Poll Res. 40 (May Suppl. Issue) : S21-S29 (2021)

ISSN 0257–8050

ELECTRICITY AND COMPOST PRODUCTION OF DIFFERENT BIOCHAR ARRANGEMENT IN SOLID PHASE BIOELECTROCHEMICAL SYSTEM

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(Received 23 August, 2020; accepted 16 December, 2020)

ABSTRACT

Composting is a commonly used method for food waste treatment. However, a critical assessment of composting combined with bioelectrochemical systems (CBES) to produce direct electricity has scanty information in literature. In this study, food waste was composted, homogenized, and mixed with rice husks (RH) and coconut shells (CS) biochar. Then, the mixture was processed anaerobically for 30 days to get a stable and mature compost. This study also compared the anode surface area to analyze its effect on CBES performance. Then, the quality of compost, which includes the ratio of carbon and nitrogen (C/N), phosphorus (P), and bioelectricity production, was evaluated to obtain suitable conditions for CBES treating food waste. The results showed that 30% CS; and 20% RH could produce better quality compost. Therefore, the addition of 10% RH and three graphene in the anode chamber yield 4.71 mW/m^2 and 6.56 mW/m^2 of maximum power density. These results indicated that rice husk was considered to produce mature compost and better power density than coconut shells.

KEY WORDS : Biochar, Bioelectrochemical system, Coconut shell, Compost, Food waste, Rice husk

INTRODUCTION

Food waste has a sizeable percentage (± 31.9% in India; ± 22.72% in Indonesia; and ± 10% in Singapore) compared to other waste compositions. Food waste is mostly produced from kitchen activities, restaurants, hotels, canteens, food, and meat industries (Barik and Paul, 2017). Many foods dumped directly into the landfill because of the lack of food waste treatment, the poor quality of food packaging, and inadequate marketing systems (Song *et al*., 2015). Beyene *et al*. (2018) stated that food waste, in general, can be processed using thermal and biological processes. Thermal processes such as incineration, pyrolysis, and gasification are highly dependent on the waste composition, which affects the energy efficiency needed in the combustion process. However, biological processes such as anaerobic digesters and composting are preferred in a developing country because of its low operational and maintenance costs. However, biological processes depend on environmental conditions such as pH, water content, temperature, and micro / macro-nutrients. Thus, maintaining ideal conditions for the growth of microorganisms becomes a critical point in the biological processes (Beyene *et al*., 2018).

Bioelectrochemical system (BES) generates electricity directly through the metabolism of organic compounds by anaerobic microorganisms (Goglio *et al*., 2019). Biochar (bio-charcoal) obtained from the pyrolysis of biomass material can be used as conductive and electro-active material in BES. Yong Yuan *et al.* (2013) used sludge from domestic wastewater to form biochar cathodes (Zhang *et al*., 2012). In another study, Haoran Yuan *et al*. (2014) also used biochar obtained from bananas as an electrode for BES (Yuan *et al*., 2014). Other researchers also use natural materials such as chicken manure, wheat straw, and sawdust (Li *et al*. 2019), maple and birch wood (Khudzari *et al*., 2016), coconut shell waste (Ayyappan *et al*. 2018), etc. for improving anode performance. Biochar can also be used as a soil amendment, which increases soil porosity, water retention, and the availability of micronutrients (Goglio *et al*., 2019). Waqas *et al*. (2018) found that biochar can increase the effectiveness of microorganism degradation and food waste mineralization. The compost quality is achievable because biochar can also increase the temperature, which grows organic compounds, ammonia, and nitrates degradation (Waqas *et al*. 2018).

Khudzari *et al*. (2016) used biochar granules as bio-anodes to increase the effectiveness of plant bioelectrochemical systems (PBES) to generate electricity (Khudzari *et al*., 2016). Li *et al*. (2019) used several types of biochar granules that were homogenized into the soil to degrade hydrocarbon compounds using soil-microbial fuel cells (SMFCs) (Li *et al*., 2019). In this research, biochar obtained from local resources (coconut shell and rice husk) was used as a bulking agent to enhance the microbial activity. Thus, the event will increase electricity production and produce better compost quality. The purpose of this study was to analyze the electricity production generated from the bioelectrochemical system (BES) and explaining the quality of compost produced from BES by adding biochar. This technology was expected to be an alternative to direct renewable energy from the composting process.

MATERIAL AND METHODS

Experimental Design

This research was carried out using a lab-scale reactor with a single chamber type consisting of one anode and one cathode and separated based on the distance of the two electrodes. A single chamber is considered more beneficial because electrons can go directly to the cathode without the need for a salt bridge. Graphite plate electrodes were used as anodes and cathodes with dimensions of 12.5 x 4 x 1 cm^3 and a surface area of 0.013 m^2. This graphite plate was then reactivated by heating at 100 ^oC for 1 hour then, it was soaked in H_2SO_4 and NaOH 1N each for 24 hours and stored in distilled water to ensure all contaminants contained in the graphite surface removed. The cathode was provided to be in direct contact with air (air-cathode), while the anaerobic process takes place in the anode space along with the leachate formed from the composting process. The electrodes were connected to an external wire and epoxy. The reactor used was cylindrical with a diameter of 15 cm and a height of 15 cm and had a working volume of 2.5 liters.

Table 1. Organic Waste Characteristics

Parameter	Food Waste	Leaves Waste
Organic - C (%)	28.41	14.14
Total - N (%)	0.58	0.42
Total - P (%)	0.25	0.01
C/N ratio	48.79	33.2
Water content (%)	56	16
pH	6	5.8

The coconut charcoal and rice husk used as a bulking agent in this study were obtained from commercial shops. At the same time, organic waste was taken from the integrated waste temporary disposal, Semarang City, Indonesia. The mixed waste was air-dried for ±2 days. Then it was chopped and placed in the reactor according to biochar arrangement, including 10%, 20%, and 30% by the dry-weight basis. Leaf and food waste were mixed homogeneously (composition 1: 1). Then, water was added to the reactor until it reaches ±60% of water content to make a suitable condition for compost production. The mixture was homogenized using cone and quartering methods, where the waste is divided into several parts and then mixed evenly.

This research was conducted in a short period (30 days) by testing the main parameters such as organic carbon (C), total-N, total-P, and COD carried out on certain days, including on D0, D3, D5, D10, D15, D20 and D30 due to consider limitations of the test equipment. Temperature, pH, moisture content, and electricity production (voltage, current strength, internal resistance) were measured every day. The seven reactors consisted of 3 reactors with different rice husk arrangements, 3 reactors with different coconut shell arrangements, and a control reactor. Details of the experimental design can be seen in Table 2. All reactors use the addition of an Effective Microorganism 4 (EM4) bio-activator of 1% by volume of waste consisting of fermented and synthetic microorganisms comprised of lactic acid bacteria (*Lactobacillus sp.*), Photosynthetic bacteria (*Rhodopseudomonas sp.*), *Actinomycetes sp.*, *Streptomyces sp.*, and yeast. The addition of bio-activators was expected to improve the physical, chemical, and biological properties of the soil, optimize the quality and quantity of compost production, speed up the fermentation process and reduce the activity of pests and diseases.

Data Analysis

Preliminary tests were carried out to determine the characteristics of leaf and food waste and determine the electrodes (especially internal barriers). Data processing and analysis include power density, C-Organic, total N, C/N ratio, total-P, and water content. Voltage (V), resistance (R), an electric current (I) data were used to measure power density. Voltage measurements can be carried out using equation (1).

$$I = \frac{V}{R} \quad .. (1)$$

Where I is the electric current,V is the voltage gradient, R is the resistance (Ohm). The current and voltage values are then entered into equation (2) to get the amount of power density (mW/m^2)

$$PD = \frac{VxI}{A} \quad .. (2)$$

Where PD is power density, and A is the surface area used by microorganisms that grow in graphene anode (m^2) with a rectangular shape of 0.025 m^2. The method used to test the levels of C-organic, total-N, total-P, and COD was performed using the spectrophotometric method. Measurement of voltage, current strength, and resistance was done by direct reading using a multimeter. Temperature and pH were tested every day regarding Indonesian Natural Standard Number 6989.23-2005 and 6989.11-2004.

RESULTS AND DISCUSSION

Temperature, pH, and Water Content Profile

The air temperature at the time of testing ranged from 28-33 °C, while the temperature fluctuations in the reactor can be seen in Fig. 1. It can be seen that the compost temperature has gradually decreased from 36 °C to the lowest point at 28 °C. The temperature of all reactors had dropped dramatically to 31 °C and increased again to 33 °C on the second day. This temperature increase illustrates the possibility of starting the composting process. This mesophilic condition lasted until the end of the study. Too low heat causes the composting process to take longer. On the other hand, too much temperature causes the oxygen content in the bulking solution to decrease. In general, the temperature can be influenced by several factors, such as the type of waste (C/N, humidity, porosity), the composition of compost (depth, shape), and oxygen content (natural ventilation or with the help of aeration). In some cases, compost does not reach the thermophilic point because of one or more limiting factors. The

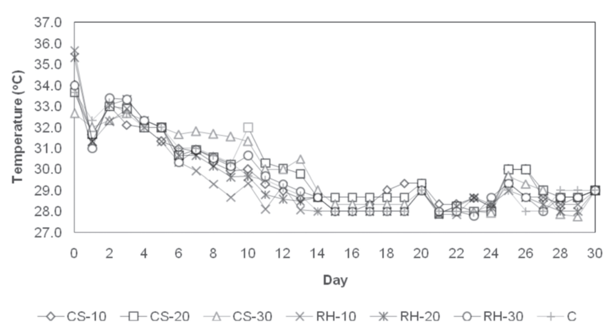

Fig. 1. Temperature fluctuations in all treatment

Table 2. Summary of Experimental Design

Treatment Code	Independent Variable	Dependent Variable
CS-10	The addition of coconut shell 10%	Measured every day in triplicate:
CS-20	The addition of coconut shell 20%	Temperature, pH, power density
CS-30	The addition of coconut shell 30%	Measured seven times in duplicate:
RH-10	The addition of rice husk 10%	Water content, C/N/P and COD
RH-20	The addition of rice husk 20%	
RH-30	The addition of rice husk 30%	
C	Control	

composting process that reaches thermophilic temperature indicates the maximum level of degradation. Other studies show that mesophilic temperatures occur at higher organic degradation than thermophilic temperatures. However, the effectiveness of destroying pathogens is far higher under thermophilic conditions.

The pH measurements were carried out to determine the acidic and alkaline atmosphere in compost. Acid-base conditions describe the process of degradation of organic compounds by microorganisms. At the beginning of composting, pH decreased due to the appearance of pure organic acids by organisms. Then the pH will gradually rise until the compost is mature at pH 7-8. The results of pH measurements for 30 days can be seen in Fig.2. In this study, the pH range occurred between 4-7. The lowest average happens on day 8 to penetrate pH 4. This condition indicates the formation of organic acids by microorganisms. Furthermore, the pH rises and stays in the range 4.5-7. Reactor control and the use of coconut shells are still tolerated because they are still in an excellent composting scale of 5-8 and at optimal conditions between 7-8. The addition of rice husk biochar reduced the pH to below five on the 30th day of the study. Nevertheless, the pH of the biochar rice husk treatment tends to increase, although not as fast as biochar coconut shells.

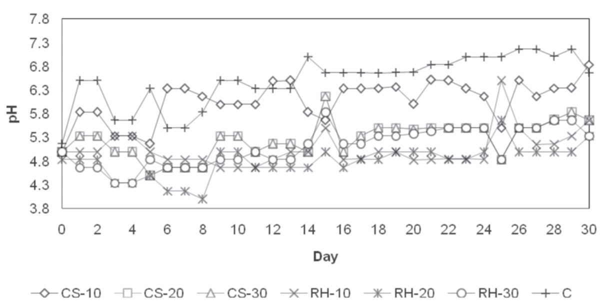

Fig. 2. pH profile in all treatment

It can be seen that the initial water content above 80% then gradually decreases to a stable between 70% to 50%. Fig. 3 is adjusted to the preliminary test results to maintain the water content between 50-70% due to loss of water content due to evaporation and absorption by waste materials and biochar. The moisture content is still the optimal composting water level. The lowest water content occurs in the CS-20 reactor, which is assumed to occur water uptake by microorganisms for the removal of organic compounds. Water content in compost affects the activity of organisms and the hydraulic conductivity of compost. Water content that is too high will prevent the entry of oxygen and carbon dioxide production so that harmful compounds are collected in the compost, causing the compost to become anaerobic. However, if the water content is less than 40%, microorganism activity will be reduced — a good range of water content for composting ranges from 50-70%. The optimum value is 55%. If the humidity condition decreases to 40%, then the composting process will run slower. When the water content is above 55%, the particles' cavities will be filled with water and will shift the air so that the anaerobic process occurs. Stirring is needed to maintain moisture during the composting process. Good water content for compost is 60%. The heat in the compost causes the water to evaporate so that the compost becomes dry. Usually, mixing or reversing compost in a conventional process will return the conditions in a pile to normal. If there is a drought in the collection, the decay process will be disrupted.

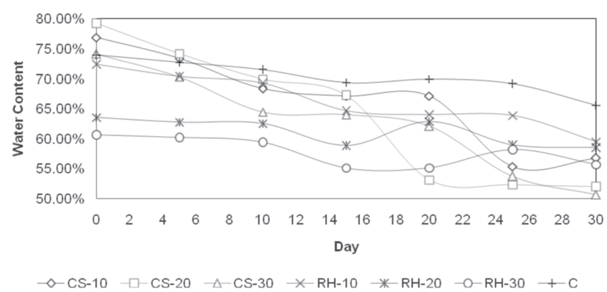

Fig. 3. Fluctuations in water content in all treatment

Carbon, Nitrogen and Phosphor Profile

The carbon and nitrogen in compost are needed to produce energy and make new microorganisms' cells. Organic compounds in the complex form are broken down by bacteria into simpler compounds. Chemical processes in the breakdown of compounds that occur produce energy used by bacteria for the decomposition process. Optimal C/N ratio values are different for aerobic and anaerobic microbial types. Compared to aerobic microbes, anaerobic microbes require a higher C/N ratio due to associated microbiological activities and energy requirements. The C/N ratio for composting is recommended between 25-35 compared to anaerobic digestion, 20-30. Low C/N conditions will produce high ammonia and the production of volatile fatty acids, which can cause an odor in the composting process.

The highest organic carbon value occurred on the 10th day then decreased on the following day. The average N value has also decreased over time (See Fig. 4). The figure illustrates a reduction in carbon and nitrogen compounds due to the metabolism of organic compounds carried out by microorganisms. In the decomposition of carbon compounds used by microorganisms as a substrate and then broken down to arrange cells, some carbon is also converted into CO_2. The change of carbon into CO_2 gas causes a reduction in the volume of waste. The decrease in waste volume varies depending on the available C/N ratio. The higher C/N ratio will make the process run imperfectly. While the lower C/N ratio will inhibit the decay process also produce odor due to the formation of ammonia. The lowest C/N value was experienced by treatment control, where the C/N ratio never exceeded 10. The most considerable C/N ratio fluctuation was experienced by RH-10, where the highest value of organic C production was experienced by the RH-10 treatment on the 10th day later, gradually decreased and ended at 16.80. The lowest average C/N value on all reactors occurred on the 25th day with an average C/N of 8.56 and the highest amount on the 10th day of 29.46 (Fig. 4). From the data obtained, the average C/N ratio rises from day 0 to day ten and then decreases to close to the average number on day 30. The optimum value of mature compost refers to the Indonesian National Standards, which ranges from 10-20.

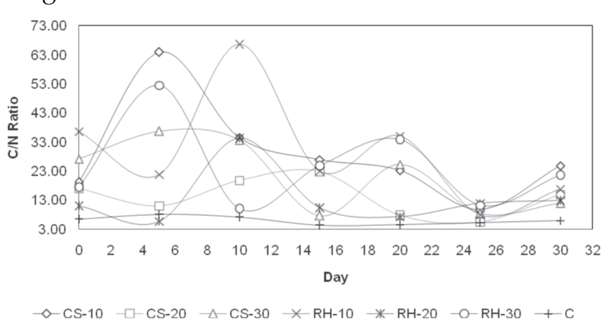

Fig. 4. C/N ratio in all treatment

Microorganisms play an essential role in the formation of phosphorus in compost. One of the configurations of organic compounds is by changing and mineralizing organic P compounds. Phosphorus (P) has an essential role in the fertility of soils derived from organic matter to help raise soil nutrients. Phosphorus is needed in cell division, tissue development, and plant growth points. Phosphorus is also required for the process of photosynthesis and the chemical physiology of plants. The P element is the second important element after nitrogen, which plays an essential role in photosynthesis, root development, flower formation, fruit, and seeds. Fig. 5 illustrated a fluctuation in the P value from shallow values to the highest point on the 20^{th} to 25^{th} day for RH-10 and RH-20. The average P value content at the end of the study was following the quality standards in SNI 19-8030-2004, which is> 0.1%.

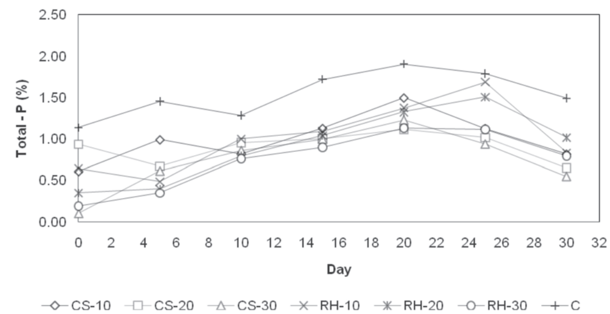

Fig. 5. Total-P concentration in all treatment

Electricity Production

Electric voltage is the potential difference in electron charge at two points expressed in volts. In a microbial fuel cell system, energy occurs due to the transfer of electrons released by bacteria when breaking up organic compounds. Electrons are transferred either directly or indirectly using the substrate to the electrodes to accumulate and cause the flow of electricity to flow from high potential to low potential. On the 10th day, almost all electricity production increased and then declined again (See Fig. 6). Electricity production increased very sharply to reach 11.70 mW/m^2. For the treatment, at the end of the study, the control treatment shows a unique behavior where the value of electricity production is quite significant compared to other treatments using biochar. This condition indicates that the addition of too much biochar will cause even more significant obstacles.

The ability to live organisms to produce electrical energy directly is called electrogenesis. In biological cells, electrochemical active transmembrane ion channels and transport proteins, such as sodium-potassium pumps, enable electricity generation by maintaining voltage imbalances from the difference in electrical potential between intracellular and extracellular space. The sodium-potassium pump simultaneously releases three Na ions away and enters two K ions into the intracellular space. This condition results in an electrical potential gradient from the uneven charge separation created. This process of consuming metabolic energy is carried out in the form of ATP.

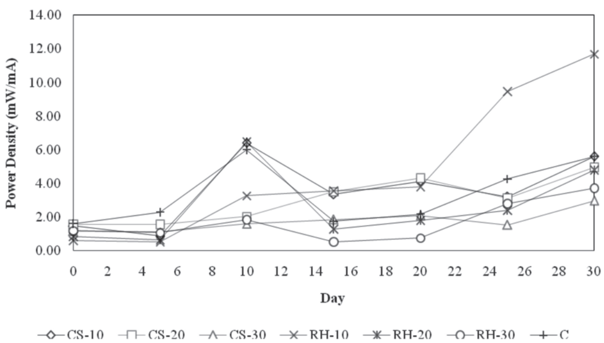

Fig. 6. Power density profile

Table 3. Comparison C-Organic, N-Total, P-Total, and C/N ratio value with National Standard

Treatment	Comparison with National Standard			
	Organic C	Total N	Total P	C/N ratio
CS-10	+	+	+	-
CS-20	+	+	+	+
CS-30	+	+	+	+
RH-10	+	+	+	+
RH-20	+	+	+	-
RH-30	+	+	+	-
C	+	+	+	-

Indonesia's National Standard number 19-7030-2004
(+) meets the criteria of Indonesia National Standard
(-) below or upper the Indonesia National Standard

DISCUSSION

Leaf waste is a component of organic solid waste found in large quantities in several areas, for example, in companies, government agencies, academic institutions, etc. Every day leaf waste is produced, where the trash takes a long time to be degraded so that it builds up in the yard, which undoubtedly reduces the aesthetic environment. Besides, other types of organic waste are generated in considerable amounts every day, such as food waste. In this context, food waste is obtained from the canteen and food stalls operations. If not treated, before being discharged into the environment, both types of waste material can cause negative impacts. One of them can cause landfill fires due to methane gas produced from organic waste undergoing fermentation. In the development of technology, alternative waste composting emerged, namely composting bioelectrochemical system (CBES). Leaf waste and food scraps mainly contain high organic content, which has been used in previous studies as a source of substrates for bacteria (Moqsud *et al*. 2013).

In this study, it can be seen that the addition of biochar can increase the C/N ratio under optimal conditions. When composting is done for 30 days, the control treatment cannot increase the C/N ratio of the waste to normal levels even though the contents of C, N, and P meet the applicable requirements. The addition of biochar is known to increase porosity and increase the availability of nutrients for microorganisms so that the effectiveness of degradation and compost mineralization from waste will increase. Therefore, biochar is considered to be able to improve the degradation process of organic compounds, ammonia, and nitrates. The bioelectrochemical system (BES) is currently classified by the material used, both the liquid and the solid phases. The difference between the two lies in the phase source of the materials. Source of substrate used in BES with liquid phase usually comes from the household, livestock, food wastewater, etc. While the source of the substrate used in the solid phase, BES often comes from food processing, factory, lignocellulosic waste, and even contaminated soil (Khudzari *et al*., 2018).

Composting-bioelectrochemical system (CBES) is a form of MFC that can be filled with solid organic wastes such as mud, sediment, and polluted soil (De Schamphelaire *et al*., 2010; Yu *et al*., 2017). CBES in electron transfer in solid-phase substrates, cells have problems such as having high internal resistance and producing too little electricity. Still, another advantage of the solid-phase microbial fuel cell is rich in organic matter so that it will increase the metabolic activity of microorganisms. The high biodegradable organic content in the organic solid waste can be effectively used to produce energy in the form of bioelectricity by integrating the fermentation technology of stable compounds with BES. Configuring CBES, the cathode is generally in contact with ambient oxygen in air or water, while the presence of the anode in an an-aerobic state lies beneath the cell (Wang *et al*., 2013).

The mechanism of action of CBES biologically is no different from the BES in general, which utilizes microbes that metabolize the medium at the anode to catalyze the conversion of organic matter into electrical energy by transferring electrons from the anode through wires and producing current to the cathode (Florio *et al*., 2019; Koók *et al*., 2016). Complexions receive electron transfers from the anode at the cathode, which have free electrons. The substrate is a substance produced by microbial metabolism or electron released by microbes when carrying out their metabolism. Contents derived from microbial metabolism are generally compounds that contain hydrogens, such as ethanol, methanol, or methane gas. This compound can be used as a source of hydrogen through a series of processes to produce electrons and produce an electric current. Any metabolic activity carried out by microbes generally involves the release of free electrons into the medium. This electron can be utilized directly at the anode in BES to produce an electric current (Ren *et al*., 2018).

The substrate is oxidized by bacteria to produce electrons and protons at the anode. Bacteria used in mediator-less MFCs must have an active electrochemical redox enzyme located on the bacterial outer membrane that can transfer electrons to external material, so there is no need to use additional exogenous chemicals (Rikame *et al*., 2012). An electrical circuit connects oxygen, hydrogen protons, and electrons from the anode to the cathode then combined catalytically with the catalyst at the cathode. A typical BES design consists of 2 separate spaces that can be inoculated with any liquid, namely anaerobic anode, and aerobic cathode space, which are generally separated by PEM such as Nafion (Moon *et al*., 2015). However, as it progressed, it was found that BESs added by artificial carrier electrons can transfer electrons to the electrodes and do not need to add exogenous chemicals. This type is called mediator-less BES (Mansoorian *et al*., 2013). The use of a single chamber is more advantageous than the dual-chamber system. Because it can increase mass transfer to the cathode, reduced operating costs because there is no need for an electron bridge, the whole process takes place in one reactor, and the design can be simplified. BES's asingle chamber, air-cathode type, also has the most significant potential for practical applications due to its simple design and direct oxygen contact in the air (Mohan and Chandrasekhar, 2011).

In planning MFCs, substrates are the most important biological factor in the electricity production process. The substrate material is considered important for composting because different substrates show different composting performance. The choice of substrate is mainly based on cellulose, which is considered the most abundant biopolymer and an ideal source of organic material. In the research of Wang *et al*. (2015), different substrates are combined and used to change the C/N ratio. Then grouped into 5 different C/N ratios (11.7: 1, 27.8: 1, 31.4: 1, 31.7: 1, 37.2: 1). As a result, the substrate combination used for the optimal C/N ratio is 31.4: 1 (a mixture of soybean dregs, coffee dregs, and rice husks with a ratio of 1: 1) can produce a power density of 4.6 mW/m^2 (Wang *et al*., 2015). Logrono *et al*. (2015) experimented with variations in the ratio of organic waste to fruit and vegetables. The relationship between the substrate and the performance of the output voltage in BES, the highest value obtained by 330 mV in BES, contains a mixture of 75:25 fruits and vegetables (Logroño *et al*., 2015). In the metabolism of living microorganisms, approximately 20 pieces of carbon are converted to CO_2, and 10 parts are synthesized to be protoplasm (Malinowski *et al*., 2019). BES has been tested in a combination of soybeans' composting process, rice husks, leaves, and coffee grounds in different C/N ratios. Combining the composting process with energy acquisition through BES is possible. A C/N ratio of 31.4:1 is obtained, which produces an excellent power density of 1,278 mW/m^2. The C/N ratio's value approaches the C/N ratio value of 30:1 optimal for general compost.

Natural composting will take a relatively long time, which is around 2-3 months or 6-12 months (Waqas *et al*., 2019). Composting can take place with faster fermentation with the help of effective inoculants or activators. Activators are all forms of substances that microbiologically stimulate the compost decomposition process. Organic activator or the starter is a material containing high nitrogen in various forms such as protein, amino acids, urea, and others. A starter is a collection of microorganisms that are expected to accelerate the composting process and enrich microbial diversity. Inoculant microorganisms were circulating in the market, including PROMI (Promoting Microbes), OrgaDec, Super Dec, ActiComp, BioPos, EM4, and Green Phoskko Organic Decomposer. EM4 is one of the easiest activators to be found in the local market.

CONCLUSION

Single chamber – bioelectrochemical system equipped with biochar has been shown to increase electricity production and speed up composting time. However, more biochar does not mean that the processing variation is optimal. The use of 30% of rice husk cannot increase electricity production, and instead, the C/N ratio produced becomes larger and does not meet standards. Conversely, a 10% rice husk is even better in increasing the C/N ratio and electricity production. The most massive electricity production that can be produced is 11.70 mW/m^2 at the use of rice husk by 10%. This study also found that rice husk's application has no effect on temperature but can reduce pH and water content quickly. This result indicates that the utilization of biochar can increase the activity of acid bacteria that can lower pH. The use of biochar can increase the activity of bacteria in processing organic compounds, thus accelerating the period of compost maturity. Several critical factors, such as water content and pH, need to be evaluated further because they dramatically affect the electricity produced.

ACKNOWLEDGMENT

The authors want to acknowledge the World Class University Program Number 205-09/UN7.P4.3/PP/2019 that gives our financial research support.

Contribution Statements

Syafrudin andMochamadAriefBudihardjo are concepting, analyzing and checking the methods and results; Agus Jatnika Effendi, Syarif Hidayat, and Candra Purnawan are reviewing, revising, commenting and finalizing the manuscript; Bimastyaji Surya Ramadan and Ichsan Hadyanare editing, analyzing, checking and submitting the final version of the manuscript. All authors have read, revised, reviewed, and approved the final version of the document.

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