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Original Research Article

Open-Bin Composting for Enhancing the Processed Fecal Sludge Quality with Co-Composting Materials as Admixture

Lucky Caesar Direstiyani[1,2]*, Fernando Gouw[1], Mochamad Adhiraga Pratama[1]
[1] Environmental Engineering Study Program, Department of Civil Engineering, Faculty of Engineering, Universitas Indonesia, Depok, Jawa Barat, Indonesia, 16424
[2] Division of Sustainable Energy and Environmental Engineering, Graduate School of Engineering, Osaka University, Suita, Osaka 565-0871, Japan
* Corresponding Author, email: direstiyani@wb.see.eng.osaka-u.ac.jp

Abstract
Processed fecal sludge generated from a sludge treatment plant rich of organic content, micronutrients, and several heavy metals that might potentially exist. Composting process recognized as a promising and cost-effective method to improve the sludge quality. The composting process was carried out in this study by using modified Compost Bag with processed sludge from fecal sludge treatment plant as the main material and organic waste and dry leaves as co-composting materials. The macro-micronutrients and heavy metal concentration of the produced compost were further analyzed. The potential application was also considered by indulging the risk assessment. The main and co-composting materials were investigated in three different ratios of processed fecal sludge (S), organic waste (OW), and dry leaves (DL) to get the optimum composition that meet the compost quality standard. Compost R2 with the ratio of 50S: 25OW: 25DL as an optimum composition which resulted good quality compost with the C/N ratio of 10.29, Total P_2O_5 about 2.45%, Total K_2O of 0.38%, and the Cu removal up to 91.17%. The produced Compost R2 has met the compost quality standard with Hazard Quotient (HQ) for non-carcinogenic effects less than 1 revealed no potential for disease-causing effects thus safe to be used in daily life.

Keywords: Composting; fecal sludge; heavy metal; dry leaves; organic waste; risk assessment

1. Introduction

Rapid population growth in urban areas is one of important factors that contribute in declining environmental quality. Population growth resulted in a great level of clean water consumption inflicting the domestic wastewater quantity increment. Jakarta as an urban area has a population of 10,6 million in 2021 (Central Bureau of Statistics, 2022a). The total volume of domestic wastewater in urban area consisting of household, commercial and industrial activities as well as rainwater runoff estimated to reach about 14.3 km^3/year (FAO, 2021). Domestic wastewater that directly discharged into water bodies without proper treatment has the potential to cause surface water pollution or even reached groundwater areas, thereby causing deterioration of water quality and aquatic life (Djuwita et al., 2021).

Black water generates from toilets contains high levels of organics, nitrogen, and phosphorus. In Indonesia, black water is usually treated separately from the source with 86% of blackwater in urban areas being treated by using septic tanks (Central Bureau of Statistics (BPS), 2019). Blackwater that collected from residential outlets in Depok consisted of chemical oxygen demand (COD) 508.6 mg/L, total suspended solid (TSS) 184.3 mg/L, Phosphate 37.6 mg/L, total nitrogen (TN) 653.3 mg/L and Copper 0.1 mg/L (Hafiza et al., 2019). The fecal sludge quality in Indonesia based on Ministry of Public Works and Spatial Planning contains COD 6-15 g/L, ammonia 0.1-0.25 g/L, and TSS 12-24 g/L (The Ministry of Public Works and Housing, 2017). The high concentration of organic, TN, and Phosphate in black water thus essential to have proper processing before being discharged to the water bodies. Excessive nitrogen and phosphate in the aquatic environment contribute to eutrophication which has a great potential to cause unbalancing aquatic communities and declining water quality (Beusen and Bouwman, 2022).

The fecal sludge treatment plant (FSTP) aims to treat black water with the effluent quality meets quality standards and safely discharged into the environment. In line with the operation of the FSTP, the accumulation of sludge keeps increasing over time and causing new problems in the FSTP environment. The sludge is a sediment of liquid waste and microorganisms as well as chemicals that used as additional materials that originating generate from blackwater treatment. Proper and planned treatment is essential to utilize the processed sludge from FSTP, therefore it does not pollute the environment and safe to be used. The processed sludge consists of humus and readily available nutrient content that indirectly provide organic material for plants and improve soil fertility (Manga et al., 2023). The dry processed sludge at the Pulo Gebang FSTP consists of 23.19% organic material, 5.17% of P, 2.3% of N, and water content about 52.53% (Fadila, 2018). Composting is a promising way to utilize the processed sludge and could degrade the organic material into humus thus provide the nutrients that needed by plants (Manga et al., 2023). The composting process is a cost-effective method that can degrade the harmful substance and bolster the heavy metals passivation (Zheng et al., 2020). The produced compost of processed sludge could be one of the potential sustainable uses that can be applied to FSTP in Indonesia.

One of the FSTPs that has been utilized processed sludge is Pulo Gebang FSTP which is located in East Jakarta with processing capacity of 300 m^3/day and average load of 115 m^3/day (Christian et al., 2022). The fecal sludge processed by the Pulo Gebang FSTP generated from septic tanks which have been sucked up and transported from buildings in the organizational, government, education, and shopping sectors. The Pulo Gebang FSTP has been used compost that made from processed sludge for cultivating Porang plants around the FSTP area. However, the study carried out by Fadila (2018) showed that the compost from processed fecal sludge has not been identified as a good compost in accordance with SNI 19-7030-2004 with no further information about micro-macronutrients components and heavy metal concentration in the compost. In addition, the optimum composition of materials for processed fecal sludge composting process was remain unclear. Therefore, this research is essential to be carried out for defining the optimum composition and compost quality, as well as ensuring safety use of the compost.

This study was specifically aimed to analysis the content of micro-macronutrients and heavy metals of compost from processed fecal sludge from Pulo Gebang FSTP. This study was also targeted to obtain the optimum composition of the processed fecal sludge and supporting materials for further recommendation of composting process at the Pulo Gebang FSTP. The selection of co-composting materials will be assessed by considering some important factors that related to composting performance and availability. The macro-micronutrients compositions and heavy metal concentration (Pb, Cd, and Cu) in the produced compost will be further analysis then supported with the risk assessment analysis for ensuring that the produced compost is safe to be used in daily life.

2. Materials and Methods

2.1. Research Configuration and Operation

This research was used processed fecal sludge from Pulo Gebang FSTP as a main compost material in the form of dry sludge originating from the sludge drying bed unit. The collection of processed sludge according to the grab sampling method with sampling procedures based on Indonesia National Standardization of SNI 8520-2018 (Indonesia National Standardization Agency, 2018). The selection of composting method and supporting materials were carried out based on pre-analysis results by using pairwise comparison charts and decision matrices. The pre-analysis was considered various important aspects including the composting process, composting efficiency, land requirements, availability, materials, and costs.

Based on the pre-analysis results, the compost supporting materials that chosen for this research were organic waste (OW) and dry leaves (DL). OW and DL were easy to get in the Pulo Gebang FSTP area so do not required a large cost. The organic waste as food waste that taken from the Widatama integrated waste disposal site and dry leaves were taken from the garden near the author's living environment in Natura Residences, Tangerang. The used of organic waste as a supporting material for composting is the best choice due to high C/N that close to the optimum value (20-40) (Fan et al., 2018). The dry leaves (DL) were chopped to a size of around 2.5-5 cm prior use to increase the surface area and accelerate the composting process. The dry leaves were added as co-composting materials that worked as bulking agent with high carbon content which can easily absorb moisture content during composting process. The addition of OW and DL as co-composting materials contributed in decreasing moisture content and increasing the C/N ratio which support effective process of sludge composting (Bai et al., 2020; Kulikowska et al., 2021)

Meanwhile, the composting method that used was open-bin composting. The open bin method did not require a large area of land and complex equipment as well as easy to carry out (Mahapatra et al., 2022). In this study, three compost bags with a total volume of 200L were used (diameter 54 cm, height 100 cm) (Figure 1a). In order to assist the aeration process during composting, each compost bag was equipped with four PVC pipes ½ inch that have been perforated vertically thus the air flow adequate to enter the compost bag evenly. Aeration is prominent in affecting the efficiency of composting process (Lai et al., 2024). In this research, three variations of reactors were used based on the different ratios of processed sludge (S) and compost supporting materials (OW and DL) in each reactor (Figure 1c).

The proportion was defined to maximize the use of processed sludge (S) about 50% for all variations and adjusting the optimum proportion of OW and DL about 15%, 25%, and 35% as co-composting materials to promote the composting process. The proportion of compost materials measured based on volume by using the measuring beaker of 5 L for simplifying the practical application owing to have different mass density. The compost materials variations as S: OW: DL of R1 (50%:35%:15%), R2 (50%25%:25%), and R3 (50%:15%:35%) (Figure 1c).

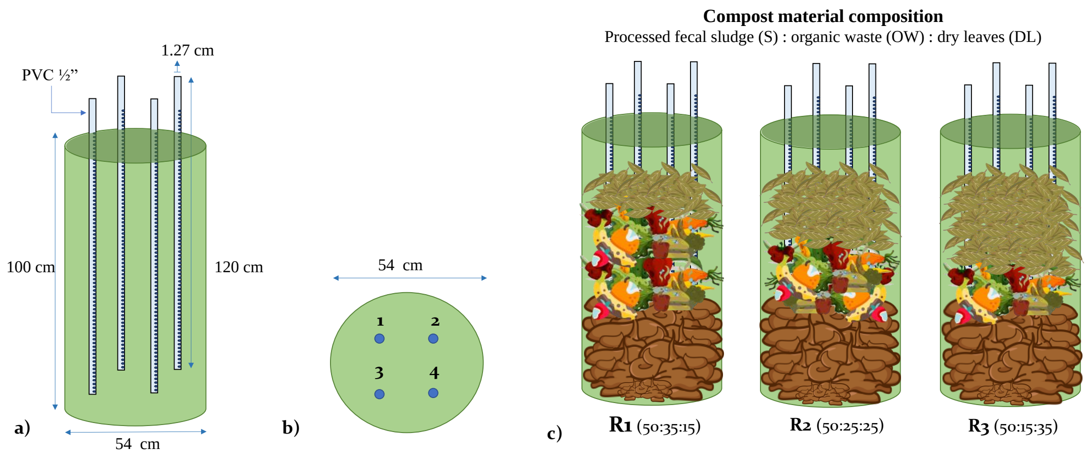

Figure 1. Composter design (a), The position of perforated pipe for promoting aeration process from top view of reactor (b), Reactor variations based on compost material compositions (c)

A bioactivator was added during the composting process by using EM4 solution that commercially available on the market. The procedure of using EM4 was following the manufactures guidelines. Previously, the EM4 bioactivator solution was activated by adding glucose and clean water with the ratio of 1:1:50. The glucose was used as food for microorganisms that consisted in EM4. The clean water of 1000 mL with the addition of 20 mL for each EM4 and glucose. The mixture was homogenized and left for 24 hours for promoting the microbial activation of EM4 . The activated of EM4 mixture then subsequently added to each reactor with a volume of 1L for improving the composting process.

2.2. Analytical Methods

The microorganism activity promoted by certain parameters, including the C/N ratio, moisture content, temperature, and pH thus prominent to be monitored (LinChitsan et al., 2016). In this study, pH, temperature, and moisture tests were carried out every 2 days. The monitoring of the physical characteristics of the compost in the form of color and odor were also investigated for every 2 days based on the munsell soil color chart and the odor index scale. Odor measurement was carried out on a scale of 0 – 10 (0 = odorless and 10 = strong odor). Color measurement was carried out using the munsell soil color chart according to hue (the dominant color of the spectrum according to the wavelength) with a value of 7.5YR (Turk & Young, 2020).

The turning over of compost pile was carried out every day to provide sufficient oxygen supply and maintain the aeration condition for promoting the biodegradation rate (Waqas et al., 2018). The initial characterization of compost raw materials, supporting materials, and produced compost were analyzed at the Testing Laboratory of the Department of Agronomy and Horticulture, Bogor Agricultural Institute show in Table 1.

2.3. Risk Assessment

The risk assessment was carried out to determine the heavy metal potential contamination to soil, plants, and humans based on the contaminant pathway that will pass through the compost. In risk assessment calculations, the bioaccumulation factor was used to determine the ability of plants to absorb and transfer heavy metals from the soil. The bioaccumulation factor for Cu is 0.1 – 0.47 kg/kg (Oladejo et al., 2017)0. The concentration of pollution in plants originating from atmospheric deposition and root uptake can be calculated according to the Eq. 1 (Fjeld et al., 2007) (Supplementary Materials)0. The process of heavy metals entering the human body can be done through dermal, ingestion, and inhalation. Heavy metals that enter body tissues will accumulate and cannot be excreted. The metal toxicity can cause tissue damage, cancer, and abnormal cell growth during pregnancy which causes serious damage to the embryo (Jaishankar et al., 2014). The intake calculation was for quantifying pollutants amount that enter the human body related to the quantity of contaminants or exposure that received by the individual. Apart from exposure rate, the amount of contaminant exposure to humans that received in a certain period was calculated as dose. The average daily dose (ADD) was carried out to determine the dose level that obtained by human body during its life period on a constant basis (Fjeld et al., 2007).

Toxicity was expressed in reference of dose and cancer slope factor (Rahman, 2007)0. The dose was divided as RfD (oral exposure) and RfC (inhalation exposure) that estimate the daily dose that is not expected to cause adverse health effects despite lifetime exposure. The risk characteristics was investigated by using Hazard Quotient (HQ) for non-carcinogenic effects (Eq. 5) and Excess Cancer Risk (ECR) for carcinogenic effects (Eq. 6). The HQ > 1 meaning that the pollutant concentration has the potential to cause detrimental effects on health, and HQ ≤ 1 meaning the pollutant concentration has no potential to cause effects on health. Risk characterization for ECR is in the range 10^{-4} – 10^{-6}. The ECR is declared safe if ECR < 10^{-4} due to cancer cases found in 10,000 human populations (Tualeka et al., 2020). The risk characterization is divided into low priority (HQ < 1 and ECR < 10^{-6}), medium priority (HQ with range 1 – 10 and ECR with range of 10^{-6} – 10^{-4}), and high priority (HQ>10 and ECR > 10-4) (Fjeld et al., 2007).

3. Results and Discussion

3.1. Characterization of Processed Sludge and Co-Composting Materials

The characterization of raw materials and supporting materials is very prominent in affecting the final quality of the produced compost. The results will be compared with the compost quality standards based on (Indonesia National Standardization Agency, 2004) as a reference to define the potential of raw materials before starting the composting process (Table 1). The C-Organic levels in the processed sludge exceed the quality standard thus increase the C/N ratio which allows composting to proceed more slowly.

Microorganisms used carbon as an energy source and released CO_2 in the reactor (Meng et al., 2021). High carbon levels enact microorganisms require longer time to decompose organic material, thus the composting process run much slower. Therefore, the peak temperature in the compost will also take longer time to reach due to carbon decomposition affects the heat release. Meanwhile, potassium was involved in the biophysical and biochemical aspects of plants. In addition, potassium also plays a prominent role in strengthening cell walls and plant resistance from disease. Therefore, potassium levels that did not meet the quality standards will give a negative impact and affect the plants performance of growth and development (Xu et al., 2020).

Table 1. Characterization of raw and supporting materials prior composting

No.	Parameter	Unit	Standard (SNI 19-7030-2004)	Processed Fecal Sludge (S)	Organic Waste (OW)	Dry Leaves (DL)
1	Water content	%	<50	31.85	80.94*	24.82
2	C-Organik	%	9.8 - 32	37.65*	n.m	n.m
3	Total- N	%	>0.4	3.7	n.m	n.m
4	C/N	%	10 - 20	10.18	n.m	n.m
5	Total P_2O_5	%	>0.1	2.24	n.m	n.m
6	Total K_2O	%	>0,2	0,12	n.m	n.m
7	Total Fe	%	<2%	1.75	n.m	n.m
8	Mn	%	<0.1%	0.04	n.m	n.m
9	Cu	mg/L	<100	380.72*	35.72	13.82
10	Pb	mg/L	<150	66.57	13.79	25.51
11	Cd	mg/L	<3	1.93	0.03	0.18

*) exceed the standard; n.m) not measured

The lead (Pb) and cadmium (Cd) concentration of processed fecal sludge below the quality standard, while copper (Cu) concentration exceed the quality standard (Table 1). Further analysis of heavy metals component in produced compost focused on Cu concentration. The contaminants can enter the human body via the food chain process. Heavy metals can be received in air and water. Contaminated air and water can have a direct impact on humans through the respiratory and digestive systems. Plants obtain heavy metals by absorption through stomata or roots, while animals receive heavy metals by eating plants containing heavy metals or drinking contaminated water. When humans consume plants or animal products that contain heavy metals contaminants make heavy metals remain in their feces as a result of the excretion process (Fjeld et al., 2007). The Cu, Pb, and Cd contained in the processed sludge of Pulo Gebang FSTP was a clear evidence of heavy metal displacement. Heavy metals that accumulate in the body will cause serious health problems. Heavy metals are also able to absorb bacterial and mineral particles on cell surfaces and precipitate together with several inorganic salts as the main route for the presence of metals in sludge (Yang et al., 2020).

The Cu can be found naturally through scraping or erosion of mineral rocks and dust containing Cu particulates in the air. Meanwhile, in water bodies, Cu is found in the form of ionic compounds such as $CuCO_3$ and CuOH. Cu can enter the air due to human activities such as air emissions, the metal plating industry, mining, and shipyards. Cu is needed by humans for metabolic activities and hemoglobin formation. The newly assigned acceptable daily intake for copper of 0.07 mg/kg body weight was took into consideration as conservative and sufficiently protective for all age groups (EFSA, 2023). However, if the amount of Cu consumed exceeds the limit, it will become toxic and caused regurgitate, diarrhea, and Wilson disease (Roychoudhury et al., 2016). In addition, acute poisoning due to Cu accumulation contamination causes symptoms such as stomach pain, vomiting, nausea, netrophysis, seizures, and can result in death. Meanwhile, for chronic poisoning, Cu causes hemolysis due to the accumulation of H_2O_2 in red blood cells that resulting in cell layers oxidation and causes the cells to burst with the subsequent effects of anemia (Kardos et al., 2018). Based on the compost supporting materials (OW and DL) characterization, the heavy metal concentration of Cu, Pb, and Cd meet the quality standards. However, the water content of organic waste exceeded quality standards. The high water content in organic waste reduces the oxygen supply in the compost and causes a foul smell when the compost is mixed. The addition of dry material and turning the compost pile become a solution to reduce the water content during composting process (Bilsens, 2018).

3.2. Monitoring of temperature, pH, and moisture during composting process

3.2.1. The changing of Temperature and Ph during Composting Process

Composting is a highly dynamic process that will take place in 3 phases, namely the mesophilic, thermophilic and maturation (Storey et al., 2015). The pH, temperature, and moisture are monitored and controlled periodically during the composting period, thus the composting process can take place quickly and produce high quality compost. The changing of temperature was directly related to microbial activity thus temperature measurements were carried out to assess the maturity of the compost. The ideal temperature during composting process ranges from 55° – 65°C (with a range of 45° – 80°C) (Debertoldi et al., 1983). The temperature increment in each reactor caused by the growth of micoorganisms. One of the bacteria that plays a significant role in the beginning of composting process namely mesophilic bacteria. High substrates that are reactive and easily degraded such as monosaccharides, starch and lipids will be breakdown by microorganisms.

At the start of composting process, R1 obtained a higher temperature compared to R2 and R3 (Figure 2a). The average temperature in R1 reached 35°C, while for R2 and III reached about 32°C. The initial phase of composting was called the mesophilic phase where microorganisms will develop by consuming organic nitrogen and organic carbon (Meng et al., 2021). Microorganisms were consumed carbon for decomposing organic material and reducing the carbon content in the pile. The small amount of nitrogen in R1 made the C/N levels in R1 still high, thereby slowing down the decomposition process and experiencing the least increasing of temperature. R3 consisted of the highest percentage of nitrogen material, resulting in low C/N levels. Consequently, the decomposition process occurred quickly at first but will slow down afterwards due to the lack of carbon as an energy source for microorganisms.

After all reactors reached a temperature of 40°C, the changing of temperature tended to stagnate until day 16 with the temperature increment in all reactors only 1-2°C. No temperature rise happened due to high moisture and lack of aeration, therefore more thorough and frequent turning of the compost was essential (Manga et al., 2023). After turning the compost over, the temperature of the compost in all reactors gradually increased, especially in R2 and R3 reached the temperature of 45°C while R1 only reached 41°C on day 24. The little temperature increment in R1 was caused by the low nitrogen content about 15% of organic waste as N source. Promoting temperature increment in R1 can be done by adding materials with high nitrogen content (SHDHEC, 2018). Nitrogen is needed by mesophilic bacteria as nutrition for microbial growth. The decomposition of organic materials will release heat thus increase the temperature of R1.

R1 showed another abnormality as decreasing of temperature until reached 39°C (day 26). This occurred due to the lack of re-compaction of the compost material after turning it over. The non-density of the compost material made the expansion of the material surface area, thus the aeration process takes place excessively and material experienced heat loss easily owing to the lack of heat insulation in the pile. After being crushed and sealed, R1 was immediately experienced a fairly high increasing temperature about 45°C (day 28). When the temperature reached 45°C, the compost entered the thermophilic phase. Thermophilic bacteria continuously decomposing organic matter until reaching the peak temperature (Biyada et al., 2021). On the same day, the temperature of R2 and R3 reached a peak of 50°C (day 28).

During the thermophilic stage, the microbial activity of heat-intolerant organisms (including pathogens) gradually decreasing and ripening off the compost mass.

Thermophilic bacteria will continue to decompose simple compounds with high energy until reaching the highest temperature in the reactor. High temperature is important for the hygiene process in order to kill pathogenic bacteria, weed seeds, as well as stimulate the composting process (Manga et al., 2023). When the decomposition process has reached peak temperature, most of the organic materials have been decomposed into humus due to running out of substrate and carbon sources for microorganisms consumption that indicated by rotten odor reduction and temperature decrement (Biyada et al., 2021). At this stage, the pathogens destruction was also occurred which is influenced by numerous factors, including temperature exposure, duration, nutrient competition, microbial antagonism (antibiotic production and parasitism), and production of organic acids and ammonia. Temperature exposure is the prominent factor in pathogen inactivation (Sunar et al., 2009).

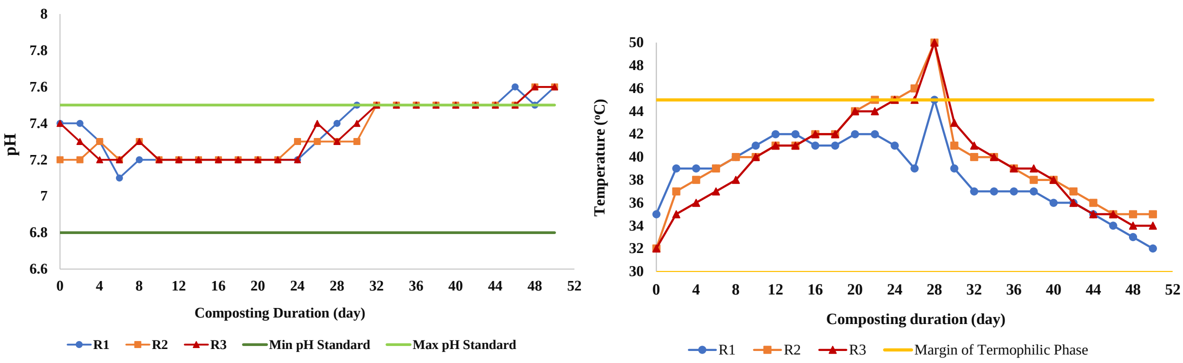

Figure 2. The changing of temperature (a) and pH (b) of R1, R2, and R3 during composting process

After the peak temperature was reached, the temperature of all reactors was decreased drastically on the day 30. The R1, R2, and R2 reached temperature of 39°C, 41°C, and 43°C, respectively. The decreasing temperature in all reactors indicates the composting process has started the maturation phase. In the maturation phase, the activity of thermophilic microorganisms was stopped due to run out of substrate and carbon thus temperature started to decrease. The role of thermophilic bacteria will gradually decrease, and mesophilic bacteria will start again by breaking down the remaining cellulose. In this phase, the composting process will still occur in a very slow rate, thus the humus content in the pile will continue to increase slowly. Apart from that, the levels of toxins, oxygen, and nitrogen were also slowly decrease. The temperature continued to gradually decrease until the temperature observations were stopped on day 50. The compost maturity was characterized by obtaining stable temperature and changing of structure and color that resembles soil (Mahapatra et al., 2022). The mature compost of Compost R1, Compost R2, and Compost R3 reached the final temperature of 32°C, 35°C, and 34°C, respectively.

The degree of acidity is another important environmental factor that affect the growth of microorganisms and promote the composting process. In the early phase of composting, R2 showed a lower pH (7.2) compared to R1 and R3 (7.3). The R2 was tended to be more stable owing to no significant change in pH in the first 8 days (pH only changed around 0.1). The change of pH become more acidic is related to the high concentration of lactic acid bacteria that consisted in the organic waste and decomposing materials especially during the initial stage of composting process (Sundberg et al., 2011). The gradual increase of pH in all reactors was caused by the decomposition of organic materials which converted organic acids into methane and CO_2. The protein and organic nitrogen decomposition also caused the increasing of pH which results in the release of OH- and ammonium ions (Zhang et al., 2022). After the compost was reached the highest temperature, pH variations during the composting process will tend to be more stable. This was indicated by the pH of all reactors since day 32 which did not experienced changes.

All reactors were showed the same increasing pH trend, although the pH fluctuations within the normal range. The pH changes indicated the activity of microorganisms in degrading organic materials. The pH level at the beginning of the composting period tended to decrease due to the formation of simple organic acids. Microbial population uses the first-produced acids from the composting process as a substrate (Davendra et al., 2023). In the maturation phase, the *Nitrosomonas* and *Nitrobacter* bacteria will grow optimally thus the nitrification process can take place and convert ammonium into nitrate and nitrate into nitrite. These changes ensure that the pH conditions in the reactor remain at optimum conditions about 6.8 – 7.49. In addition, high pH also supports metal precipitation and reduces the mobility of heavy metals (Zheng et al., 2020).

3.2.2. Moisture Changes During the Composting Process

Moisture during composting process is essential to be maintained in order to help the growth and microrganisms activity. If the moisture is less than the ideal moisture, the composting process will be hampered due to lack of air to dissolve the organic material which will be degraded by microorganisms. High moisture content will make low oxygen supply due to high porosity in the compost thus oxygen hard to diffuse (Lai et al., 2024). Maintaining moisture content to reach ideal condition is done by turning the compost regularly (SHDHEC, 2018). High moisture content will affect the decomposition rate of organic materials due to the free air space in the compost was covered by water, thus the porosity becomes high disturb the aeration process owing to oxygen cannot diffuse in it. This will make the reactor become anaerobic and make the duration of composting become longer. Moreover, an unpleasant odor will appear and prevent the increasing temperature of compost (Sundberg et al., 2013). R1 had a lower moisture level about 79% compared to R2 and R3 about 98%, and 100%, respectively (Figure 1. Supplementary Materials). This was owing to R1 has higher level of dry leaves around 35% of the total compost thus has greater the absorption of water content (Bilsens, 2018). The moisture level continued to decrease within the high limit more than 70% until day 24. In the end, the moisture level can be maintained within the optimum range of 50% thus the composting process can continue smoothly.

The high level of moisture means that the temperature in the reactor does not increase significantly due to low oxygen supply. The low oxygen supply is caused by cavities in the Compost being covered with water, thus microorganisms did not get enough energy to degrade organic material. This was proven by the temperature in the reactor on the day 28 which gradually rose towards the thermophilic stage while the moisture content gradually decreased. The proper turning over of the compost pile was also carried out in the middle of the composting process in order to help reducing the moisture content in all reactors. Therefore, the temperature increment was allowed thermophilic bacteria to grow. Until the end of the composting process, the moisture content continues to be controlled by turning the compost depending the water content thus the moisture always within the optimum range and made composting process run smoothly (Getahun et al., 2012).

3.2.3. Color and Odor Observation During Composting Process

The mature compost resembles structure, color, and the odor of soil with stable final temperature. The changing of color, odor and texture during the composting process indicate the decomposition activity by microorganisms. Organic materials were broken down into elements that can be absorbed by microorganisms, thus the size of the materials became smaller and shrinks. On the early phase of the composting process, the stench that arises was very pungent and insects were easily attracted. The condition of the compost which was still damp made the continuous emergence of strong odor. This was owing to the decomposition process of organic material was still on-process carried out by microorganisms. The condition of the compost began to show changes in the 3rd week where the compost supporting materials began to decompose (Figure 2. Supplementary Materials). This was also supported by temperature increment followed with moisture decrement. At this stage, the decomposition process will change and break down detritus (dead plants, animals, and microbes) physically and chemically. There will be the decrement of material mass due to the conversion of the detrital into a material similar to soil, namely humus. Microorganisms were also used organic materials, oxygen, and water in this process.

All reactors were reached the highest temperature on the 4th week (day 28). This was supported by the size reduction of compost supporting material accompanied by the odor reduction (Cholis and Mursita, 2022). Moreover, insects were also rarely seen. The color of the compost was begun to resemble soil and became odorless in the 5th week. The color of the compost was changed to blackish brown as well as the smells also resembled soil, thus in terms of physical characteristics, the compost was declared as mature (Rafeah et al., 2018). The appearance of an earthy smell was caused by the dehumidification process and the change of organic material into more stable material.

3.3. Quality Analysis of Produced Compost

The produced compost was further analyzed for the content of macro-micro nutrients and heavy metals in order to determine the compost quality. The C-organic content of Compost R1 reached 36.49%, Compost R2 reached 36.75%, and Compost R3 reached 37.65% (Table 2). The C-organic content of Compost R1 and Compost R2 tend to decrease when compared with the initial raw materials. Carbon content was decreased during composting process due to its use by microorganisms for metabolic systems that cause mineralization as CO2 (Azim et al., 2018). The changing concentration of carbon and nitrogen levels reflected the decomposition during the composting process. C/N levels were closely related to carbon and nitrogen mineralization. This revealed that the materials used in compost will indirectly affect the C/N value. In general, the C/N ratio was decreased due to the use of carbon as an energy source in decomposing organic material into compost and nitrogen as the formation of protein cells to encourage the growth of microorganisms. During the composting process, CO2 was released owing to organic material decomposition and contribute to carbon level reduction in the compost (Meng et al., 2021). Furthermore, nitrogen transformation has close association with nitrogen emission (Zhang et al., 2022). In the middle of composting process, the organic material decomposition was released ammonium thus N levels will increase. The ammonia volatilization was undergoing through ammonification which was a primary way to remove nitrogen (Yang et al., 2019).

Table 2. Quality of produced compost

No.	Parameter	Standard [a]	Unit	Initial Content	R1 (Compost R1)	R2 (Compost R2)	R3 (Compost R3)
1	Water content	<50	%	31.85	36.29	38.09	48.6
2	C-Organik	9.8 - 32	%	37.65*	36.49*	36.75*	37.75*
3	Total- N	>0.4	%	3.7	3.34	3.57	3.58
4	C/N	10 - 20		10.18	10.93	10.29	10.54
5	Total P_2O_5	>0.1	%	2.24	2.46	2.45	2.49
6	Total K_2O	>0.2	%	0.12**	0.32	0.38	0.61
7	Total Fe	<2%	%	1.75	1.59	1.97	1.56
8	Mn	<0.1%	%	0.04	0.02	0.03	0.02
9	Cu	<100	mg/L	380.72*	358.84*	33.6	329.01*

[a]) Standard according to Indonesia National Standardization of SNI 19-7030-2004; *) Exceed the standard; **) Below the standard

However, the released ammonium will immediately experience a nitrification process to be converted into nitrite by *Nitrosomonas* and nitrate by *Nitrobacter* then through the denitrification will be converted to N2 and released into air thus decrease the N levels (Cáceres et al., 2018). Evaporation as

NH_3, nitrogen oxide (NO_x), nitrous oxide (N_2O), or dinitrogen (N_2), which mostly occurs during the thermophilic phase, accounts for approximately 40–70% of the initial N content contributed in N levels decrement during the composting process (Nigussie et al., 2016). The results of this study showed the C/N level was increased from the initial test. The C/N ratio of Compost R1 of 10.93, Compost R2 of 10.29, and Compost R3 of 10.54. This can be caused by the organic materials (organic waste and dry leaves) addition to the processed sludge promote the composting process to produce compost with good and stable content. Based on the C/N ratio in the three composts still categorized as good compost owing to the C/N ratio in in the range of regulated in (Indonesia National Standardization Agency, 2004). The C/N ratio provides an overview of compost stability with the value of 12 is frequently considered as a sign of a fully mature compost, whereas a final C/N ratio less than 20 indicates compost with adequate maturation (Mahapatra et al., 2022).

The composting process has been proven in increasing P and K levels in all produced compost. The K levels have a higher increment concentration compared to P. This was due to P elements were used more by microorganisms in the composting process. The use of the P element by microorganisms allows the microorganisms to grow and well-develop thus the process of stabilizing other elements in the compost can run well (Tian et al., 2021). In this study, the micronutrients were analyzed as Fe and Mn levels. The micro element is needed by plants in small concentrations and will have bad effects on plants if the content above the recommended concentration. The Fe and Mn levels of produced compost revealed below quality standards, thus the compost declared as safe to use. The quality standard for the Fe content of compost was below 2%, about 1.59%, 1.97% and 1.56% for Compost R1, Compost R2, and Compost R3, respectively. The Fe content of Compost R2 was increased about 1.75% compared to the initial content of processed sludge. The increasing of Fe content possibly caused by mass loss in the composting process which follows the decomposition of organic material, the release of carbon dioxide and water, and the mineralization process (Biyada et al., 2019). In addition, the increased level of Fe was also occurred due to the Fe content accumulation in supporting materials. The composting process of this study was succeeded in reducing the Mn content from 0.4%, to 0.02% for Compost R1 and R3, and 0.03% for Compost R2. These three values were also far below standard with a threshold of 0.1%. This proves that the composting process can reduce Mn levels that caused by the leaching process (Vandecasteele et al., 2013). The leaching process was occurred as a physical process of transferring small mineral ions from organic compounds that were easily soluble in water through the media.

Furthermore, the Cu content showed significant differences before and after composting. In this study, all compost experienced Cu degradation. Compost R2 experienced the highest reduction of Cu about 33.6 mg/L, followed by Compost R3 and R1 about 329.01 mg/L and 358.84 mg/L, respectively. This revealed that the composting process worked well even though only Compost R2 met the quality standard. The passivation method through transferring heavy metals from biological to the stable phase was contributed in the environmental risk reduction of heavy metals effect (Zheng et al., 2020). The organic amendments are often employed to immobilize heavy metals since humic acid changes the highly bioavailable form of heavy metals to the much less bioavailable portions associated with organic matter, metal oxides, or carbonates (Bekele et al., 2023). The nature of the metal distribution was affected the metal mobility in the compost and influenced the final quality of the produced compost. The reduced levels of heavy metals were also caused by the leaching process that occurred during composting. In addition, the decrement of metal content during the aerobic composting process as the consequence of mass loss and heavy metals complexation increment which become strongly bound to the compost matrix and turn to limit the solubility of metals (Smith, 2009). The results of this research showed that composting process revealed positive influence in improving the quality of processed sludge from Pulo Gebang FSTP.

3.4. Risk Assessment of Produced Compost Implementation

Bioaccumulation of heavy metals were occurred due to the exposure of contaminated media that entry into the organism's body. In this research, the sources of heavy metals were divided into processed sludge from the Pulo Gebang FSTP, organic waste, and dry leaves. The metals in processed sludge were obtained from human consumption of plants or animal products that contain heavy metals contaminants which are excreted in feces. Meanwhile, metals in organic waste were might came from the unseparated collection of organic and metal waste in household level. Metals in dry leaves were from accumulation in stomata and absorption of metals through the roots which transported throughout the plant. These three materials were mixed and processed as compost which subsequently used as growing media of plants. Heavy metals in these three materials will accumulate in the soil and possibly be absorbed by plant roots. The plants that contain heavy metals then finally picked and consumed by humans and have a significant effect on their health.

The risk assessment is a systematic analysis to assess and manage the risks of contaminants released into the environment. One of the risk assessments is formulating a conceptual model for each pathway of contaminant exposure to the environment. The results then further evaluated to determine the possibility in creating detrimental factors to the environment and living creatures (Jensen and Aven, 2018). One route of heavy metals exposure in plants was the uptake process through the soil. In this case, the compost that used can potentially transport heavy metals into the plant thus achieved heavy metals through root absorption. The possible contaminant pathway of heavy metals from the implementation of produced compost in this study could be seen in Figure 3. The risk assessment was essential to determine the potential amount of pollutants obtained by humans (Fjeld et al., 2007). The risk calculation was carried out for heavy metals exposure that obtained by humans during their lifetime if they consume vegetables and fruits which indicated to contain heavy metals. The detailed of some assumptions that were used in this study can be seen in Supplementary Materials.

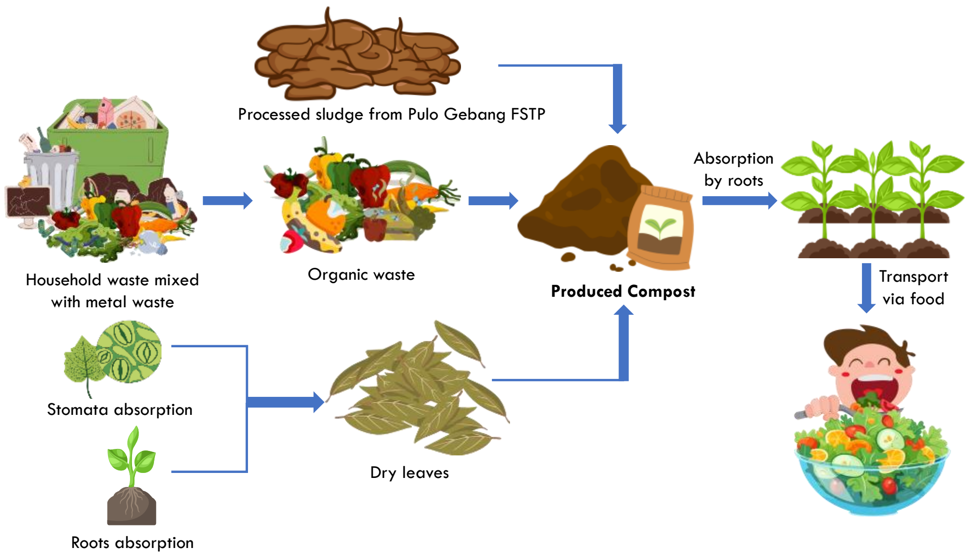

Figure 3. The contaminant pathway in humans derived from produced compost implementation

The average daily dose (ADD) of Cu that received by men (throughout their lives) was obtained in the case of direct implementation of processed sludge from FSTP to the plant without composting process with bioaccumulation factor of Cu about 0.1 kg/kg. The lowest range of ADD about 0.0294 mg Cu /kgfruit.vegetables.day and 0.986 mg Cu/kgfruit.vegetables.day for male and female, respectively. The calculation was carried out by using the formula for heavy metals absorption through roots. The absorption of heavy metals through the stomata in plants was ignored in this calculation due to the compost implement as a growing media of plants, thus the heavy metals transport was carried out through plant roots. The intake rate calculation was carried out twice to calculate the average consumption of vegetables and fruit for children (0 – 12 years) and adults.

Subsequent obtaining the intake rate, the calculation was continued by looking for the contaminant dose which states the amount of contaminants that received by humans in a certain period. In this study, it was assumed to occur throughout life. The contaminant dose calculations were carried out several times, adjusting for different intake rates, exposure times and body weights within a certain age range. Risk assessment was carried out on produced compost. The produced compost will be applied as growing media for various plants thus potentially enter the human body through the food chain process.

Analysis of dose response was subsequently carried out to determine the level of risk according to the contaminants received by humans when consuming vegetables or fruit grown in compost media. The HQ calculation was carried out by dividing the average daily dose of Cu contaminants by the reference dose (RfD), which was the value of heavy metal exposure that enters orally. Based on the calculations, it was revealed that Cu contaminants in the Compost R2 product could not cause disease-causing effects with the HQ<1 for both low and high range (Table 3).

Table 3. Cu contaminants doses entering the human body after produced compost implementation

Compost	Cu Content (mg/L)	ADD Male (mg/kg.day)		ADD Female (mg/kg.day)		HQ Male		HQ Female	
		Low Range	High Range	Low Range	High Range	Low Range	High Range	Low Range	High Range
Compost R1	358.84	0.0277	0.3277	0.0930	1.2143	0.1963	2.3240	0.6593	8.6119
Compost R2	33.6	0.0026	0.0307	0.0087	0.1137	0.0184	0.2176	0.0617	0.8064
Compost R3	329.01	0.0254	0.3004	0.0852	1.1133	0.1800	2.1308	0.6045	7.8960

It can be concluded by referring the Compost R2 had HQ results < 1 for low and high range, this classified as low priority. The Cu content of Compost R2 does not have the potential to cause carcinogenic diseases in humans, thus the Excess Cancer Risk (ECR) calculations were not carried out. At low consumption levels, the Cu content was considered to have no health effects. The produced Compost R2 had macro-micronutrients and heavy metals content that have been met the compost quality standard thus recommended to be used in daily life. In addition, the materials composition of Compost R2 was also proposed to be implemented in Pulo Gebang FSTP as an optimum condition of composting process. Further research is essential for constructing practical guidance for large scale composting and for setting up strategy in increasing the economy value of produced compost from processed fecal sludge.

4. Conclusions

All reactors were succeeded in increasing the levels of macronutrient, reducing the micro nutrients content, and degrading the levels of heavy metals. Reactor 2 with the best material composition of 50:25:25 (S:OW:DL) was obtained the high quality compost with the C/N ratio, Total P_2O_5 and Total K_2O concentration about 10.29, 2.45% and 0.38%, respectively, and obtained high removal in reducing Cu content about 91.17 %. The risk assessment of Cu content in Compost R2 was revealed as safe to use for daily compost due to no side effects on health, either carcinogenic or non-carcinogenic. Further investigation of produced compost implementation as growing media is essential to see the plant growth affected by the presence or absence of compost.

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