fractions during the composting and maturation processes was observed (Table 4). It is emphasized that the percent reduction of the carbon fractions with time can measure the rate of decomposition of the raw materials. The initial carbon contents in Bin 1, Bin 2, and Bin 3 were 66.45%, 70.14%, 71.24%, respectively. After mineralisation process, these carbon values declined to 14.54%, 15.26%, and 17.97% in Bin 1, Bin 2 and Bin 3, respectively. Therefore, carbon loss was between 74 and 79% of the initial carbon. Such results were caused by the loss of CO_2 during the composting process (Getahun et al. 2012). The decrease of carbon content can be caused by biodegradation of compounds such as carbohydrates and proteins during the thermophilic phase (Soto-Paz et al. 2019). The percentages of remaining carbon in final products, essentially, help stabilize nitrogen in the compost pile (Etesami et al. 2019). During the decomposition process, only 30–40% carbon is stored in cellular components of microorganisms. C/N ratio of 30/1 in the compost materials means only 12 units of carbon for every unit of nitrogen (Bernai et al. 1998; Haug 2018).

Nitrogen loss

TN profile was monitored over the experiment (Table 4). The initial TN contents were 2.43%, 2.32%, and 1.89%, respectively; these values declined to 1.7%, 1.6%, and 1.56% in Bin 1, Bin 2 and Bin 3, respectively. During composting, nitrogen loss of Bin 1, Bin 2, and Bin 3 accounted for 30%, 31%, and 17% of the initial total nitrogen content, respectively. Thus, Bin 3 (C/N = 37.7/1) containing a larger amount of mango by-products and less amount of biogas residue showed a lower nitrogen loss (17%). Lower C/N ratios of Bin 1 and Bin 2 (27.4/1 and 30.23/1, respectively) demonstrated that the N content exceeds the balanced nutrient level required for the microbes, resulting in high N loss. According to Wong et al. Wong et al. (2017), the contributions to nitrogen loss include NH_3 volatilization under high pH; water-soluble nitrogen leached with the seepage water; and denitrification. In our work, all the bins showed a pH below 8.0 (Fig. 5) and a maximum temperature of 46°C (Fig. 3). Thus, nitrogen loss by NH_3 volatilization was an insignificant contribution. The concentrations of N-NO_3^- after mineralization process were high in all bins (> 900 mg/100g). The presence of N-NO_3^- in the composting piles at a high level showed that denitrification was not significant. Therefore, the primary cause of nitrogen loss may be water-soluble nitrogen. As analysis previously, at the end of the experiment, the C/N ratios of Bin 1, Bin 2, and Bin 3 decreased to 8.5/1, 11.23/1, and 9.8/1, respectively (Table 4). Such results demonstrated microorganisms used a large amount of organic carbon and assimilated a little amount of nitrogen in the raw material for cell growth.

Phosphorus loss

The initial TP contents in Bin 1, Bin 2, and Bin 3 were 1.93%, 1.87%, and 1.28%, respectively (Table 4). TP concentration decreased in Bin 1 and Bin 2 (1.75% for Bin 1 and 1.5% for Bin 2). However, Bin 3 showed an increase in TP concentration, from 1.28% to 1.46%. Such findings showed that different C/N ratios have a certain effect on TP concentrations in composting piles, which defines the amount of available P_2O_5 produced for compost. A previous study showed that TP variations were determined by the mineralization process of organic phosphorus, the activity of organism community, and the changes of the net of dry mass throughout the composting process (Kalamdhad and Kazmi 2009). The decline in TP content in Bin 1 and Bin 2 may stem from the consumption of bacteria. Moreover, phosphorus in materials was also transformed to Orthophosphate (P-PO_4^{3-}), which is dissolved in leachate, contributing to the decrease in TP concentration. The increase of TP in Bin 3 might be because of organic

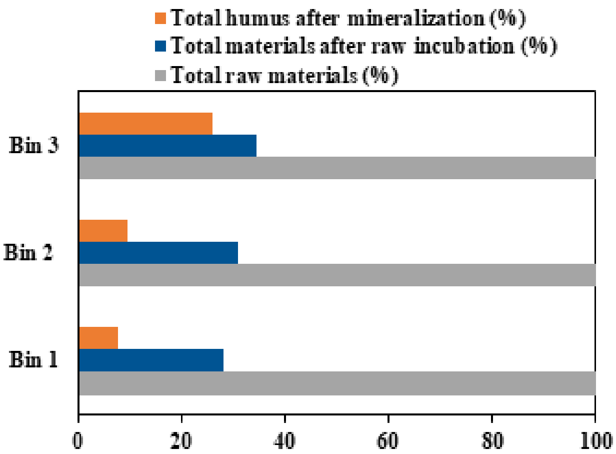

Figure 7. The percentage of products from composting of mango by-products and biogas solid residue.

phosphorus mineralization. In this process, microbial metabolism converted organic phosphorus into inorganic phosphorus. As we can see in Table 4, P_2O_5 increased to 3.26% compared to the initial P_2O_5 (2.73%).

Mass loss

Humus is the result of the decomposition of organic matter by mineralization (humification). Fig. 7 illustrates total humus concentrations of all bins after 57 days of composting (21 days of mineralization) in comparison with total material after raw incubation. From 300 kg of initial raw material in all trials, the final compost masses in Bin 1, Bin 2 and Bin 3 were 26.2 kg, 32.7 kg, and 88.1 kg, respectively. Such results showed that increasing the proportion of mango by-products supplied to compost bins would raise the proportion of final compost.

The total dry material masses in all bins decreased obviously during composting. Material masses, after raw incubation in Bin 1, Bin 2, and Bin 3 accounted for roughly 28%, 31%, and 35% of the initial raw materials. Mass reduction after complete mineralization in Bin 1, Bin 2, and Bin 3 was nearly 92%, 90% and 74%, respectively. Mass losses reported in this study were higher than (mass loss < 72%), which used food waste and dried leaves for composting with the C/N ratio of 20, 25 and 30 and turning with three frequencies: once a day, once per 2 days, and once per 3 days (Nguyen et al. 2020). Michel et al. also reported huge mass losses of up to 83% when co-composting dairy manure and sawdust (Michel et al. 2004). The primary reasons for mass losses are water loss in evaporation, and C and N loss by gas emissions (Tiquia et al. 2002).

4. Conclusion

Our research showed that mango by-products can be mixed with biogas solid residue to produce valuable compost products. Also, initial C/N ratio influenced the maturity of the final compost. The incubation period determined was 57 days of incubation, including 36 days of raw incubation and 21 days of mineralization. Among three C/N ratios surveyed, comprising C/N = 27.4/1 (Bin 1), C/N = 30.23/1 (Bin 2) and C/N = 37.7/1 (Bin 3), the highest C/N one (C/N = 37.7/1) in Bin 3 showed the best-favoured condition for mango by-products treatment and generate the highest amount of humus (obtained 88.1 kg from 300 kg of initial raw material). Compared to Bin 1 and Bin 2, Bin 3 also showed a higher percentage of remaining carbon in final products (17.97%), a lower in nitrogen loss (17%), and an increase by 0.5% in available P_2O_5 content. An initial C/N ratio of 37.7/1 could be used in the aerobic co-composting of biogas residue and mango by-products.

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Authors contribution

D.T.M.P: data analysis,writing first draft of the manuscript;L.H.V: research idea conceptualization;supervised the study;N.T.D: data collection and analysis;N.X.L: manuscript revision and editing.All authors read and approved the final manuscript.

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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