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Title:
Waste Valorization using Solid-phase Microbial Fuel Cells (SMFCs): Recent Trends and Status

Authors:
Mochamad Arief Budihardjo, Syafrudin, Agus Jatnika Effendi, Syarif Hidayat, Candra Purnawan, Ayudya Izzati Dyah Lantasi, Fadel Iqbal Muhammad, Bimastyaji Surya Ramadan

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Environmental Science (Environmental Engineering, Management Monitoring Policy and Law, Waste Management and Disposal) – H Index 179 – Q1 SJR 1.44

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3 messages

Jason Evans <eesserver@eesmail.elsevier.com> Mon, Jan 27, 2020 at 10:08 PM
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Following this message are the reviews of the above-referenced manuscript. We'll be glad to consider this paper for publication after it's been revised substantially in accordance with the reviewers' comments.

Due to space limitations in the printed journal, we are requesting that all authors reduce the length of their papers by at least 10% if possible. If your paper includes large tables or datasets, it is preferred that these be published as supplementary material in Science Direct rather than in print. Further information is provided at the end of this message.

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Associate Editor
Dear authors, on the basis of the review reports received and having examined the manuscript myself, the manuscript topic is relevant for the journal. However, in its present form the manuscript fails to provide a critical assessment and comparative discussion of the matter. This is very critical for review papers, if they are intended to provide a useful scientific contribution to the knowledge in the field. I therefore invite you to submit a revised version of the manuscript, taking in due consideration all such issues, as indicated in further detail in the reviewers' reports. When preparing the revisions, please make sure to: 1) provide a "Response to reviewers" document in which a detailed point-by-point response to the comments/questions received is included and the related changes made to the text are clearly reported; 2) clearly highlight in the revised text all the changes made to the original version (you may preferably use the "Track changes" tool in MS Word, or
highlight the new text using a different colour and mark deletions with strikethrough font). It is recommended that the "Response to reviewers" document is arranged to include a table containing (in separate columns) the original reviewers' questions/comments, the related motivated response, and the revised text in the manuscript
Please be advised that, once received, the manuscript will be subjected to another round of reviews to judge whether all the required changes will have been adequately incorporated in the revised version.

Reviewer #1: The paper presents a review on the recent trends for the exploitation of solid organic waste in Microbial Fuel Cells (MFCs).
The topic is of great interest for the community, but the following enhancements are mandatory, before the final acceptance:
1) The English language is not always very clear and some typos are found in the text. The Authors are encouraged to let a native English speaker review the language;
2) The quality of the Figures must be improved: the Figures grabbed from other papers should be vectorial (eps of pdf), in order not to let them appear rasterized (such as Fig. 2, for example);
3) Many recent works on the exploitation of solid waste are not included in the review. Please expand the scientific background and the pertinent literature references cited

Reviewer #2: The article is written quite well, but on a popular topic with an imposing amount of articles on the literature, therefore from my point of view the authors have to bring out the originality of this work and revise the English.

The abstract is very short and it does not summarize the article, without attracting the readers on the focus of the article.

The authors are kindly exhort to revise the introduction, going in the deep of the arguments, raising the value of the review.

Please, in all the article use just number to enumerate chapters and paragraphs (1.1 - 1.2 - etc.)

Chapter 2 is written quite well with a clear explanation of the situation.

Chapter 3 is well explained but the authors are kindly exhort to increase this part, explaining and increasing the main arguments of the review. Moreover, the authors have to delay paragraphs 3.5 and chapter 4 because they are out of topic.

From my point of view, it is brilliant in chapter 5 the part about the comparison between AD and MFC, please increase this part making a comparison also with other technologies (composting, incinerator, etc.) adding also percentages of transformation and mass balances.

The conclusion is too short, the authors do not draw the sum up of the article, please revise it.

Reviewer #3: The authors reviewed some progress in solid phase microbial fuel cells. However, the contents of the review are not very detailed and lack of effective introduction and discussion. The detailed comments and suggestions are given below.

1. P8, "Fundamental Process of Solid Phase MFC", solid waste was used as substrate in SMFC, it was different of the traditional MFC with wastewater, the author should indicate the type of solid waste, sludge? soil? Why didn't the author contain sediment microbial fuel cell, which belongs to solid phase MFC.
2. P11, "Materials that are widely used are graphite fiber brush, carbon cloth, graphite rod, carbon paper", references should be cited.
3. P11, "Radical oxygen produced in the anode chamber (equation (2))", But the authors give in equation 2 is hydrogen. What's more, this reaction does not occur in the anode, where the organic matter is oxidized to produce protons and electrons.
4. P12, "The absence of separator or PEM in SMFCs can cause pH splitting, namely an increase in pH in the cathode chamber and an extreme decrease in pH in the anode chamber." This phenomenon should be more serious in the presence of separator or PEM, not in the absence of a membrane.
5. P12, "which have a distance between electrodes of 5 cm", the distance was 5cm, why?
6. P12, Table 1,maximum power density was based on the projected area? Or specific surface area of electrode? It should be compared under the same calculation method.
7. P19, "Substrates or materials used as organic sources for SMFCs can use various types of waste that contain high cellulose". Some waste, such as soil and sludge, didnot contains high cellulose, and waste should contain high organic matter.
8. P20, equation 2, How to derive? And it should become equation 3
9. P27, "Rice plants are used because of their abundance at the location of the study", references should be cited.
10. The biggest limitation in SMFC is the slow substrate mass transfer rate. The author's review does not well discuss this aspect in this paper.

Response to reviewer comment of the first version of the manuscript

*Response to Reviewers

Response to Reviewers Questions / Comments

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	Additional Changes outside Reviewer Comments		
1	Additional author	We add "Ayudya Izzati Dyah Lantasi" as author since she helped us to revise some editor comments	Ayudya Izzati Dyah Lantasi Master of Environmental Sciences, School of Postgraduate Studies, Universitas Diponegoro, Semarang 50241, Indonesia
	Editor		
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2	in its present form the manuscript fails to provide a critical assessment and comparative discussion of the matter. This is very critical for review papers, if they are intended to provide a useful scientific contribution to the knowledge in the field.	Thank you for your comment, we increase the critical assessment as per reviewer suggestion	-

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3	The English language is not always very clear and some typos are found in the text. The Authors are encouraged to let a native English speaker review the language	We have already made a substantial revision for correcting the English written structure by the help of international proofreader. The revisions and editing certificate are attached.	Revised texts for grammar correction are marked by blue color in the manuscript
4	The quality of the Figures must be improved: the Figures grabbed from other papers should be vectorial (eps of pdf), in order not to let them appear rasterized (such as Fig. 2, for example)	We redraw and redesign all of the figures to ensure and improve the figure quality	All figures have been improved and figure 3 and 5 have been removed.
5	Many recent works on the exploitation of solid waste are not included in the review. Please expand the scientific background and the pertinent literature references cited	We added some recent works on the exploitation of solid waste and expand the scientific background through a discussion in MFCs comparation and integration with other solid waste processing technologies such as anaerobic digestion and aerobic composting	Assi, A., Bilo, F., Zanoletti, A., Ponti, J., Valsesia, A., Spina, R.L., Zacco, A., Bontempi, E., 2020. Journal of Cleaner Production 245, 118779. Barik, S., Paul, K.K., 2017. Potential reuse of kitchen food waste. Journal of Environmental Chemical Engineering 5, 196-204. Bernstad, A., la Cour Jansen, J., 2012. Review of comparative LCAs of food waste management systems – Current status and potential improvements. Waste Management 32, 2439 – 2455. Chu, Z., Fan, X., Wang, W., Huang, W. 2019. Quantitative evaluation of heavy metals' pollution

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			hazards and estimation of heavy metals' environmental costs in leachate during food waste composting. Waste Management 84, 119-128. Li, D., Shi, Y., Gao, F., Yang, L., Kehoe, D.K., Romeral, L., Gun'ko, Y.K., Lyons, M.G., Wang, J.J., Mullarkey, D., Shvets, I.V., Xiao, L., 2020 Characterising and control of ammonia emission in microbial fuel cells. Chemical Engineering Journal 389, 124462. Quezada, B.C., Delia, M.L., Bergel, A., 2010. Testing various food-industry wastes for electricity production in microbial fuel cell. Bioresource Technology 101, 2748-2754. Rincon, C.A., Guardia, A.D., Couvert, A., Roux, S.L., Soutrel, I., Daumoin, M., Benoist, J.C., 2019. Chemical and odor characterization of gas emissions released during composting of solid wastes and digestates Santos, L.A.d., Valenca, R.B., Silva, L.C.S.d., Holanda, S.H.d.B., Silva, A.F.V.d., Juca, J.F.T., Santos, A.F.M.S., 2020. Methane generation potential through anaerobic digestion of fruit waste. Journal of Cleaner Production 256, 120389 Song, Y., Xiao, L., Jayamani, I., He, Z., Cupples, A.M., 2015. A novel method to characterize bacterial

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			communities affected by carbon source and electricity generation in microbial fuel cells using stable isotope probing and Illumina sequencing. Journal of Microbiological Methods 108, 4-11. Smith, M.M., and Aber, J.D., 2018. Energy recovery from commercial-scale composting as a novel waste management strategy. Applied Energy 211, 194-199. Song, Y., Xiao, L., Jayamani, I., He, Z., Cupples, A.M., 2015. A novel method to characterize bacterial communities affected by carbon source and electricity generation in microbial fuel cells using stable isotope probing and Illumina sequencing. Journal of Microbiological Methods 108, 4-11. Velis, C.A., Longhurst, P.J., Drew, G.H., Smith, R., Pollard, S.J.T., 2009. Biodrying for mechanical-biological treatment of wastes: A review of process science and engineering. Bioresource Technology 2009, 2747-2761. Xiao, L. He, Z., 2014. Applications and perspectives of phototrophic microorganisms for electricity generation from organic compounds in microbial fuel cells. Renewable and Sustainable Energy Reviews 32, 550-559.
	Reviewer #2		

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6	The article is written quite well, but on a popular topic with an imposing amount of articles on the literature, therefore from my point of view the authors have to bring out the originality of this work and revise the English.	We have already made a substantial revision for correcting the English written structure by the help of international proofreader. The revisions and editing certificate are attached.	Revised texts are marked by underline and red (additional sentences) + blue color (grammar and structure) in the manuscript
7	The abstract is very short and it does not summarize the article, without attracting the readers on the focus of the article.	As per reviewer suggestion, we add more words and outline the discussion part in the abstract	The critical factors affecting SMFCs performance is the efficiency of electron and proton transfer through solid media. However, this limitation may be overcome by electrode system enhancement and regular substrate mixing. In the other hand, the integration of SMFCs with other conventional solid waste treatment could produce sustainable green energy. Although SMFCs produce relatively small energy than other waste to energy treatment (around 6 to 18 times to achieve the same energy output as combustion process), SMFCs is still quite promising to achieve zero emission treatment. Therefore, this article is expected to address the challenges and also fill the gaps in SMFCs research and development
8	The authors are kindly exhort to revise the introduction, going in the deep of the arguments, raising the value of the review.	We reconstructed again the introduction as reviewer suggestion "Various studies were conducted…. Because of the different roles	The increasing of municipal solid waste generation is an issue faced by almost all countries in the world, due to an increase in industrial activity and global development. In developing countries, almost 90% of municipal waste is transported to landfills directly without any intermediate

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		of each microorganism in degrading the substrate." is removed because we think that this paragraph is part of discussion. And we moved some sentences into chapter 3.	treatment that can reduce the volume of solid waste (Barik and Paul, 2017). This waste management activity even contributes to greenhouse gas emissions by 5% compared to total world greenhouse gas emissions. Recycling, effective waste treatment and source-segregation are the main strategies in reducing emissions and environmental impacts due to increased waste generation (Florio et al., 2019). Waste is considered to still have a large enough energy content, so waste to energy is one of the alternatives that is considered (Chiu et al., 2016). Composting and anaerobic digestion are biological treatment technologies that have been used and explored massively in various countries (Yu et al., 2015; Xin et al., 2018). However, conventional composting under aerobic condition requires more energy for mixing and air supply and may produce a huge amount of leachate (Chu et al., 2019). Anaerobic composting which is commonly known as anaerobic digestion can be an alternative solution for converting solid waste into reusable energy and biofuel (Khudzari et al., 2016). Many recent works revealed that anaerobic digestion has many constraints such as long residence time, relatively low purification of biomethane and its conversion to electricity, and many safety issues which make this technology cannot be a perfect

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			solution for zero discharge treatment (Xin et al., 2018). Recently, microbial fuel cells (MFCs) is found as an alternative treatment for generating electricity from waste (waste valorization) without intermediate treatment as anaerobic digestion does by utilizing electrogenic (anodophilic) microorganisms (Xin et al., 2018). Bioelectric energy of MFCs is depending on the electron transfer process and biodegradation efficiency of solid waste (Song et al., 2015). Many researchers use the terms of solid phase MFCs (SMFCs / SPMFCs) (Logrono et al., 2015; Wang et al., 2015; Mohan et al., 2011) and a few of them use the terms of compost MFCs (cMFCs) (Khudzari et al., 2016) and biogas slurry MFCs (BSMFCs) (Wang et al., 2019a) to name MFCs which converting solid waste into electricity.
9	Please, in all the article use just number to enumerate chapters and paragraphs (1.1 - 1.2 - etc.)	As per reviewer suggestion, some sub chapters are changed to number	2.1. Process in the Anode 2.2. Process in the Cathode 2.3. PEM/Distance Between Anode and Cathode
10	Chapter 2 is written quite well with a clear explanation of the situation.	Thank you for your comment	-
11	Chapter 3 is well explained but the authors are kindly exhort to increase this part, explaining and increasing the main arguments of the review. Moreover, the	Thank you for your comment, we deleted subsection 3.5 and chapter 4. We also added some discussion in the chapter 3, in the	The biggest limitation of microbial process in solid phase ecosystem is substrate / mass transfer rate (Rahimnejad et al., 2011). Transfer resistance would be higher since the absence of sufficient solution homogenized the distribution of

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	authors have to delay paragraphs 3.5 and chapter 4 because they are out of topic.	substrate sub section as other reviewer request.	substrate to microorganism and also the electrons to electrode. Reducing electrode distance may increase the rate of electron transfer, but some other problems occur such as the increasing of oxygen penetration and active surface electrode which lead to the decreasing power output (Sharma and Li, 2010). Water content is the other critical point to note when working with SMFCs. Ideally, 60% of distributed moisture will make the process occur in a good condition (Wang et al., 2015). As many SMFCs reactor working in gravitational direction of electrodes, anode chamber will be flooded and exceeded 60% of moisture content soon after the process is working. The use of Xanthan 80 SF can significantly improve the performance of the SMFCs reactor because the nature of Xanthan 80 SF is able to maintain moisture in the compost and prevent the effects of gravity so that water does not accumulate at the bottom of the reactor. Therefore, cathode chamber will dry and decrease the proton transfer rate which make a lower power production. In this case, drainage and circulation system may be useful for maintaining the power production. This finding is expected because the moisture in the compost is reduced, which in turn inhibits the compost decomposition process and decreases the microbial activity, thereby inhibiting ion transfer and

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			energy production. These results indicate that the use of Xanthan 80 SF can increase the amount of electricity generated and extend the period of electrical energy release (Wang et al., 2017; Samudro et al., 2018). Li et al. (2019) tried to solve the transfer rate problem by using biochar amendment in soil which has limited water content. Biochar could increase electron transfer rate and kinetics because of the presence of electroactive surface. The addition of biochar also can support microbial colonization and increase the rate of biodegradation process. Therefore, knowing the optimization of biochar mass that will be used is important since biochar may decrease the electrical conductivity because of its ability to adsorb ions in soils.
12	From my point of view, it is brilliant in chapter 5 the part about the comparison between AD and MFC, please increase this part making a comparison also with other technologies (composting, incinerator, etc.) adding also percentages of transformation and mass balances.	Thank you for your comment, we add more discussion in this part and renew the title to be "Integration of SMFCs with Other Solid Waste Treatment" We cannot find the percentages of transformation, but we added more explanation about potential system and energy balances if SMFCs is applied	Solid phase microbial fuel cells (SMFCs) seems to have many potentials when compare to other solid waste treatment. This technology only needs relatively small energy input for supporting chemical reaction in cathode. Moreover, air-cathode MFCs does not need a supply oxygen since it is provided by its system configuration. SMFCs produce a less sludge as an anaerobic power generation system and convert organic matter into direct electricity and biohydrogen. The processed organic matter could be a mature compost and fertilizer. The used electrode could be a soil conditioner, to increase the

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
			fertility of soil. It is also producing a less emissions such as CH4, CO2, NH3, N2O. The same characteristics can be seen in the anaerobic digestion which has the same processing stage as SMFCs. Aerobic composting needs a lot of energy for aeration and mixing and only produce compost with excessive amount of leachate. This type of composting also produces a significant amount of odor and VOC which interfere the environment. While incineration has many benefits for treating solid waste, it also generates dioxin and furan (especially when is working with plastic-based material), CO2 and N2O. If the incineration is not controlled properly, the emission and byproduct (fly and bottom ash / slag) may harmful for the environment. Table 2 Comparison of SMFCs with other conventional solid waste treatment Typically, energy generated from MFCs treating food and organic waste (in the form of liquid fraction / hydrolysate) is around 0.28 – 0.78 MJ/kg COD (Xin et al., 2018; Xiao and He, 2014). The total energy can be higher until reached 2.48 MJ/kg COD when MFCs is fed by anaerobic sewage sludge and 3.52 MJ/kg COD by food waste hydrolysate (Wang et al., 2013b; Xin et al., 2019). That energy values are promising, especially when it is compared with

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
			other waste to energy (WtE) technology such as incineration which can provide energy values ranging from 3.60 MJ/kg to 4.96 MJ/kg of food waste (Carmona-Cabello et al., 2018). However, the condition will be more challenging when SMFCs is implemented to process the solid fraction of municipal waste. The electricity generation from solid phase MFCs is relatively small, amounted of 0.072 MJ/kg of food waste as reported by Moqsud et al. (2014). This is related to its mass transfer limitation which resulted to the low electricity generation of SMFCs. Therefore, those values are still in a laboratory scale which is still in doubt that the process efficiency will be much lower than a pilot or even industrial scale. This limitation might be solved by integrating other waste processing technologies. Xin et al. (2018) showed that the amount of electric power generated by MFCs is greater than by anaerobic digester (AD). This finding can be attributed to the fact that the AD process requires a longer residence time than the MFCs technology, thereby affecting the size of the reactor used. The MFCs reactor can be 5.5 times smaller than the AD reactor. The MFCs application is considered to be more practical, more environmentally friendly, and more economically feasible in terms of electricity

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
			conversion and production costs than AD. The MFCs is expected to become a solution for processing food waste that ensures the rapid recovery of resources and electricity sources by not producing any other waste. Strengthening Xin et al. (2018) proposed scheme, Antonopoulou et al. (2019) also proposed a food waste management system, using an integrated biochemical process. Food waste is grinded and heated (as waste pre-processing system) then carbonaceous COD is extracted to produce two fractions of product, liquid and solid fraction. The liquid fraction is processed using MFCs continuously and the solid fraction is processed using anaerobic digester. This scheme is considered to be applied in pilot scale because it produces more energy recovery value of 12.32 MJ/kg of total solids (TS), or almost comparable to the maximum net calorific value using various types of combustion, amounting to 18.09 - 18.38 MJ/kg TS. The total energy produced from MFCs and anaerobic digester are still positive, especially to cover the pre-processing energy needs of 8 MJ/kg TS (Antonopoulou et al., 2019; Wang et al., 2013b; Xin et al., 2018). This energy balance can still be reduced if it uses cheap and energy-friendly drying technology such as bio-drying or low-cost decanters to reduce the excessive amount of water content in the food waste (Velis et al.,

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			2009). In case of integration with aerobic composting, the leachate can be processed using MFCs for further substrate conversion. The generated energy could be used as self-supporting system for aerating the compost pile. In other hand, MFCs itself can be directly treat the organic fraction of solid waste without the help of anaerobic and aerobic composting. However, this option is not feasible since the energy generated is lower and need further investigation to enhance the productivity of electricity. Figure 3 shows the proposed mechanism for integrating other solid waste treatment with SMFCs. Figure 3. SMFCs and other solid waste treatment achieving sustainable energy production adapted from Antonopoulou et al. (2019) and Xin et al. (2018)
13	The conclusion is too short, the authors do not draw the sum up of the article, please revise it.	We add some sentences in the conclusion	SMFCs are an alternative technology of generating electricity that is environmentally friendly and sustainable. Various studies have been conducted to determine the optimum configuration of the MFC reactor and its development potential to generate electrical energy. The various factors that affect the performance of SMFC reactors, such as substrates, electrodes, microorganisms involved, and reactor configuration, need to be further investigated. The presence of separator and electrode distance used in the SMFC reactor are important to

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
			determine since it is related to the electron and proton transfer. Mass transfer process is also important in a solid phase, ensuring the microorganism can breakdown the substrate properly. Therefore, this limitation may be further studied, and finding the best configuration system may enhanced the electricity generated by the SMFCs. Integrating this technology with other solid waste processing system could be possible and reliable, since SMFCs itself has many limitation. The proposed system is combining the preprocessing system, anaerobic digestion, composting, and also SMFCs in a sequential system. After solid waste processed by using pretreatment technology, solid waste is sending to composter, both in anaerobic or aerobic composting system. Then, the leachate, slurry or hydrolysate from the process may be treated by using SMFCs. The direct electricity can be used as alternative energy sources for other treatment needs. SMFCs also could be used as a single solid waste treatment, but the efficiency may be lower than the proposed system instead and not feasible for field application.
	Reviewer #3		
14	The authors reviewed some progress in solid phase microbial fuel cells. However, the contents of the review are not very	Thank you for your comment, we add some discussion in the mass transfer limitation and also the	The increasing of municipal solid waste generation is an issue faced by almost all countries in the world, due to an increase in industrial activity and global development. In developing

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
	detailed and lack of effective introduction and discussion.	possible integration with anaerobic digestion	countries, almost 90% of municipal waste is transported to landfills directly without any intermediate treatment that can reduce the volume of solid waste (Barik and Paul, 2017). This waste management activity even contributes to greenhouse gas emissions by 5% compared to total world greenhouse gas emissions. Recycling, effective waste treatment and source-segregation are the main strategies in reducing emissions and environmental impacts due to increased waste generation (Florio et al., 2019). Waste is considered to still have a large enough energy content, so waste to energy is one of the alternatives that is considered (Chiu et al., 2016). Composting and anaerobic digestion are alternative biological treatment technologies that have been used and explored massively in various countries (Yu et al., 2015; Xin et al., 2018). However, conventional composting under aerobic condition requires more energy for mixing and air supply and may produce a huge amount of leachate (Chu et al., 2019). Anaerobic composting which commonly stated as anaerobic digestion can be an alternative solution for converting solid waste into reusable energy and biofuel (Khudzari et al., 2016). Many recent works revealed that anaerobic digestion has many constraints such as long residence time, relatively low purification of biomethane and its

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
			conversion to electricity, and many safety issues which make this technology cannot be a perfect solution for zero discharge treatment (Xin et al., 2018). Recently, microbial fuel cells (MFCs) is found as an alternative treatment for generating electricity from waste (waste valorization) without intermediate treatment as anaerobic digestion does by utilizing electrogenic (anodophilic) microorganisms (Xin et al., 2018). Bioelectric energy of MFCs is depending on the electron transfer process and biodegradation efficiency of solid waste (Song et al., 2015). Many researchers use the terms of solid phase MFCs (SMFCs / SPMFCs) (Logrono et al., 2015; Wang et al., 2015; Mohan et al., 2011) and a few of them use the terms of compost MFCs (cMFCs) (Khudzari et al., 2016) and biogas slurry MFCs (BSMFCs) (Wang et al., 2019) to name MFCs which converting solid waste into electricity.
15	P8, "Fundamental Process of Solid Phase MFC", solid waste was used as substrate in SMFC, it was different of the traditional MFC with wastewater, the author should indicate the type of solid waste, sludge? soil? Why didn't the author contain sediment microbial fuel cell, which belongs to	We make a boundary to make the review more acceptable: the fundamental process of MFCs treated waste which is processed in solid (moisture content below 80%) and slurry phase. Sludge and soil contamination are not	-

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
	solid phase MFC.	studied deeply in this paper and the term would be "remediation" if we also discussed about that.	
16	P11, "Materials that are widely used are graphite fiber brush, carbon cloth, graphite rod, carbon paper", references should be cited.	Thank you for your comment, we already add the citation for it.	Materials that are widely used are graphite carbon in different shapes, including: fiber brush, cloth, rod, paper, and felt because they have a high conductivity and a large surface area (Cercado-Quezada et al., 2010; Ghasemi et al., 2013; Li et al., 2019; Sharma and Li, 2010; Xin et al., 2019).
17	P11, "Radical oxygen produced in the anode chamber (equation (2))", But the authors give in equation 2 is hydrogen. What's more, this reaction does not occur in the anode, where the organic matter is oxidized to produce protons and electrons.	Thank you for your comment, we remove the equation because it is not relevant and not validated by the authors.	-
18	P12, "The absence of separator or PEM in SMFCs can cause pH splitting, namely an increase in pH in the cathode chamber and an extreme decrease in pH in the anode chamber." This phenomenon should be more serious in the presence of separator or PEM, not in the absence of a membrane.	Yes, we agreed with your suggestion. As we can find it in many recent literatures.	The presence of a separator or PEM in SMFCs can cause pH splitting, that is, an increase in pH in the cathode chamber and a decrease in pH in the anode chamber (Rahimnejad et al., 2015)

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19	P12, "which have a distance between electrodes of 5 cm", the distance was 5cm, why?	Because the authors in that research think that the electrode should be located in the middle of the reactor, and they compared the configuration efficiency with sandwhiched-electrode and PEM However, we removed the sentences and changed it to make a clear explanation about the distance of electrode. The paragraph is moved to section 3.2.	The distance between the electrodes in a single-chamber SMFCs can also affect the amount of electrical energy generated (Miran et al., 2016; Oh et al., 2010; Mohan et al., 2010). Sandwiched electrodes producing the lowest electrical power output compared to a system which have a distance between the electrodes. The shorter the distance of electrodes (assuming the electrode is located in the middle of the reactor) could produce greater electricity because of the active surface area ensures a high electrical gradient since protons can move to the cathode easily (Mohan and Chandrasekhar, 2011). Therefore, the distance of electrodes can significantly reduce the electricity since the protons need to move further to the cathode. This condition means that determining the optimal distance is essential when working with single chamber SMFCs. Even though the distance between the electrodes must be kept small, sandwiched electrodes and PEM can increase the likelihood of substrate transfer from the anode to the cathode and oxygen transfer from the air to the cathode (Hassan et al., 2014; Palanisamy et al., 2019; Peighambardoust et al., 2010).
20	P12, Table 1,maximum power density was based on the projected area? Or specific surface area of electrode? It should be compared under the same	Because each research has different characteristic and treatment, we added the explanation in each treatment	All of changes are stated in Table 1

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
	calculation method.		
21	P19, "Substrates or materials used as organic sources for SMFCs can use various types of waste that contain high cellulose". Some waste, such as soil and sludge, didnot contains high cellulose, and waste should contain high organic matter.	As per reviewer suggestion, we replace the words 'cellulose' to 'organic matter'	Substrates or materials used as organic sources for SMFCs can use various types of wastes that contain high organic matter
22	P20, equation 2, How to derive? And it should become equation 3	As you may see in the paper entitled "Determination of The Specific Energy of Mixed Waste Decomposition in Compost Solid Phase Microbial Fuel Cells (CSMFCs)" The authors were deriving the equation by their experiments. In this case, we think that the equation cannot be applied in other case, so we decide to remove the equation	This equation has been removed.
23	P27, "Rice plants are used because of their abundance at the location of the study", references should be cited.	As per other reviewer suggestion, the plant-MFCs part has been removed.	This sentence has been removed.
24	The biggest limitation in SMFC is the slow substrate mass transfer rate. The author's review	As per reviewer suggestion, we make additional discussion in the "3.1. Substrate"	The biggest limitation of microbial process in solid phase ecosystem is substrate / mass transfer rate (Rahimnejad et al., 2011). Transfer

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
	does not well discuss this aspect in this paper.	subsection	resistance would be higher since the absence of sufficient solution that transfer the substrate to microorganism and also the electrons to electrode. Reducing electrode distance may increase the rate of electron transfer, but some other problems occur such as the increasing of oxygen penetration and active surface electrode which lead to the decreasing power output (Sharma and Li, 2010). Water content is the other critical point to note when working with SMFCs. Ideally, 60% of distributed moisture will make the process occur in a good condition (Wang et al., 2015). As many SMFCs reactor working in gravitational direction of electrodes, anode chamber will be flooded and exceeded 60% of moisture content very soon after the process is working. Therefore, cathode chamber will dry and decrease the proton transfer rate which make a lower power production. In this case, drainage and circulation system may be useful for maintaining the power production (Wang et al., 2017; Samudro et al., 2018). Li et al. (2019) tried to solve this problem by using biochar amendment in soil which has limited water content. Biochar could increase electron transfer rate and kinetics because of the presence of electroactive surface. The addition of biochar also can support microbial colonization and increase the rate of biodegradation process. Therefore, knowing the optimization of biochar

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			mass that will be used is important since biochar may decrease the electrical conductivity because of its ability to adsorb ions in soils.

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Abstract

This review article discusses the use of solid waste processed in solid phase microbial fuel cells (SMFCs) as electrical energy source. MFCs are usually operated in the liquid phase because of the ease of the ion transfer process in liquid media. Nevertheless, some researchers say that the potential for MFCs in the solid phase (particularly for treating solid waste) is also quite promising if several important factors, such as the type and amount of substrate, microorganism community, system configuration, type and number of electrodes, are optimized, thereby increasing the amount of electricity generated. The critical factors affecting SMFCs performance is the efficiency of electron and proton transfer through solid media. However, this limitation may be overcome by electrode system enhancement and regular substrate mixing. In the other hand, the integration of SMFCs with other conventional solid waste treatment could produce sustainable green energy. Although SMFCs produce relatively small energy than other waste to energy treatment (around 6 to 18 times to achieve the same energy output as combustion process), SMFCs is still quite promising to achieve zero emission treatment. Therefore, this article is expected to address the challenges and also fill the gaps in SMFCs research and development.This review article discusses the use of solid waste processed in microbial fuel cells (MFCs) as a source of electrical energy by using microbial fuel cells. Microbial fuel cells, MFCs are usually used in the liquid phase because of the ease of the ion transfer process in the liquid media. Nevertheless, some researchers say that the potential for microbial fuel cellsMFCs in the solid phase (especiallyparticularly for treating solid waste) is also quite promising by optimizingif several important factors, such as the type and amount of substrate, microorganism community, reactor configuration, distance, type and number of electrodes, and the use of plants as activators of several types of microorganisms, are optimized, thereby increasing the amount of

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electricity produced. Reviews are takengenerated. Articles are searched and extracted from various online databases withusing the keywords "“solid + phase + microbial + fuel + cells + compost + waste + soil".” Then, the interrelationships between papersarticles are analyzed to understand the fundamental processes that work on solid _phase microbial fuel cells (SMFCSMFCs) and discoverdetermine the main factors that affect the performance of solid phase microbial fuel cells (SMFCs).SMFCSMFCs. The trend of utilization and research on microbial fuel cells istrends of MFCs have been increasing from time to time.in recent years. This article is expected to answeraddress the challenges in developing solid phase microbial fuel cellsSMFCSMFCs in the future.

Keywords: anaerobic digestion, compost, microbial fuel cells, remediation, solid phase, compost, remediation

1. Introduction

The increasing of municipal solid waste generation is an issue faced by almost all countries in the world, due to an increase in industrial activity and global development. In developing countries, almost 90% of municipal waste is transported to landfills directly without any intermediate treatment that can reduce the volume of solid waste (Barik and Paul, 2017). This waste management activity even contributes to greenhouse gas emissions by 5% compared to total world greenhouse gas emissions. Recycling, effective waste treatment and source-segregation are the main strategies in reducing emissions and environmental impacts due to increased waste generation (Florio et al., 2019). Waste is considered to still have a large enough energy content, so waste to energy is one of the alternatives that is considered (Chiu et al., 2016).

Composting and anaerobic digestion are biological treatment technologies that have been used and explored massively in various countries (Yu et al., 2015; Xin et al., 2018). However, conventional composting under aerobic condition requires more energy for mixing and air supply and may produce a huge amount of leachate (Chu et al., 2019). Anaerobic composting which is commonly known as anaerobic digestion can be an alternative solution for converting solid waste into reusable energy and biofuel (Khudzari et al., 2016). Many recent works revealed that anaerobic digestion has many constraints such as long residence time, relatively low purification of biomethane and its conversion to electricity, and many safety issues which make this technology cannot be a perfect solution for zero discharge treatment (Xin et al., 2018).

Recently, microbial fuel cells (MFCs) are is found as an alternative treatment to producefor generating electrical energyelectricity –from waste (waste valorization) without intermediate treatment as anaerobic digestion does by utilizing electrogenic (anodophilic) microorganisms (Xin et al., 2018);. Bioelectric energy of MFCs is depending on the electron transfer process and biodegradation efficiency of solid waste (Song et al., 2015). Many researchers use the terms of solid phase MFCs (SMFCs / SPMFCs) (Logrono et al., 2015; Wang et al., 2015; Mohan et al., 2011) and a few of them use the terms of compost MFCs (cMFCs) (Khudzari et al., 2016) and biogas slurry MFCs (BSMFCs) (Wang et al., 2019a) to name MFCs which converting solid waste into electricity. Solid--phase MFCsmicrobial fuel cells (SMFCSMFCs) are one of the MFCs technology developments in MFCs technology that are can be applied to solid waste and are claimed to be able to accelerate the process of anaerobic waste degradation while at the same time be used to, harvest electrical energy directly, and produce mature compost from the process of overhauling organic compounds (Choudhury et al., 2017; Moqsud et al., 2013; Moqsud et al.,

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2015; Pandey et al., 2016; Santoro et al., 2017). SMFCSMFCs is quite profitable because it only requires low-cost materials (Du et al., 2007; He et al., 2017). Besides that, the abilityMoreover, its capability to producegenerate electricity directly makes thisit an alternative renewable energy source one of the topics that get a lot of, attracting considerable attention to be studied and researchedfrom researchers (Do et al., 2018; Escapa et al., 2016; Xia et al., 2018). In addition, solid waste which is used as substrate also makes SMFCSMFCs are to be an alternative to overcomemethod for overcoming the problem of solid waste treatment that is ablebecause it uses solid waste as a substrate to provide a certainty of an environmentally friendly and sustainable source of electricity (Gude, 2016; Yasri et al., 2019). This makesThus, SMFCs are considered to be capable of addressing multi-sectoral problems since it can be integrated with other processing waste treatment such as aerobic composting and or anaerobic digestion (Kadier et al., 2016; Logan, 2009; Trapero et al., 2017; Utomo et al., 2017).

Various studies were conducted to optimize the SMFCSMFC technology of SMFCs. In 2014, Moqsud et al. (2013) conducted research on bioelectricity generation using kitchen waste and bamboo wastes. In this research, the configuration system used is a single chamber MFC with carbon fiber as the electrodes. The maximum power output produced is 60 mW/m^2 for kitchen waste and 40 mW/m^2 for bamboo waste. Whereas withBy contrast, using the same configuration system, Wang et al. (2013a) able to produceobtained a higher maximum power output. In theiir study, the substrate used is different from that used in the research of Moqsud et al. (2013). AdequateWith an adequate supply of glucose, complex substrates rich in monosaccharides, organic acids, and other micromolecules can be directly utilized as MFC substrates so that bacteria become more active and producegenerate higher stresses (Pant et al., 2010; Wang et al., 2019a). In addition, by knowing thewith a constant C/N ratio, nutrients (carbon, nitrogen, phosphorus, and potassium content), water content, and bio-enzyme addition are also considered able tocan increase the electrical power output inof SMFCSMFCs (Ganjar et al., 2018; Wang et al., 2015; Wang et al., 2013b). The different substrates used in their study produced different power outputs even though they used the same reactor configuration. In addition to the substrate, the electrode material can also affect the harvestinggeneration of SMFCs electrical energy by SMFCSMFCs. Electrodes whichthat are in direct contact with biomass and higherhave a large surface area of electrodes are able to produce highergenerate a large amount of electrical energy as well (Nastro et al., 2017). Microorganisms that play a role in decomposing organic matter on the substrate are also important factors in the harvestinggeneration of electrical energy. Diverse bacterial cultures in SMFCSMFCs are considered capable of increasing the electrical energy harvestedgenerated by enriching the substrate and ecsxoelectrogenic activity. The diversity of the genus of microorganisms contained in SMFCSMFCs influences reactorthe performance of the reactor because of the different roles of each microorganism in degrading the substrate (Lu et al., 2019; Reiche and Kirkwood, 2012; Wang et al., 2015; Wang et al., 2019b; Zhi et al., 2014).

TheResearchers have focused considerable attention of researchers on microbial fuel cells the development is very large of MFCs. Over the past 5five years alone (2016—-2020 as article in press), 2,499 review articles were found, 1,193 book chapters, and 1,513 research articles on sciencedirect.com relating to the utilization of microbial fuel cellsMFCs in various treatments. were found on sciencedirect.com (beyond . This amountnumber has not been added from information to that obtained from Google Scholar, Scopus, and other Sscholarly databases). Nevertheless, it is quite difficult to findfinding articles that discuss the solid phaseuse of SMFCSMFCs for handling comprehensive solid waste management is quite difficult.

Rahimnejad et al. (2015) explains explained in detail the application of MFCs in detail aboutto processes at anodes— cathodes, proton transfer processes through cation exchange membranes, anion exchange membranes, or bipolar membranes and applications of MFCs for, the production of biohydrogen, bioelectric, bioelectricity, and biosensors, and wastewater treatment, and biosensors. Information about advanced developments, in the use and manufacturing process of electrodes and MFCs membranes has also been updated by Palanisamy et al. (2019). Meanwhile, information about the development of this technology as a whole has also been discussed by Zhang et al. (2016) and Khudzari et al. (2016). Both of them use theThey used bibliometric study methodmethods to measure the extent of global research trends, research, and developments regarding MFCs using the sScopus database, and wWeb of sSciences database, or specifically in several journals, which are the main platforms that of report the progress of MFCs researchprogress report. Technology that is quite close to the basics of the process with solid phase MFCsbasic processes involved in the SMFCSMFC technology, namely, plant MFCsmicrobial fuel cells (PMFCs)), has also been discussed in depth by Kabutey et al. (2019). In his explanation, he mentionedThey explained that PMFCs can be used asfor waste treatment, remediation of polluted sediments and surface water, and biosensing (Kabutey et al., 2019; Kumar et al., 2018; Kumar et al., 2019). Goglio et al. (2019) discussed microbial recycling cells (MRCs) where the focus isand focused on the potential fabrication of recycleable materials that can be used as bio electrodesbioelectrodes, separators, and reactor structures. These materials can be used as soil conditioners or mineral-rich organic fertilizers. However, as far asto the author understandsauthors' understanding, there has not been a single article that summarizes, discusses, and provides a detailed description of the development of solid phase MFCsSMFCSMFCs for treating solid waste.

The factors that influence the optimization of the performance of the ~~SMFC~~SMFCs reactor ~~performance as~~ mentioned previously need to be further ~~known~~investigated through various ~~studies and~~ in-depth and comprehensive ~~research~~studies. This review article was written ~~in order~~ to understand and ~~study~~analyze the technological basics of ~~SMFC~~SMFC and the factors that influence it, ~~, such as reactor configuration, type and amount of substrate, electrode material used, microorganisms that play a role in decomposing organic matter on the substrate,~~ as well as ~~the~~ potential ~~and~~ obstacles that may be encountered in the future~~, came~~ in its development toward~~towards~~ ~~the~~industrial commercialization~~ and industrialization process.~~. Through this article, we can ~~find out~~collate the results of recent studies that have been ~~carried out~~conducted to optimize the performance of ~~SMFC~~SMFCs and its possible integration and comparation with other technologies~~,~~ as well as the various ~~advantages and~~ improvements needed to ~~improve~~enhance the results of ~~harvesting~~generating electricity ~~through~~using ~~SMFC~~SMFCs.

~~1.~~2. Fundamental Process of ~~Solid Phase MFC~~~~SMFC~~SMFC

~~SMFC~~SMFCs ~~are~~ is a technology~~ies~~ used to ~~produce~~generate environmentally friendly ~~energy~~ electricity from biomass ~~using~~by utilizing microorganisms (Garita-Meza et al., 2018; Mäkinen et al., 2013; Pushkar et al., 2016). ~~SMFC~~SMFCs ~~utilize~~employ the bioelectrogenesis capability of microorganisms to utilize organic compounds as electron acceptors where energy is ~~formed~~generated in the process. This system ~~aims to be able to harvest~~harvests the energy ~~produced~~generated by these microorganisms directly without the need ~~to burn~~for combustion (Calignano et al., 2015; Minutillo et al., 2018; Nastro et al., 2017). Generally, SMFCs configuration systems consist of two chambers: ~~, namely, the~~ cathode and anode ~~spaces~~ chamber,

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which separated by specific membranes. ~~Microorganisms produce electrons and protons when decomposing material in an anaerobic anode.~~ The cathode is a ~~space~~ chamber which is full of oxygen, where protons will move toward the cathode chamber to form water molecules (Logroño et al., 2016a; Moqsud et al., 2013). The two electrode chambers are separated by a membrane as a mediator capable of moving protons from the anode to the cathode, ~~flowing~~transferring electrons between the ~~2~~two electrodes, and inhibiting the entry of oxygen into the anode. However, there are also SMFCs that do not use membranes and rely on the distance ~~from~~between the two electrodes (Logroño et al., 2016a; Logroño et al., 2016b; Mohan and Chandrasekhar, 2011). ~~The following are~~Figure 1 generally ~~illustrations of~~illustrates the processes that occur in the ~~solid phase MFC.SMFC~~SMFCs.

Figure 1. Modified ~~Illustration~~ illustration of ~~Solid phase MFC~~the ~~SMFC~~SMFCs process (Adapted from Nastro et al., 2017 and Logroño et al., 2015)

Chemical energy present in the ~~substrate~~ organic waste will be oxidized by microorganisms in the anode chamber. Microorganisms extract the energy needed to build biomass through ~~the~~ metabolism process ~~of anabolism~~ (Palanisamy et al., 2019). The effectiveness of SMFCs reactors is influenced by several factors, such as oxygen supply and consumption in the cathode chamber, oxidation of the substrate in the anode ~~space~~chamber, electron transfer from the anode ~~space~~ chamber to the anode surface, and ~~PEM~~proton exchange membrane (PEM) permeability (Rahimnejad et al., 2015; Sharma and Li, 2010). In other cases, circuit connection is also important to note, since it can increase the voltage output to 344.11% times greater than a single reactor (Utomo et al., 2017).

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2.1. Process in the Anode

~~Anode~~The anode ~~space~~ chamber is an important component of SMFCs. Microorganisms that play a role in ~~breaking down the~~ substrate ~~disintegration~~degradation and electron production ~~are attached~~attach to the electrodes in the anode chamber. The process ~~that takes place~~occurs at the anode ~~is in~~under anaerobic conditions. ~~These conditions are very important to support the process of degradation process of the substrate in the anode space.~~ The presence of oxygen in the anode chamber can inhibit the generation of electricity ~~production~~ by microorganisms ~~so~~. ~~Thus, the MFC system needs to be designed so in such a manner that microorganisms in the anode chamber do not get oxygen supply.~~ In addition to the electrodes and microorganisms, there are also substrates and mediators in the anode chamber. The general reactions that occur at the anode are expressed ~~as~~ in ~~follows~~Equation (1~~:~~).

$$Biodegradable\ orgar \xrightarrow[\text{~~Anaerobic environment~~ nent}]{\text{~~Active microorganism~~ sm}} CO_2 + H^+ + e^- \quad (1)$$

~~$H_2 \rightarrow 2H^+ + 2e^-$ (2)~~

The microorganisms present in the anode act as catalysts capable of breaking the substrate into simpler ~~chains~~molecules. This active biocatalyst is able to oxidize the substrate and produce electrons and protons. The resulting protons are forwarded to the cathode via the PEM ~~while~~,

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whereas the electrons are forwarded to the external path (Antonopoulou et al., 2010; Du et al., 2007; Ghasemi et al., 2013; Rahimnejad et al., 2015; Rahimnejad et al., 2011).

Figure 2. Working mechanism Electron transport mechanism in of electrode and separator in MFCsthe SMFCs anode

(Adapted from Mohan et al., 2014)

Modification of the material used as an anode is able to influenceinfluences the performance of the SMFCSMFCs reactor. Based on previousPrevious studies, showed that the use of different electrode materials at the anode will producegenerates different amounts of electrical energy so that; thus, it can affect the overall performance of the SMFCSMFCs reactor. Materials that are widely used are graphite graphite carbon in different shapes, including: fiber brush, carbon cloth, graphite rod, carbon paper, and carbon felt because they have a high conductivity and a large surface area (Cercado-Quezada et al., 2010; Ghasemi et al., 2013; Li et al., 2019; Sharma and Li, 2010; Xin et al., 2019)Materials that are widely used are graphite fiber brush, carbon cloth, graphite rod, carbon paper because they have a high conductivity and a large surface area.

2.2. Process in the Cathode

The cathode and anode chambers in the MFC work continuously to producegenerate electrical energy that can be utilized. Protons move from the anode chamber will move to the cathode chamber through the PEM, which perfectsrefines the electric current.

$H_2 \rightarrow 2H^+ + 2e^-$ (2)

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$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ (32)

Radical oxygen produced in the anode chamber (eEquation (2) will move)) moves to the cathode chamber and forms water that spreads aton the cathode with the help of a catalyst. Equilibrium flow can be generated reached based on the two equations abovebasis of Eequations (2) and (3) by connecting the cathode and the anode with external cable connections. affect theThe performance of MFCs on the cathode is different from that on the anode. The concentration and type of electron receiver, the availability of protons, the performance of the catalyst, the electrode structure, and the abilitycapability of the catalyst affect the performance of the cathode. The availability, strong oxidation potential, and does not produce toxicnontoxic end products makeof oxygen widely used asmake it a suitable electron acceptors finally inacceptor for the cathode chamber Ssome cathodes are configured by placing one side of the cathode in direct contact with the cathode chamber and the other side in direct contact with free air.

2.3. Electrode PEM/distance between anode & cathode

2.3. PEM/Distance Between Anode and CathodeSeparator

In general, SMFCSMFCs consist of anode and cathode spaces chamber separated by proton exchange membranes ortheproton exchange membrane (PEM) protons. Biopotential that occurs due to the metabolic activity of microorganisms and the condition of electron acceptors can encourageinduce the productiongeneration of bioelectricity in SMFCSMFCs. The PEM or other separator in SMFCSMFCs, which acts as a separator in addition to physically separatinges the cathode space and the anode spaceschamber, also acts to preventprevents the transfer of

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dissolved oxygen contained in the cathode chamber to the anode chamber so that the anaerobic conditions in the anode space chamber can be maintained. SeparatorsThe separators or PEM can facilitate the transfer of protons produced in the anode chamber without the transfer of substrate and oxygen to the cathode chamber. WhatThe following may occur when the PEM is not used in SMFCSMFCs, namely: the displacement of oxygen and substrate can result in columbicdecreased coulombic efficiency (CE) and decreased microorganism activity, which in turn has an impacteffect on reactorthe performance of the reactor and stability of the system instability. The absence of a separator or PEM in SMFCSMFCs can cause pH splitting, namelythat is, an increase in pH in the cathode chamber and an extremea decrease in pH in the anode chamber. So thatThus, various researchesstudies are carried outconducted to find outdetermine the type of separator that supports the optimization of the SMFCSMFC reactor so that the electrical energy harvestedgenerated can reach the optimum figuresamount (Li et al., 2018; Mohan and Chandrasekhar, 2011; Wang et al., 2015).

The distance between the electrodes in the SMFCSMFC reactor can also affect the amount of electrical energy produced fromgenerated by the entire SMFCSMFC reactorOh et al., 2010; Mohan et al., 2010. Electrodes coincide with the PEM betweenin producing the lowest electrical power output compared towith other reactors, which have a distance of 5 cm between the electrodes of 5 cm even without using the PEM (Miran et al., 2016; Mohan and Chandrasekhar, 2011; Oh et al., 2010; Mohan et al., 2010). Even though the distance between the electrodes must be kept small, coincident electrodes can increase the likelihood of substrate transfer from the anode to the cathode and oxygen transfer from the cathode to the anode (Hassan et al., 2014; Palanisamy et al., 2019; Peighambardoust et al., 2010).

If this happens,occurs, then the stability of the reactor will be disrupted and result in harvestingthe generation of a suboptimal amount of electricity that is not optimum.

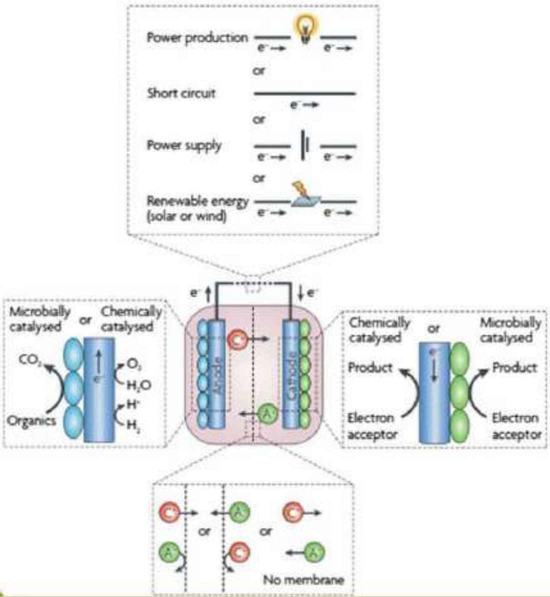

Figure 3. Electrode and PEM workWorking mechanism of the electrode and PEM in MFCs

One of the challenges faced in SMFCusing SMFCSMFCs is related to the application of the PEM and the distance between the electrodes. The existenceapplication of the PEM, as well as the distance between the electrodes, plays a veryan important role in the generation of electrical energy generated fromby SMFCSMFCs. ButHowever, it is also known that the application of the PEM is one of the factors that influences the value of internal barriers that areis quite large.

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SoThus, various studies have been carried outconducted to make different reactor configurations to suppress the MFC internal resistance values, for example, single-chamber MFCs, up-flowupflow MFCs, and stacked MFCs (Rahimnejad et al., 2015; Rahimnejad et al., 2012; Rahimnejad et al., 2011).

3. Factors Affecting SMFCsthe Performance of SMFCSMFCs

Electricity generated from solid MFCsby SMFCSMFCs is influenced by various factors, such as electrode material and the type of membrane used, salinity and alkalinity, type of waste, and composting factors, such as pH, and C/N ratio. Based on On the basis of the research conducted by Moqsud et al. (2013),) stated that SMFCs with a good performance has a low internal resistance and a high electromotive force. Table 1 shows some of the optimizations that have been made to increase the amount of electricity production using solid phase - MFCsgenerated by SMFCSMFCs.

Table 1 Recent studies related to improvement of MFCs performances treating solid wastesTable 1 Recent Studies Related to Enhance Solid Phase MFCs Performancesthe Improvement of the Performance of SMFCSMFCs

3.1 Substrate

Substrates or materials used as organic sources for SMFCSMFCs can use various types of wastes that contain high organic matter, such as Types of kitchen waste and bamboo wastes used as SMFCSMFCs show a different trend. The voltage generated by kitchen waste rapidly increases in the initial phase ~~increases rapidly then~~ and gradually ~~is~~becomes constant at the voltage of 620 mV. Conversely, in bamboo waste, the voltage generated gradually increases to 540 mV. This finding is expected because ~~there are~~some fruits ~~containing~~in kitchen waste contain large amounts of glucose~~ in kitchen waste.~~. An adequate supply of glucose ~~makes~~activates bacteria ~~become active~~ and produces a higher voltage~~. The use of waste or solid waste is considered to be able to overcome the problem of solid waste management~~ (Moqsud et al., 2014). ~~The material used in the research of~~ Utomo et al. (2017) ~~i~~used~~s~~ sludge originating from a communal waste treatment plant that has a different age. ~~It was~~They observed that the stress generated at the anode with fresh sludge material has a higher value than ~~the~~that with stored sludge material.

~~A study conducted by~~ Xin et al. (2019) ~~to find out~~determine the effect of the ~~compound~~ complex compound (glucose, sodium acetate, and food waste hydrolysate) used in MFC on the production of electrical energy~~ so that three different substrates were used, namely, glucose, sodium acetate, and food waste hydrolyzsate~~. The ~~electricity~~ electrical density produced by the MFC reactor with a food waste hydroly~~z~~sate substrate ~~sho~~was higher ~~results compared to~~than that with glucose and sodium acetate. Wang et al. (2013a) obtained a higher power output using different substrates. With an adequate supply of glucose, complex substrates rich in monosaccharides, organic acids, and other micro-molecules can be directly utilized as SMFCs substrates so that bacteria become more active and generate higher stresses (Pant et al., 2010; Wang et al., 2019a). Similar results were obtained by Jia et al. (2013) and Li et al. (2018)~~which states~~, that is, ~~SMFC~~SMFCs can produce ~~greater~~a larger amount of energy with substrates in the form of mixed carbon rather ~~compared to~~than single type of ~~mixed~~ carbon.

In different studies, biogas slurry is used as a substrate for MFC (BS-MFC). Biogas slurry as waste from biogas technology that has been widely applied is considered to cause new problems. Biogas slurry is rich in monosaccharides, organic acids, and other micro-molecules that can be directly utilized as MFC substrates (Pant et al., 2010; Wang et al., 2019a). ~~The results of electrical measurements pre~~conducted ~~in the study of~~ Wang et al. (2019a) ~~showed~~ found that microbial acclimation was achieved on the 10th day at 150.4 ± 14.6 mV. The second cycle, which was ~~carried out~~conducted with the addition of substrates, showed a voltage of 622.7 ± 30.3 mV on the 2~~1~~0th day, indicating that biofilms ~~had~~were formed at the anode. The accumulation of electrical voltage in these ~~3~~three cycles ~~results in a~~reaches its maximum value and is stable for a sufficiently long period of time. However, the BS-MFC hydrolysis reaction and the long operational period lead to a high~~er~~ level of energy demand and a low~~er~~ average ~~coulumbic efficiency (~~CE~~)~~ production of 4.1% (Wang et al., 2019a).

In addition to the type of waste or organic solid waste used, the degree of alkalinity (Moqsud et al., 2013) and the amount of waste used as ~~a~~ substrate also determine the amount of electrical energy that can be ~~harvested~~generated (Samudro et al., 2018). Large amounts of waste can provide substrates and nutrients for microorganisms that will increase specific energy. ~~Based o~~The addition of alkaline materials can also increase the electrical power ~~produced by~~output of ~~SMFC~~SMFCs. The addition of fly ash, for example, ~~to the compost - MFC (CMFCs)~~ produced a maximum electric power per cathode surface area of 54.4 mW/m^2. This value is two times greater than that of ~~solid MFC~~~~SMFC~~SMFCs without added fly ash (Moqsud et al., 2013). In different studies, rice husk, soybean residue, coffee residue, and leaves were used as substrate. The choice of substrate is based on the nature of each substrate that is rich in cellulose and

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biopolymers and is an ideal source of organic matter and the abundance of substrates. Rice husk can increase hydraulic conductivity and porosity on SMFCs reactors. Therefore, substrate composition can affect the community of microorganisms that grow at the anode, as well as the output of electrical energy (Wang et al., 2015).

Another composting factor that is considered to affect reactorthe performance of the reactor is the water content in the solid MFCSMFCSMFCs material used. The power density produced fromby the solid MFCSMFCSMFCs reactor is measured to be higher in the substrate, which has a higher water content as well. The maximum measured power density is 17.74 mW/m^2 with a water content of 60%, with 4four times the stirring mixing frequency, and a C/N ratio of 30:1. In theThe same study, it was found showed that the range of water content that allows the reactor to operate at its optimum is 40-% to 60%. In anotherAnother study, it was stated showed that the ideal water content conditions for SMFCSMFC werewas 60%; meanwhile, at 40%a water content of 40%, the fermentation process and microorganism activity were inhibited (Wang et al., 2013a; Wang et al., 2017). Before the research iswas conducted, it is important to know in advance the macro- and microCNPK nutrient content, C/N ratio, and water content to be able were determined in advance to ensure that the process of harvestinggenerating electrical energy and making compost runnings optimally (Ganjar et al., 2018; Wang et al., 2015). The C/N ratio of substrate which is close to 31:-1, water content of 60%%, and pH aroundof 6-–8 are known to haveensure optimum performance. This indicates, indicating that SMFCSMFCs can be integrated into compost processing. Additionthe composting process. The addition of bio-enzymes to the substrate increases the power density by up to 8.5 times and can reducedecrease the internal resistance by 31% (Wang et al., 2015; Wang et al., 2013b). SMFCSMFCs that use solid waste tend to have high levels of chemical oxygen demand (COD). In athe study conducted by Samudro et al. (2018), it was foundthey determined that the leavesleaf waste, which had a COD content of 16.567 mg COD/lL, had a higher COD removal efficiency of up to 87.67% and a more stable power density atof 4.71 mW/m^2 compared towith canteen and mixed wastes. However, in this study, it is known that high levels of COD do not mean they havelead to a high COD removal efficiency and a high power density outputs as well. Optimumoutput. The optimum COD levels can produce greaterlead to high power densities.

Water content in compost is also one of the factors that influence the performance of microorganisms to degradein degrading organic compounds. In this study, Xanthan 80 Smoother fFlow (SF) and drainage design engineering inof the SMFCSMFC reactor were used (Wang et al., 2017). Xanthan 80 SF is a microbial polymer producedobtained from the fermentation process. Xanthan 80 SF is a thickener and stabilizer, which is very effective against the flow pseudoplastic properties. The most experiencedsignificant obstacle in the SMFCSMFC process is the effect of gravity, which causes that water collectsto accumulate at the anode and increauses the water content at the anode to be more than 60%. This condition can trigger the growth of anaerobic microorganisms and causesuppress the growth of depressed aerobic microorganisms so that the production of electrical energy decreases. In this study, this obstacle was overcome by creating a drainage system under the anode so that the water content at the anode can be maintained at 60%. The use of Xanthan 80 SF can significantly improve the performance of the SMFCSMFC reactor because the nature of the Xanthan 80 SF is able to maintain moisture in the compost and prevent the effects of gravity so that water does not accumulate at the bottom of the reactor. The use of Xanthan 80 SF in SMFCSMFC makes a significant difference. The resulting voltage is increased toby more than 3three times from day 3 to day 8 with a voltage of 138.09 mV and the greatesthighest measured power density wasof 10,157 mW/m^2. Reactors that do not use a combination of Xanthan 80 SF and drainage systems do not produce much power. This finding is expected because the moisture in the compost is reduced so that it can inhibit, which in turn inhibits the process of compost decomposition process and decreased decreases the microbial activity, thereby inhibiting ion transfer and energy production. Based on theseThese results it can also be seenindicate that the use of Xanthan 80 SF can increase the amount of electricity productiongenerated and extend the period of electrical energy release (Wang et al., 2017).

The biggest limitation of microbial process in solid phase ecosystem is substrate / mass transfer rate (Rahimnejad et al., 2011). Transfer resistance would be higher since the absence of sufficient solution homogenized the distribution of substrate to microorganism and also the electrons to electrode. Reducing electrode distance may increase the rate of electron transfer, but some other problems occur such as the increasing of oxygen penetration and active surface electrode which lead to the decreasing power output (Sharma and Li, 2010). Water content is the other critical point to note when working with SMFCs. Ideally, 60% of distributed moisture will make the process occur in a good condition (Wang et al., 2015). As many SMFCs reactor working in gravitational direction of electrodes, anode chamber will be flooded and exceeded 60% of moisture content soon after the process is working. The use of Xanthan 80 SF can significantly improve the performance of the SMFCs reactor because the nature of Xanthan 80 SF is able to maintain moisture in the compost and prevent the effects of gravity so that water does not accumulate at the bottom of the reactor. Therefore, cathode chamber will dry and decrease the proton transfer rate which make a lower power production. In this case, drainage and circulation system may be useful for maintaining the power production. This finding is expected because the moisture in the compost is reduced, which in turn inhibits the compost decomposition process and decreases the microbial activity, thereby inhibiting ion transfer and energy production. These results indicate that the use of Xanthan 80 SF can increase the amount of electricity generated and extend the period of electrical energy release (Wang et al., 2017; Samudro et al., 2018). Li et al. (2019) tried to solve the transfer rate problem by using biochar amendment in soil which has limited water content. Biochar could increase electron transfer rate and kinetics because of the presence of electroactive surface. The addition of biochar also can support microbial colonization and increase the rate of biodegradation process. Therefore, knowing the optimization of biochar mass that will be used is important since biochar may decrease the electrical conductivity because of its ability to adsorb ions in soils.

3.2 Electrode and System Configuration

In a study conducted by Moqsud et al. (2013), the use of bamboo charcoal with iron wire as an anode material produces the highest electrical voltage compared ~~to~~with carbon fiber alone and carbon fiber with iron wire. The electrical voltage generated in the reactor with bamboo charcoal electrodes with iron wire reaches 420 mV ~~while~~, whereas that in the reactor with carbon fiber with iron wire reaches ~~the second highest number which is~~ 260 mV ~~where the figure is reached~~ after 3 days of research. ~~Based on these studies it is known~~This study showed that the addition of iron wire slightly increases the electrical voltage ~~during the study. Maximum~~. The maximum power density of 394 mW/m^2 is achieved in reactors with carbon fiber electrode material. This ~~figure~~value is ~~much~~ higher ~~compared to~~than that achieved in reactors with bamboo charcoal, which only reaches ~~a power density of~~ 8 mW/m^2 (Moqsud et al., 2013). This ~~is because~~finding can be attributed to the fact that the contact of biomass with electrodes is higher in carbon fiber ~~compared to~~than that in bamboo charcoal. ~~In that study it was known that although~~Although bamboo charcoal is ~~cheaper~~inexpensive and environmentally friendly, ~~bamboo charcoal~~ it is less recommended ~~when used~~for use as ~~a~~ cathode material because its wavy shape causes lowe~~r~~ biomass contact. In addition, the ~~MFC~~ performance ~~to produce~~of MFCs in generating electrical energy will ~~increase~~be improved if the surface area of the electrodes is increased with respect to the reactor volume (Nastro et al., 2017). In ~~different studies~~another study, a double anode with graphene material is used because graphene is considered to have a ~~greater~~larger surface area ~~compared to~~than carbon graphite (Samudro et al., 2018). Meanwhile, ~~in other studies,~~ carbon felt was interesting to be used as an electrode because it ~~has porosity~~is porous and has a large~~r~~ surface area, which are suitable for microorganism growth, adhesion, and reduced impedance activation (Kim et al., 2011).

The presence of a separator or PEM in SMFCs can also cause pH splitting, that is, an increase in pH in the cathode chamber and a decrease in pH in the anode chamber (Rahimnejad et al., 2015). Thus, various studies are conducted to determine the type of separator that supports the optimization of the SMFC reactor so that the electrical energy generated can reach the optimum value (Li et al., 2018; Mohan and Chandrasekhar, 2011; Wang et al., 2015). Moqsud et al. (2013) said that the voltage generated by the SMFCs reactor with cellophane separator has the highest value compared with that by the SMFCs reactor with filter paper and PEM. Cellophane is considered to have a lower electrical resistance value than filter paper and PEM. The dry surface of PEM is considered to be the cause of its higher resistance value than cellophane and filter paper. Filter paper is considered to be more permeable than PEM and cellophane. Meanwhile, cellophane is more easily damaged; thus, its quality is low and it cannot be reused. In another study, a single-chamber reactor was used so it did not need a membrane separator or separator material (Moqsud et al., 2014). However, it is also known that the application of PEM can increase the internal resistance. Thus, various studies have been conducted to make different reactor configurations to suppress the MFC internal resistance values, for example, single-chamber MFCs, up-flow MFCs, and stacked MFCs (Rahimnejad et al., 2015; Rahimnejad et al., 2012; Rahimnejad et al., 2011).

The distance between the electrodes in a single-chamber SMFCs can also affect the amount of electrical energy generated (Miran et al., 2016; Oh et al., 2010; Mohan et al., 2010). Sandwiched electrodes producing the lowest electrical power output compared to a system which have a distance between the electrodes. The shorter the distance of electrodes (assuming the electrode is located in the middle of the reactor) could produce greater electricity because of the active surface area ensures a high electrical gradient since protons can move to the cathode easily (Mohan and Chandrasekhar, 2011). Therefore, the distance of electrodes can significantly reduce the electricity since the protons need to move further to the cathode. This condition means that determining the optimal distance is essential when working with single chamber SMFCs. Even though the distance between the electrodes must be kept small, sandwiched electrodes and PEM can increase the likelihood of substrate transfer from the anode to the cathode and oxygen transfer from the air to the cathode (Hassan et al., 2014; Palanisamy et al., 2019; Peighambardoust et al., 2010).

3.3 ~~Bacteria~~Microorganisms

Microorganisms involved during the process are also considered an important to be able tofactor that helps improve reactorthe performance. Based on of the reactor. On the basis of the research conducted by Parot et al. (2009), it is known that tThe substrate in the SMFCs is not the only factor influencing the type of dominant microorganisms that exist in the anode. The dominant microorganisms at the anode can also be influenced by the inoculum and the conditions when the reactor is operating (Parot et al., (2009). OnIn another study, Reiche and Kirkwood (2012) stated that SMFCSMFCss reactors with mixed culture biocatalysts obtained from three different types of compost produce a maximum electric power density of 12.3 mW/m^2. Mixed culturesculture biocatalysts obtained from three different types of compost were considered to be able to enrich the substrate and ecsxoelectrogenic activity. The efficiency of electron transfer that occurs in SMFCSMFCs can be influenced by the selection of biocatalysts to be used. Ion and substrate transport through solid media is an important factor that influences the performance of SMFCs. If those transport is slow, then the electrochemical reactions are reduced. Therefore, transport system in SMFCs becoming critical since water content is limited. In that case, maintaining water content in optimum condition (around 60 – 80%) is necessary (Oliot et al., 2016; Wang et al., 2017).

Similar to the research conducted by Reiche and Kirkwood (2012), Xin et al. (2019) used food waste that had been givenundergone enzymatic treatment as a substrate in SMFCSMFCs. The three substrates that are used to compare the species of microorganisms involved in the process of SMFCSMFCs at the anode, namely are glucose, sodium acetate, and hydrolyzed food waste hydrolysate. In the same operational condition, the complex carbon substrate has higher microorganism diversity compared tothan the glucose and sodium acetate substrate. Found 5

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substrates. The five main phyla identified at the anode of SMFCSMFCs namelywere *Actinobacteria*, *Bacteroidetes*, *Deinococcus*-_*Thermus*, *Firmicutes*, and *Proteobacteria*. These five phyla have different capabilities and are able to degrade organic material to producegenerate electricity through extracellular electron transport with a variety of electron donors. SMFCSMFCs with complex carbon substrate have a higherhigh microorganism diversity of microorganisms with the dominance of, with *Rummeliibacillus*, *Burkholderia*, *Enterococcus*, and *Clostridium* which all havehaving a dominant role in bioelectelktrogenesis. In the reactor with complex carbon substrate also identified the , uniformity of microorganisms betweenin the anodic community, was observed. Compliance with functional genes can increase synanthropic potential interactions and collaborations with functional species on anode biofilms, thereby increasing MFC the amount of electricity productiongenerated by MFCs (Xin et al., 2019).

Wang et al. (2019a) stated that the type of inoculum can determine the rate of substrate decomposition and affect the productiongeneration of electrical energy. Based onIn this research with biogas slurry as a substrate and domestic wastewater as an inoculum source at the anode, the dominant genus identified on the anode biofilm was the genus *Pseudomonas* by (5% on the anode biofilm.%). *Pseudomonas* can produce chemical intermediaries that can transfer electrons to electrodes. In addition there is also, *Hydrogenophaga* of (5% in%) was the dominant genus identified on biofilms derived from household wastewater. The genus consumes H_2 in the anode chamber, thereby inhibiting the productiongeneration of electricity by SMFCSMFCs with biogas slurry electricityas substrate. In addition to the analysis of the genus level, it is known that there are four genera of hydrolytic bacteria that can break down the cellulose, protein, and starch chains into organic micro-molecules, thereby increasing sugar degradation and volatile fatty acids (VFA) in SMFCSMFCs with biogas slurry as substrate. The diversity of the genus of microorganisms contained in SMFCs influences the performance of the reactor because of the different roles of each microorganism in degrading the substrate (Lu et al., 2019; Reiche and Kirkwood, 2012; Wang et al., 2015; Wang et al., 2019b; Zhi et al., 2014

The electrical energy producedgenerated by SMFCSMFCs is highly influenced by the type of feed used in the reactor. In different studies used, rice husk substrate, soybean residue, coffee residue, and leaves were used as substrate. The choice of substrate is based on the nature of each substrate that is rich in cellulose and is considered to be rich in biopolymers and is an ideal source of organic matter and the abundance of substrates at the study site. Rice husk can increase hydraulic conductivity and porosity on SMFCSMFC reactors. Feed composition can affect the community of microorganisms that grow at the anode, as well as the output of electrical energy produced (Wang et al., 2015).

3.4 System Configuration

Optimization of the MFC reactor can also be done to increase the amount of electrical energy that can be harvestedgenerated, as doneconducted in the study of Utomo et al. (2017) by modifyingwhere the anode and cathode chamber volume factors, PEM contact area, the anode and cathode distances from the PEM are modified. The optimum voltage can be measured when the pH 7 buffer solution is replaced with athe NaCl solution as the solution at the cathode reaches 758 mV. The differencevariance can also be influenced by differences the difference in conductivity between the two. The pH 7 buffer solution has a conductivity of 4.63 mS/cm while,

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whereas the NaCl solution has a conductivity of 4.39 S/cm. Ion transport through electrolytes is an important factor influencing MFCthat influences the performance of MFCs. If ion transport is slow, then it can reducethe electrochemical reactions are reduced (Oliot et al., 2016). The voltage generated atby the MFC reactor tends to be stable after reaching 500 _580 mV while the Fabricated MFCs , whereas the voltage generated by the fabricated microbial fuel cell (FMFC) reactor (FMFC) voltage tends to continue to increase because of theits larger volume so that the, larger number of microorganisms, and larger amount of substrates that are in the reactor is greater. In the same study, 4four FMFC reactors were connected and producedgenerated a voltage 344.11% times greater than the voltage generated by 1one FMFC reactor. ItThus, it can also be concluded that connecting the reactor in a circuit can increase the output voltage (Utomo et al., 2017).

The use of a membrane separator or separator material between the cathode chamber and the anode chamber also affects the performance of SMFCSMFCs. Based onOn the basis of the research conducted by Moqsud et al. (2013), the voltage generated by the SMFCSMFCs reactor with cellophane separator has the highest value compared towith that by the SMFCSMFC reactor with filter paper and PEM (proton exchange membrane)., Cellophane is considered to have a lower electrical resistance value than filter paper and PEM. The drier PEMdry surface of PEM is thoughtconsidered to be the cause of theits higher resistance value compared tothan cellophane and filter paper. Filter paper is considered to be more permeable than PEM and cellophane. WhileMeanwhile, cellophane is more easily damaged and decreases; thus, its quality sois low and it cannot be reused. In another study the reactor used was , a single-chamber reactor was used so it did not need a membrane separator or separator material (Moqsud et al., 2014). Single-

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chamber reactors are, which were made from acrylic with carbon felt as electrode material, were also used in the study of Wang et al. (2017).

4. Integration of SMFCs with Other Solid Waste TreatmentType of Plants in Plant Microbial Fuel CellsPMFCs

5. In addition to using waste substrates there is also, a development technology that uses plants and a bacterial consortium at the root of the plant to help speed up the process of pollutant degradation and increase electricity productiongeneration due to the production of rhizodeposit (rhizodeposits, that is, PMFC - microbial fuel cell plant). The voltage generated from research conducted by, was developed, Moqsud et al. (2014) ofcompared the voltage generated by six variations of the reactor used in the study founddifferent reactors and determined that withe PMFC the generated higher electric voltage will be higher inthan composted rice plants with a; its maximum voltage reachinged 700 mV. This figureresult was also achieved in the reactor with 1% composted rice plants that added 1% compost. When the results of the voltage generated by all reactors are compared, it is known thatthe value of the pot or reactor without plants and compost showsis 95% lower than the highest measured voltage value. Rice plants are used because of their abundance atin the location of the study, namelythat is, Japan, where rice is the main commodity with a total agricultural area of approximately 2.5 million hectaresha. On paddy fields, the surface of land that is flooded with water will experience anaerobic conditions so that; thus, anaerobic microorganisms are abundant. This condition has the potential to be utilized as a system offor SMFCs. If the same system is used in Europe, then this system has the potential to producegenerate electrical energy of 21 GJ/ha years using the mannagrass plant.

6. In athe study conducted by Sophia and Sreeja (2017) harvesting, electrical energy was carried outgenerated using three different types of plants, namely, *Brassica juncea*, *Trigonella foenumgraecumfoenum-graecum*, and *Canna sStuttgart*. Similar results were obtained, namelythat is, the electric voltage obtainedmeasured in the pot with higher compost was high and continued to increase over time. Compost is considered to increase nutrients in the soil and increase bio-energy production. Organic compost nourishes plants with high soil microflora density so that it can accelerate plant growth. In addition, it is known that different types of plants also affect the voltage generated. *Cuanna Stuttgart* is known to have the highest electric power density of 222.54 mW/m^2 compared towith the two other two plants used in the study amounting to 222.54 mW/m2.. The high density of electric power generated is estimated dueattributed to the type of roots, the use of compost, and rootingthe root deposits that can be decomposed by microorganisms in the soil so that; thus, it can contribute electrons to the PMFC system. Sunlight also affects the electrical energy producedgenerated as a product of the photosynthetic activity of plants. Photosynthesis in plants produces organic substances that are released as rhizhodepocysites in the soil around the plant through the roots. This method of harvestinggenerating electrical energy is considered safe and does not interfere with the growth of rice plants at all. PMFC is also considered to have greatthe potential to produce sustainable and environmentally friendly energy. PMFC can be done onused agricultural land and, does not require additional land, and can be integrated with unproductive land, such as wetlands and roofs. So thatThus, the application of PMFC is considered to be able to prevent deforestation.

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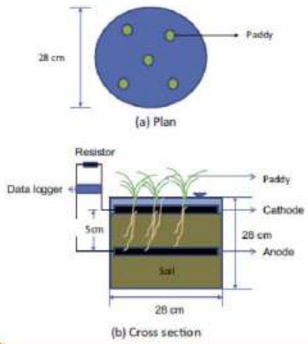

7.

8. Figure 4. Illustration of the PMFC mechanism illustration

9. (Moqsud et al., 2014)

10.

11. By products of MFCs

12. SMFCs have aThe by product of SMFCs is in the form of solids whichthat have been degraded by microorganisms in organic matter by microorganisms. This by product has the potential to be usedfor use as fertilizer. The contents of N, P, and K in kitchen waste and bamboo waste, respectivelywastes are in the range of 1.5 % to 1.7%;%, 0.6 % to 0.8%;%, and 1.3 % to 1.7%%, respectively (Moqsud et al., 2014). The C/N ratio of kitchen waste and bamboo waste observedwastes was 18 and 17, respectively were 18 and 17. The, These value wasare slightly higher when compared to the C/N ratio valuethose obtained in a previous studiesy conducted by the same researcher (Moqsud et al., 2013). However, this value is still in the safe range and hasensures the potential to be usedfor use as fertilizer so that the reduction of soil organic matter can be overcome. In different studies it is knownAnother

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study showedby the SMFC reactor meets the requirements of a mature compost standard on the 20th day (Ganjar et al., 2018).

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14.4. **Challenges and Future Perspective**

Solid phase microbial fuel cells (SMFCs) seems to have many potentials when compare to other solid waste treatment. This technology only needs relatively small energy input for supporting chemical reaction in cathode. Moreover, air-cathode MFCs does not need a supply oxygen since it is provided by its system configuration. SMFCs produce a less sludge as an anaerobic power generation system and convert organic matter into direct electricity and biohydrogen. The processed organic matter could be a mature compost and fertilizer. The used electrode could be a soil conditioner, to increase the fertility of soil. It is also producing a less emissions such as CH_4, CO_2, NH_3, N_2O. The same characteristics can be seen in the anaerobic digestion which has the same processing stage as SMFCs. Aerobic composting needs a lot of energy for aeration and mixing and only produce compost with excessive amount of leachate. This type of composting also produces a significant amount of odor and VOC which interfere the environment. While incineration has many benefits for treating solid waste, it also generates dioxin and furan (especially when is working with plastic-based material), CO_2 and N_2O. If the incineration is not controlled properly, the emission and byproduct (fly and bottom ash / slag) may harmful for the environment.

Table 2 Comparison of SMFCs with other conventional solid waste treatment

Typically, energy generated from MFCs treating food and organic waste (in the form of liquid fraction / hydrolysate) is around 0.28 – 0.78 MJ/kg COD (Xin et al., 2018; Xiao and He, 2014).

The total energy can be higher until reached 2.48 MJ/kg COD when MFCs is fed by anaerobic sewage sludge and 3.52 MJ/kg COD by food waste hydrolysate (Wang et al., 2013b; Xin et al., 2019). That energy values are promising, especially when it is compared with other waste to energy (WtE) technology such as incineration which can provide energy values ranging from 3.60 MJ/kg to 4.96 MJ/kg of food waste (Carmona-Cabello et al., 2018). However, the condition will be more challenging when SMFCs is implemented to process the solid fraction of municipal waste. The electricity generation from solid phase MFCs is relatively small, amounted of 0.072 MJ/kg of food waste as reported by Moqsud et al. (2014). This is related to its mass transfer limitation which resulted to the low electricity generation of SMFCs. Therefore, those values are still in a laboratory scale which is still in doubt that the process efficiency will be much lower than a pilot or even industrial scale. This limitation might be solved by integrating other waste processing technologies.

SMFCSMFCs have been in the spotlight as an alternative totechnology to generate environmentally friendly, sustainable, and renewable electricity. The application of SMFCSMFCs will help reduce the use of fossil energy and be able to use waste or solid waste as an energy source. BesidesIn addition to being able to overcome energy problems, SMFCs are also able to overcome the problem of organic waste in various developing countries. SMFCSMFCs also have the potential to be able to process toxic wastes, such as phenols and petroleum compounds, as well as the processing of waste generated from spacecraft, into electrical energy (Rahimnejad et al., 2015). SMFCSMFCs may not necessarily change the direction of the world in terms of fulfilling the demand for electricity, but SMFCs are capable of producinggenerating energy equivalent to coal-fired power plants. TheThus, there is a need for the development of this technology into power generation technology with a larger scale. However, in operation, SMFCSMFCs require water to produce a mixture of wastewater according to needs,the need of the country and energy for stirring and controlling odors that may arise (Moqsud et al., 2014; Nastro et al., 2017). Based onOn the basis of previous studies that have been doneconducted, to increase the effectiveness of SMFCSMFC reactors, it is necessary to first treat the chemical substrate both chemically and physically. The initial treatment requires considerable investment (Wang et al., 2013a) SMFCSMFC(Rahimnejad et al., 2015). Xin et al. (2018) showed that the amount of electric power generated by MFCs is greater than by anaerobic digester (AD). This finding can be attributed to the fact that the AD process requires a longer residence time than the MFCs technology, thereby affecting the size of the reactor used. The MFCs reactor can be 5.5 times smaller than the AD reactor. The MFCs application is considered to be more practical, more environmentally friendly, and more economically feasible in terms of electricity conversion and production costs than AD. The MFCs is expected to become a solution for processing food waste that ensures the rapid recovery of resources and electricity sources by not producing any other waste.

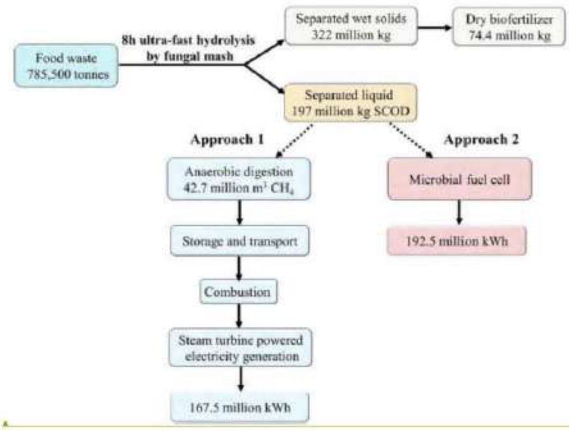

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Figure 5. Comparison of AD with MFC

(Xin et al., 2018)

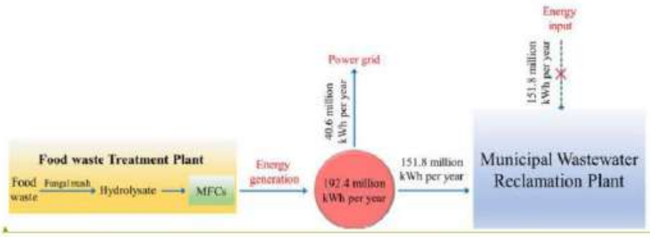

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Figure 6. Co-locationColocation illustration of food waste processing and WWTP

SMFC(adapted from Xin et al., 2018)

Strengthening Xin et al. (2018) proposed scheme, Antonopoulou et al. (2019) also proposed a food waste management system, using an integrated biochemical process. Food waste is grinded and heated (as waste pre-processing system) then carbonaceous COD is extracted to produce two

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fractions of product, liquid and solid fraction. The liquid fraction is processed using MFCs continuously and the solid fraction is processed using anaerobic digester. This scheme is considered to be applied in pilot scale because it produces more energy recovery value of 12.32 MJ/kg of total solids (TS), or almost comparable to the maximum net calorific value using various types of combustion, amounting to 18.09 - 18.38 MJ/kg TS. The total energy produced from MFCs and anaerobic digester are still positive, especially to cover the pre-processing energy needs of 8 MJ/kg TS (Antonopoulou et al., 2019; Wang et al., 2013b; Xin et al., 2018). This energy balance can still be reduced if it uses cheap and energy-friendly drying technology such as bio-drying or low-cost decanters to reduce the excessive amount of water content in the food waste (Velis et al., 2009). In case of integration with aerobic composting, the leachate can be processed using MFCs for further substrate conversion. The generated energy could be used as self-supporting system for aerating the compost pile. In other hand, MFCs itself can be directly treat the organic fraction of solid waste without the help of anaerobic and aerobic composting. However, this option is not feasible since the energy generated is lower and need further investigation to enhance the productivity of electricity. Figure 3 shows the proposed mechanism for integrating other solid waste treatment with SMFCs.

Figure 63. SCo-locationColocation illustration of food waste processing and WWTP -MFCs and other solid waste treatment achieving sustainable energy production adapted from Antonopoulou et al. (2019) and Xin et al. (2018)

The electric power generated by the cell may not be enough to support the operation of the sensor or transmitter continuously. This is a basic problem forof SMFCs. In addition, SMFCs also cannot operate at very low temperatures because it can disrupt the activities of microorganisms whose reactions will slow down as the temperature of the environment decreases (Rahimnejad et al., 2015). Xin et al. (2018) identified the potential use of food waste by comparing the anaerobic digestion (AD) method with the MFC method. Based on theseThese studies it is knownshowed that the amount of electric power produced fromgenerated by MFC is greater than that by AD. This is because finding can be attributed to the fact that the AD process requires a much longer residence time compared tothan the MFC so that it can affecttechnology, thereby affecting the size of the reactor used where the. The MFC reactor can reachbe 5.5 times smaller than the AD so as to reduce reactor, thereby reducing the land usearea needed for the reactor. Based on the picture above, it can also be seenThe figures show that the process undertaken to obtain methane gas is quite complex compared towith MFC. The MFC application is considered to be more practical, more environmentally friendly, and more economically feasible in terms of electricity conversion and production costs compared to anaerobic digestion (than AD).. MFC is expected to become a solution for processing food waste into a fastthat ensures the rapid recovery of resources and electricity sources by not producing any solid waste. Based onOn the basis of the concept shown in Figure 5, it is known that the concept of co-locationcolocation SMFCcan provide several benefits, namely, the synergy of energy and material use, integration with local business people and industrial activities (incineration, etc.)), and joint use of equipment for harvesting and conditioning of biomass, which in the future can reduce capital requirements and operational costs (Moreno-Garcia et al., 2017; Xin et al., 2018). In addition to overcoming energy problems, SMFCSMFCs are also considered to be able to overcome two problems at once, namelythat is, the problems of agro-industry and energy, because compost can effectively solve the problem of solid waste and generate energy during the process of making compost produced energy (Wang et al., 2017). Based onOn the basis of the research conducted by Utomo et al. (2017) and Wang et al. (2019a), it can also be seen that

SMFCSMFCs have the potential to enlarge the for large-scale. Besides that application. Moreover, SMFCSMFCs with biogas slurry as substrate have goodexhibit stable electricity production stability so that the potential to be able to produce electricitygeneration capability.

15.5. Conclusions

SMFCSMFCs are an alternative sourcetechnology of generating electricity that is environmentally friendly and sustainable. Various studies have been carried outconducted to determine the optimum configuration of the MFC reactor and its development potential to be developed in order to be able to producegenerate electrical energy. The various factors that affect the performance of SMFCSMFC reactors, such as substrates, electrodes, microorganisms involved, and reactor configuration, need to be further investigated. One factor that needs to be further investigated is related to tThe presence of separator and electrode distance used in the SMFCSMFC reactor, both of which are important to determine since it is related to the process of electron and proton transfer. and tMass transfer process is also important in a solid phase, ensuring the microorganism can breakdown the substrate properly. Therefore, this limitation may be further studied, and finding the best configuration system may enhanced the electricity generated by the SMFCs.he harvestinggeneration of electrical energy generated by microorganisms fromthrough their metabolic processes. Integrating this technology with other solid waste processing system could be possible and reliable, since SMFCs itself has many limitation. The proposed system is combining the preprocessing system, anaerobic digestion, composting, and also SMFCs in a sequential system. After solid waste processed by using pretreatment technology, solid waste is sending to composter, both in anaerobic or aerobic composting system. Then, the leachate, slurry or hydrolysate from the process may be treated by using SMFCs. The direct electricity can be used as alternative energy sources for other treatment needs. SMFCs also could be used as a single solid waste treatment, but the efficiency may be lower than the proposed system instead and not feasible for field application.

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Figure
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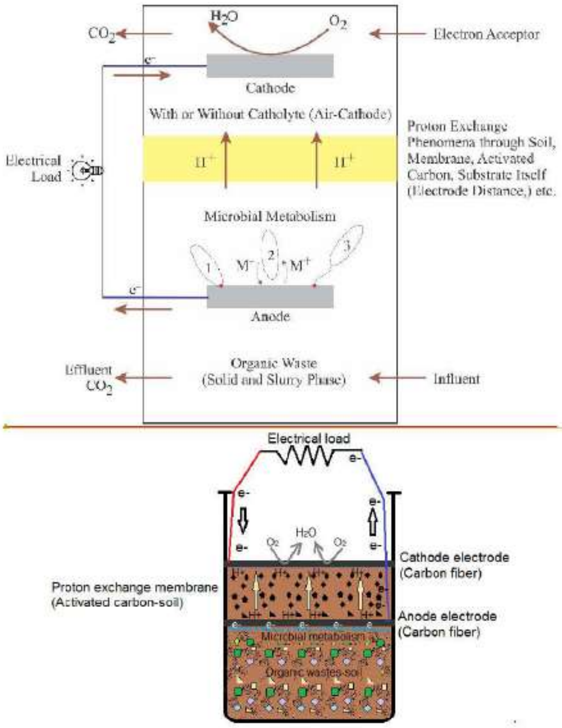

Figure 1. Modified Illustration illustration of Solid phase MFCthe SMFCSPMFC process

(Adapted from Nastro et al., 2017 and Logroño et al., 2015)

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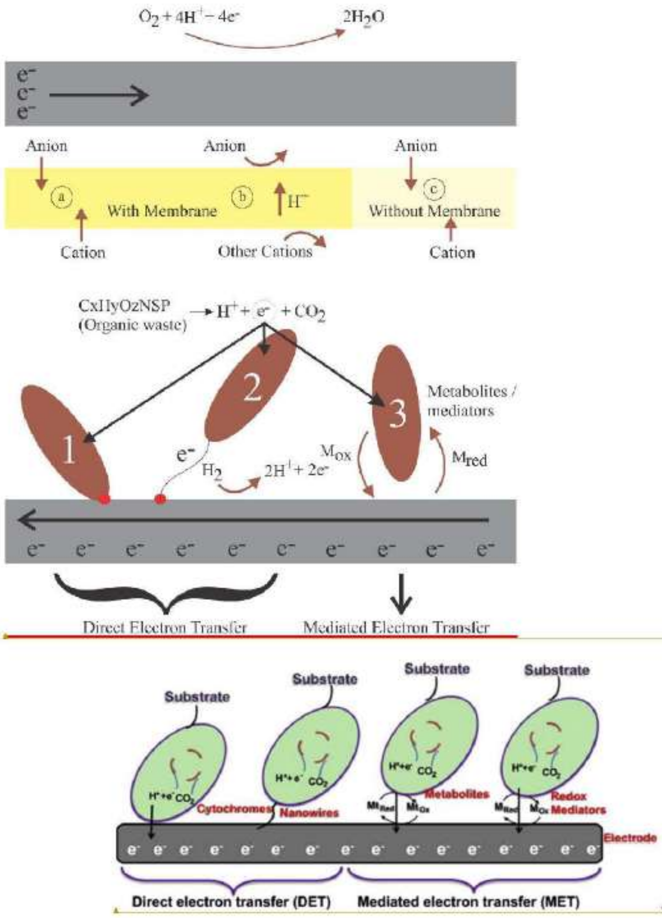

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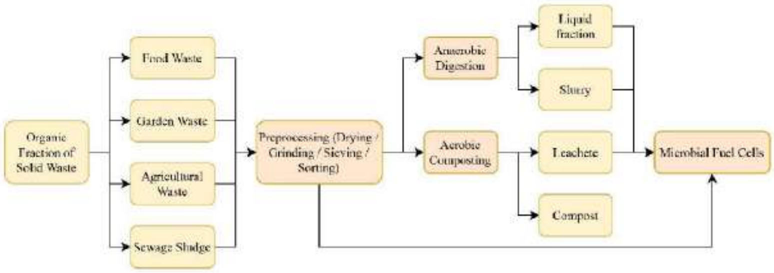
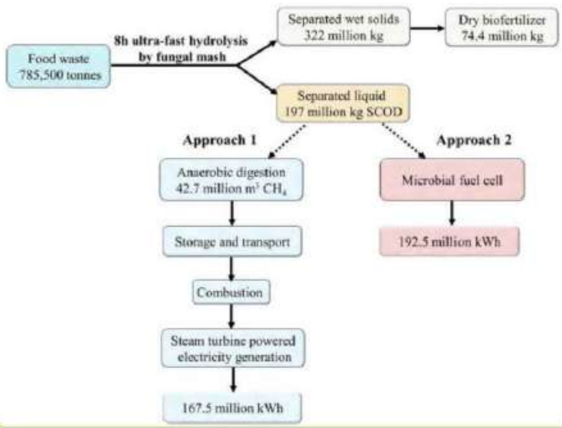
Figure 2. Working mechanism ~~Electron transport mechanism in~~ of electrode and separator in ~~MFCsthe~~ SPMFCs ~~anode~~

(Adapted from Mohan et al., 2014)





~~Figure 5. Comparison of AD with MFC~~

~~(Xin et al., 2018)~~

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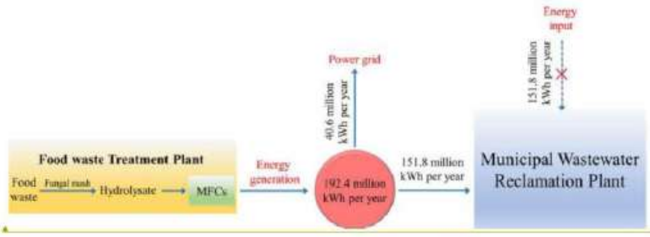

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Figure 63. Co-locationColocation illustration of food waste processing and WWTP -MFCs and other solid waste treatment achieving sustainable energy production adapted from Antonopoulou et al. (2019) and Xin et al. (2018)

Table
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Table 1 Recent studies related to improvement of MFCs performances treating solid wastes

Substrate	Electrode		Separator	Bacteria	Operating Phase	System Configuration	Maximum Power Density	References
	Anode	Cathode						
Household food waste (glucose) hydrolysate	Graphite granules	MnO_2	Nd	Mixed anaerobic microbial culture	Liquid	Single chamber	11,800 mW/m^3 ~~of~~ per anode working volume	Antonopoulou et al. (2019)
Organic fraction of municipal waste	Graphite plates	Graphite plates	Membraneless	*Lactobacillaceae*, *Bacillaceae*, *Clostridia*, and *Pseudomonadaceae*, with *Pseudomonas aeruginosa*	Solid	Single chamber	1.75 mW/m^2 ~~of~~ per ~~electrode~~ anode specific surface area	Florio et al. (2019)
Food waste hydrolysate	Carbon brush	Plain carbon cloth	Nd	*Moheibacter*, *Azospirillum*, *Geobacter*, *Petrimonas*, *Alicycliphilus*, *Rhodococcus*, *Pseudomonas*	Liquid	Single chamber	173 mW/m^2 ~~of~~ per total working surface area	Xin et al. (2018)
Vegetable and fruit residues	Carbon fiber	Ceramic disk	Nd	Nd	Solid	Single chamber	Nd	Nastro et al. (2017)
Municipal solid waste	Carbon felt, stainless steel, carbon paper, and carbon plate		Oxygen and $K_3Fe(CN)_6$	Nd	Solid	Dual chamber	1,817 mW/m^2 per anode specific surface area	Chiu et al. (2016)
Mix of apples, lettuce, green beans, and soil	Carbon felt	MnO_2	Nd	*Gammaproteobacteria* and *Bacilli*	Solid	Single chamber	5.29 mW/m^2 ~~of~~ per ~~electrode~~ anode specific	Khudzari et al. (2016)

Substrate	Electrode		Separator	Bacteria	Operating Phase	System Configuration	Maximum Power Density	References
	Anode	Cathode						
(potting mix)							surface area	
Dewatered sludge	Graphite fiber	Titanium wire	PEM (Nafion 117, Dupont Company)	Electricigens, the common fermentation bacterial colonies	Solid	Dual chamber	5,600 mW/m^3 of per anode anode working volume	Yu et al. (2015)
Kitchen and yard wastes	Carbon fiber	Carbon fiber	Nd		Solid	Single chamber	39.2 mW/m^2 of per electrode anode specific surface area	Moqsud et al. (2015)
Vegetable and fruit wastes	Carbon fiber		Soil-activated carbon	Mixed anaerobic microbial culture	Solid	Single chamber	Nd	Logroño et al. (2015)
Rice husks, soybean residue, coffee residue, and leaf mold	Carbon felt		Nd	Nd	Solid	Single chamber	4.6 mW/m^2 of per electrode anode specific surface area	Wang et al. (2015)
Wastes from compost facility	Tin-coated copper mesh	Coil spring	Soil-activated carbon	Mixed anaerobic microbial culture	Solid	Single chamber	47.6 mW/m^2 ofper electrode anode specific surface area	Karluvalı et al. (2015)
Kitchen garbage and bamboo waste (glucose)	Carbon fiber	Carbon fiber	Soil-activated carbon	Mixed anaerobic microbial culture	Solid	Single chamber	60 mW/m^2 per anode specific surface area	Moqsud et al. (2014)
Dewatered sludge	Graphite fiber	Titanium wire	PEM (Nafion 117, Dupont Company)	Electricigens, the common fermentation bacterial colonies		Dual chamber	5,600	(Yu et al., (2015)

Substrate	Electrode		Separator	Bacteria	Operating Phase	System Configuration	Maximum Power Density	References
	Anode	Cathode						
Organic fraction of municipal waste	Graphite plates	Graphite plates	Membraneless	*Lactobacillaceae*, bacillaceae, clostridia*Bacillaceae*, *Clostridia*, and p*Pseudomonadaceae*, with p*Pseudomonas aeruginosa*		Single chamber	1.75	(Florio et al., (2019)
Kitchen and yard wastes	Carbon fiber	Carbon fiber	Nd			Single chamber	39.2	(Moqsud et al., (2015)
Mix of apples, lettuce, green beans, and soil (potting mix)	Carbon felt	Mno_2	Nd	*Gammaproteobacteria* and b*Bacilli*		Single chamber	5.29	(Md Khudzari et al., (2016)
Food waste	Carbon brush	Plain carbon cloth	Nd	Moheibacter, azospirillum, geobacter, petrimonas, alicycliphilus, rhodococcus, pseudomonas, geobacter*Moheibacter*, *Azospirillum*, *Geobacter*, *Petrimonas*, *Alicycliphilus*, *Rhodococcus*, *Pseudomonas*		Single chamber	173	(Xin et al., (2018)
Food waste hydrolysate	Brushes	Carbon cloth	Nd	Mixed anaerobic microbial culture	Liquid	Single chamber	~556 mW/m^2 per anode	Jia et al. (2013)

Substrate	Electrode		Separator	Bacteria	Operating Phase	System Configuration	Maximum Power Density	References
	Anode	Cathode						
							specific surface area	
Grass cuttings, leaf mold, rice bran, oil cake, and chicken droppings	Carbon fiber	Carbon fiber	Filter paper, cellophane, and PEM	Nd	Solid	Dual chamber	394 mW/m^2 per cathode specific surface area	Moqsud et al. (2013)
Sewage sludge	Carbon felt and rod	Carbon felt and rod	Proton exchange membrane	Mixed anaerobic microbial culture	Solid	Single chamber	38.1 W/m^3 per anode working volume	Wang et al. (2013b)
Rice hull, bean residue, and ground ~~coffe waste~~coffee wastes	Carbon felt	Carbon felt	Nd	Nd	Solid	Single chamber	264~~,~~.7 mW/m^2 per anode specific surface area	Wang et al. (2013a)
~~Grass cuttings, leaf mold, rice bran, oil cake, and chicken droppings~~	~~Carbon fiber~~	~~Carbon fiber~~	~~Filter paper, cellophane, and PEM~~	~~Nd~~		~~Dual chamber~~	~~394~~	~~(Moqsud et al., (2013)~~
~~Vegetables and fruits wastes~~	~~Carbon fiber~~		~~Soil-activated carbon~~	~~Mixed anaerobic microbial culture~~		~~Single chamber~~	~~-~~	~~(Logroño et al., (2015)~~
~~Rice husks~~	~~Carbon felt~~		~~Nd~~	~~Nm~~		~~Single chamber~~	~~1.278~~	~~(Wang et al., (2015)~~
~~Food waste~~	~~Brushes~~	~~Carbon cloth~~	~~Nd~~	~~Mixed anaerobic microbial culture~~		~~Single chamber~~	~~-556~~	~~(Jia et al., (2013)~~

Substrate	Electrode		Separator	Bacteria	Operating Phase	System Configuration	Maximum Power Density	References
	Anode	Cathode						
~~Wastes from compost facility~~	~~Tin-coated copper mesh~~	~~Coil spring~~	~~Soil-activated carbon~~	~~Mixed anaerobic microbial culture~~		~~Single chamber~~	~~47.6~~	~~(Karluvalı et al., (2015)~~
~~Municipal solid waste~~	~~Carbon felt, stainless steel, carbon paper, and carbon plate~~		~~Oxygen and $K_3Fe(CN)_6$~~	~~Nd~~		~~Dual chamber~~	~~12.04~~	~~(Chiu et al., (2016)~~
~~Vegetables and fruits residues~~	~~Carbon fiber~~	~~Ceramic disk~~	~~Nd~~	~~Nd~~		~~Single chamber~~	~~Nd~~	~~(Nastro et al., (2017)~~

Nd: Not defined

Table 2 Comparison of SMFCs with other conventional solid waste treatment

Solid Waste Treatment	Energy Input	Products	Byproducts	Emissions	References
Solid Phase Microbial Fuel Cells	Half aeration in cathode and ignored when working in air-cathode Mixing (if necessary)	- Electricity - Soil conditioner - Compost - Fertilizer (in slurry phase) - Biohydrogen	Less sludge	CH_4, CO_2, NH_3, N_2O	Li et al., (2020)
Aerobic Composting	Full aeration Mixing	Compost	Leachate	Odor, CO_2, CH_4, VOC, NH_3, N_2O	Rincon et al., (2019) Smith and Aber, (2018) Bernstad and la Cour Jansen (2012)
Anaerobic Digestion	Mixing (if necessary)	- Fertilizer - Biogas - Soil conditioner - Non-direct electricity (from heat) - Compost	Less sludge	CH_4, CO_2, NH_3, N_2O	Santos et al., (2020) Rincon et al., (2019)
Incineration	Full aeration	- Heat/steam - Electricity	Ash and slag	Dioxin and furan (if the waste contains plastic-based material), CO_2, N_2O	Assi et al., (2020)

*Declaration of Interest Statement

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Submission of the second version of the manuscript

Faculty of Engineering
Diponegoro University

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Dear authors, on the basis of the review reports received and having examined the manuscript myself, there are still issues that require revisions. For these reasons, it may be considered for publication after some significant revisions, as indicated in the reviewers' reports. I therefore invite you to submit a revised version of the manuscript. When preparing the revisions, please make sure to: 1) provide a "Response to reviewers" document in which a detailed point-by-point response to the comments/questions received is included and the related changes made to the text are clearly reported; 2) clearly highlight in the revised text all the changes made to the original version (you may preferably use the "Track changes" tool in MS Word, or highlight the new text using a different colour and mark deletions with strikethrough font). It is recommended that the "Response to reviewers" document is arranged to include a table containing (in separate columns) the original reviewers'
questions/comments, the related motivated response, and the revised text in the manuscript

Reviewer #1: The Authors have partially acknowledged the recommendations by this Referee.
More specifically:
- They have enlarged the abstract, but the sentence "(around 6 to 18 times to achieve the same energy output as combustion process)" needs a thorough reference from the literature, as in the largest part of the studies , MFC are remarkably below such a value, especially when compared to combustion processes. The Authors should look to literature papers in which the industrial outlook of MFC is proposed.
- Many typos are still present in the manuscript (i.e. "...microbial fuel cellS IS....", "SMFCs is quite profitable...")
- The title of Section 2.3 is not clear... Is it just "Electrode"? Electrode Separator?
- It is not true that "in general" there is a PEM. Many other layouts have been proposed in the literature, with more general cationic membranes, but also with porous clay (work by Prof. Ieropoulos' Group). The Authors should acknowledge such contributions, especially in a Review paper.
- Substrate section: no hints on the dark fermentation phase proposed by Prof. Logan are found: the authors should mention it.
- No particular emphasis is posed on pH evolution within the chamber. The Authors should acknowledge that pH has a dramatic role in the performance of the whole reactor, as pointed out in many recent works.
The Authors must enhance the discussion on this aspect, due to its cruciality for MFC performance and include proper references in their paper.

Reviewer #2:
The authors replied to the comments, increased the missing parts and revised the text. With the changes made, from my point of view, the article should be accepted.

****

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Response to reviewer comment of the second version of the manuscript

***Response to Reviewers**

Response to Reviewers Questions / Comments

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
	Reviewer #1		
1	- They have enlarged the abstract, but the sentence "(around 6 to 18 times to achieve the same energy output as combustion process)" needs a thorough reference from the literature, as in the largest part of the studies, MFC are remarkably below such a value, especially when compared to combustion processes. The Authors should look to literature papers in which the industrial outlook of MFC is proposed.	We made changes in the abstract. The sentence in the bracket has been removed, but replaced into the discussion section. However, the energy generation from industrial outlook cannot be stated clearly since the exact use of SMFCs in the industrial scale is not available. The sentences "The total energy can be higher until reached 2.48 MJ/kg of COD when MFCs is fed by anaerobic sewage sludge and 3.52 MJ/kg of COD by food waste hydrolysate" is based on the literature that proposed a pilot scale MFCs. However, the MFCs are proposed in a liquid fraction which is not comparable with the incineration process.	…. That energy values may lower, especially when it is compared with other waste to energy (WtE) technology such as incineration which can result in energy values ranging from 3.60 MJ/kg to 6.00 MJ/kg of food waste (Carmona-Cabello et al., 2018; Chen and Christensen, 2010). Although the MFCs energy generation seems promising since only 8 to 12 SMFCs systems might achieve the same energy output as combustion, the energy generation sustainability is doubted compare to thermal processing technologies such as incineration. The condition will be more challenging when SMFCs is implemented to process the solid fraction of municipal waste. The maximum electricity generation from solid-phase MFCs is relatively small and amounted to 0.072 MJ/kg of food waste, as reported by Moqsud et al. (2014). This condition is related to its mass transfer limitation, which resulted in the low electricity generation of SMFCs. Therefore, those values are still on a laboratory scale (none SMFCs in larger scale), which is still in doubt that the process efficiency will be much lower than a pilot or even industrial scale. At the pilot / industrial scale, MFCs reactor must be constructed in a minimum dimension to ensure the power per unit

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
		However, we add this sentence "Although the MFCs energy generation seems promising since only 8 to 12 SMFCs systems might achieve the same energy output as combustion, the energy generation sustainability is doubted compared to thermal processing technologies such as incineration" to bridge and highlight the gaps of SMFCs research.	area of the electrode or reactor volume is lower, making the energy generation higher. An ideal substrate supply rate can also be provided in smaller sized reactors (Greenman and Ieropoulos, 2017). This limitation might be solved by integrating other waste processing technologies.
2	Many typos are still present in the manuscript (i.e. "...microbial fuel cellS IS....", "SMFCs is quite profitable...")	We have checked the typos line by line as per reviewer suggestion.	Modified words or senteces are tracked and marked using red color
3	The title of Section 2.3 is not clear... Is it just "Electrode"? Electrode Separator?	We changed the title "2.3. Electrode Separator"	The title is modified into: "Process in Separator or Membrane"
4	It is not true that "in general" there is a PEM. Many other layouts have been proposed in the literature, with more general cationic membranes, but also with porous clay (work by Prof. Ieropoulos' Group). The Authors should acknowledge such contributions, especially in	As per reviewer suggestion, we enriched the section 2.3. using recent literature about the use of clayware membrane and porous clay system.	SMFCs consists of anode and cathode chamber separated by cationic membrane or proton exchange membrane, porous ceramic, clayware membrane (Yousefi et al., 2017), and electrode distance (by configuring the placement of electrodes) (Moqsud et al., 2017). Biopotential that occurs due to the metabolic activity of microorganisms and the condition of electron acceptors can induce bioelectricity in SMFCs. The proton

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
	a Review paper.		exchange membrane (PEM) or other separators in SMFCs, which physically separates the cathode and anode chamber, also prevents the transfer of dissolved oxygen contained in the cathode chamber to the anode chamber so that the anaerobic conditions in the anode chamber can be maintained (Ghasemi et al., 2013). The separators or PEM can facilitate the transfer of protons produced in the anode chamber without the transfer of substrate and oxygen to the cathode chamber. The following may occur when the PEM is not applied in SMFCs: the displacement of oxygen and substrate can result in decreased coulombic efficiency (CE) and microorganism activity, which has a dramatic effect on the system performance and stability. The highly cost PEM / CEM makes many researchers looking for alternative separator substitution. Porous clay, such as novel porous clay earthenware (NCE), could produce higher power output compared to the use of PEM as electrode separator (Daud et al., 2020). Therefore, the higher the thickness of the porous clay, the lower the power generation produced by SMFCs. The difference of the thickness can change the hydraulic pressure and also the transport of fluid through the SMFCs system. The flow of ions will be slower when the thicker clay membrane is applied (Jimenez et al., 2017).

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
5	Substrate section: no hints on the dark fermentation phase proposed by Prof. Logan are found: the authors should mention it.	As per reviewer suggestion, we added this discussion in the revised manuscript. Since many recent works are discussing about the integrative process of MFCs with DF, we put this paragraph in the "Integration of SMFCs with Other Solid Waste Treatment"	Dark fermentation (DF) is a technology commonly used to recover bio-hydrogen from high cellulose content materials. Through fermentation reactions, cellulose is hydrolyzed to hexoses and produces acetate and hydrogen gas (Wang et al., 2011). However, the DF system is only able to recover 1/3 of the total theoretical energy that could be recovered. The combination of microbial fuel cells and microbial electrolysis cells (MFC-MEC) to treat DF effluent could increase bioenergy production. MFC could support MEC's energy needs for converting substrate into H2, as well as direct electricity for the system as a whole (Chookaew et al., 2014). Increased power density in MFCs also resulted from the use of dark fermentation effluents where the maximum power density increased to 4 times more significant based on research conducted by Varanasi et al. (2017). The combination of DF-SLS (Solid Liquid Separation)-MFC can also be used to treat cellulose waste such as swine manure and rice bran. As a post-treatment of DF and SLS, MFC can improve the energy recovery process in the form of bio-electricity. MFC efficiency will also increase due to higher degradable COD available from DF and SLS processes (Schievano et al., 2016). The potential for utilizing integrative technology might be explored more intensely to get better system durability and

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
			sustainability.
6	No particular emphasis is posed on pH evolution within the chamber. The Authors should acknowledge that pH has a dramatic role in the performance of the whole reactor, as pointed out in many recent works. The Authors must enhance the discussion on this aspect, due to its cruciality for MFC performance and include proper references in their paper.	As per reviewer suggestion, we added this discussion in the revised manuscript.	The pH plays a vital role in maintaining the performance of solid-phase microbial fuel cells. The pH can activate several reactions and affect microorganisms' performance in consuming substrates, thus produce bioelectricity (Jadhav and Ghangrekar, 2009). Higher electricity production can occur in a neutral pH range because of exoelectrogens like neutral environmental conditions (He et al., 2009). Low pH condition which is very likely to occur in the anode chamber, can cause the soluble metals to be precipitated, thereby covering the cathode's layer and inhibiting the transfer of electrons to the cathode, and protons to the membrane/separator (Makinen et al., 2013). An increase in the cathode chamber's pH and a decrease in the anode chamber's pH or pH splitting can occur when a separator or PEM in SMFCs is available. This risk might occur since the membrane/separator cannot effectively transfer the protons to the cathode chamber and electrons to the electrode (Rahimnejad et al., 2015). The biggest SMFCs issue is the mass transfer, including the transfer of protons and electrons in a solid-state system (Chiu et al., 2016). Mixing is essential to ensure the uniformity of mass transfer, thus prevent the pH splitting between anode and cathode chamber (Nastro et al., 2017).
	Reviewer #2		

No	Reviewers Questions / Comments	Response	Revised Text in the Manuscript
1	The authors replied to the comments, increased the missing parts and revised the text. With the changes made, from my point of view, the article should be accepted.	Thank you for your valuable comment and support.	-

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Article Type: Review Article

Keywords: anaerobic digestion; compost; mass transfer; microbial fuel cells; solid-phase

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Abstract: This review article discusses the use of solid waste processed in solid phase microbial fuel cells (SMFCs) as electrical energy source. MFCs are usually operated in the liquid phase because of the ease of the ion transfer process in liquid media. Nevertheless, some researchers say that the potential for MFCs in the solid phase (particularly for treating solid waste) is also quite promising if several important factors, such as the type and amount of substrate, microorganism community, system configuration, type and number of electrodes, are optimized, thereby increasing the amount of electricity generated. The critical factors affecting SMFCs performance is the efficiency of electron and proton transfer through solid media. However, this limitation may be overcome by electrode system enhancement and regular substrate mixing. In the other hand, the integration of SMFCs with other conventional solid waste treatment could produce sustainable green energy. Although SMFCs produce relatively small energy than other waste to energy treatment, SMFCs is still quite promising to achieve zero emission treatment. Therefore, this article is expected to address the challenges and also fill the gaps in SMFCs research and development.

HIGHLIGHTS

- Solid-phase microbial fuel cells (SMFCs) could process organic waste into electricity directly.
- The results of electricity generation have been summarized from the literature.
- Ion and mass transfer are the biggest limitation of SMFCs
- SMFCs is promising to achieve zero discharge treatment of solid waste
- Integration of SMFCs with other conventional solid waste treatment is investigated

Abstract

This review article discusses the use of solid waste processed in solid phase microbial fuel cells (SMFCs) as electrical energy source. MFCs are usually operated in the liquid phase because of the ease of the ion transfer process in liquid media. Nevertheless, some researchers say that the potential for MFCs in the solid phase (particularly for treating solid waste) is also quite promising if several important factors, such as the type and amount of substrate, microorganism community, system configuration, type and number of electrodes, are optimized, thereby increasing the amount of electricity generated. The critical factors affecting SMFCs performance is the efficiency of electron and proton transfer through solid media. However, this limitation may be overcome by electrode system enhancement and regular substrate mixing. In the other hand, the integration of SMFCs with other conventional solid waste treatment could produce sustainable green energy. Although SMFCs produce relatively small energy than other waste to energy treatment (around 6 to 18 times to achieve the same energy output as combustion process), SMFCs is still quite promising to achieve zero emission treatment. Therefore, this article is expected to address the challenges and also fill the gaps in SMFCs research and development.

Keywords: anaerobic digestion, compost, mass transfer, microbial fuel cells, remediation, solid-phase

1. Introduction

The increasing of municipal solid waste generation is an issue faced by almost all countries in the world, due to an increase in industrial activity and global development. In developing countries, almost 90% of municipal waste is transported to landfills directly without any intermediate treatment that can reduce the volume of solid waste (Barik and Paul, 2017). This waste management activity even contributes to greenhouse gas emissions by 5% compared to total world greenhouse gas emissions. Recycling, effective waste treatment and source-segregation are the main strategies in reducing emissions and environmental impacts due to increased waste generation (Florio et al., 2019). Waste is considered to still have a large enough energy content, so waste to energy is one of the alternatives that is considered (Chiu et al., 2016). Composting and anaerobic digestion are biological treatment technologies that have been used and explored massively in various countries (Yu et al., 2015; Xin et al., 2018). However, conventional composting under aerobic condition requires more energy for mixing and air supply and may produce a huge amount of leachate (Chu et al., 2019). Anaerobic composting which is commonly known as anaerobic digestion can be an alternative solution for converting solid waste into reusable energy and biofuel (Khudzari et al., 2016). Many recent works revealed that anaerobic digestion has many constraints such as long residence time, relatively low purification of biomethane and its conversion to electricity, and many safety issues which make this technology cannot be a perfect solution for zero discharge treatment (Xin et al., 2018).

Recently, microbial fuel cells (MFCs) is found as an alternative treatment for generating electricity from waste (waste valorization) without intermediate treatment as anaerobic digestion does by utilizing electrogenic (anodophilic) microorganisms (Xin et al., 2018). Bioelectric energy of MFCs is depending on the electron transfer process and biodegradation efficiency of solid waste (Song et al., 2015). Many researchers use the terms of solid phase MFCs (SMFCs / SPMFCs) (Logrono et al., 2015; Wang et al., 2015; Mohan et al., 2011) and a few of them use the terms of compost MFCs (cMFCs) (Khudzari et al., 2016) and biogas slurry MFCs (BSMFCs)

(Wang et al., 2019a) to name MFCs which converting solid waste into electricity. Solid-phase microbial fuel cells (SMFCs) are one of the developments in MFCs technology that can be applied to solid waste and are claimed to be able to accelerate the process of anaerobic waste degradation, harvest electrical energy directly, and produce mature compost from organic compounds (Choudhury et al., 2017; Moqsud et al., 2013; Moqsud et al., 2015; Pandey et al., 2016; Santoro et al., 2017). SMFCs is ~~quite~~ profitable because it only requires low-cost materials (Du et al., 2007; He et al., 2017). Moreover, its capability to generate electricity directly makes it an alternative renewable energy source, attracting considerable attention from researchers (Do et al., 2018; Escapa et al., 2016; Xia et al., 2018). In addition, solid waste which is used as substrate also makes SMFCs to be an alternative method for overcoming the problem of solid waste treatment because it uses solid waste as a substrate to provide an environmentally friendly and sustainable source of electricity (Gude, 2016; Yasri et al., 2019). Thus, SMFCs are considered to be capable of addressing multi-sectoral problems since it can be integrated with other processing waste treatment such as aerobic composting or anaerobic digestion (Kadier et al., 2016; Logan, 2009; Trapero et al., 2017; Utomo et al., 2017).

Over the past five years alone (2016–2020 as article in press), 2,499 review articles, 1,193 book chapters, and 1,513 research articles relating to the utilization of MFCs in various treatments were found on sciencedirect.com (beyond other scholarly databases). Nevertheless, finding articles that discuss the use of SMFCs for comprehensive solid waste management is quite difficult. Rahimnejad et al. (2015) explained in detail the application of MFCs to processes at anodes–cathodes, proton transfer processes through cation exchange membranes, anion exchange membranes, or bipolar membranes, the production of biohydrogen, bioelectricity, and biosensors, and wastewater treatment. Information about advanced developments in the use and manufacturing process of electrodes and MFC membranes has also been updated by Palanisamy et al. (2019). Meanwhile, Zhang et al. (2016) and Khudzari et al. (2016) used bibliometric methods to measure the extent of global research trends, research, and developments regarding MFCs using the Scopus and Web of Sciences database, or specifically in several journals, which are the main platforms of MFC progress report. However, to the authors' understanding, there has not been a single article that summarizes, discusses, and provides a detailed description of the development of SMFCs for treating solid waste. The factors that influence the optimization of the performance of the SMFCs reactor mentioned previously need to be further investigated through various in-depth and comprehensive studies. This review article was written to understand and analyze the technological basics of SMFC and the factors that influence it, as well as potential obstacles that may be encountered in the future in its development toward industrial commercialization. Through this article, we can collate the results of recent studies that have been conducted to optimize the performance of SMFCs and its possible integration and comparation with other technologies as well as the various improvements needed to enhance the results of generating electricity using SMFCs.

2. Fundamental Process of SMFC

SMFCs is a technology used to generate environmentally friendly electricity from biomass by utilizing microorganisms (Garita-Meza et al., 2018; Mäkinen et al., 2013; Pushkar et al., 2016). SMFCs employ the bioelectrogenesis capability of microorganisms to utilize organic compounds as electron acceptors where energy is generated in the process. This system harvests the energy generated by the microorganisms directly without the need for combustion (Calignano et al., 2015; Minutillo et al., 2018; Nastro et al., 2017). Generally, SMFCs configuration systems consist of two chambers: cathode and anode chamber, which separated by specific membranes. The cathode is a chamber which is full of oxygen, where protons will move toward the cathode chamber to form water molecules (Logroño et al., 2016a; Moqsud et al., 2013). The two electrode chambers are separated by a membrane as a mediator capable of moving protons from the anode to the cathode, transferring electrons between the two electrodes, and inhibiting the entry of oxygen into the anode. However, there are also SMFCs that do not use membranes and rely on the distance between the two electrodes (Logroño et al., 2016a; Logroño et al., 2016b; Mohan and Chandrasekhar, 2011). Figure 1 generally illustrates the processes that occur in the SMFCs.

Figure 1. Schematic illustration of the SMFCs process (Modified from Nastro et al., 2017 and Logroño et al., 2015)

Chemical energy present in the organic waste will be oxidized by microorganisms in the anode chamber. Microorganisms extract the energy needed to build biomass through metabolism process (Palanisamy et al., 2019). The effectiveness of SMFCs reactors is influenced by several factors, such as oxygen supply and consumption in the cathode chamber, oxidation of the substrate in the anode chamber, electron transfer from the anode chamber to the anode surface, and proton exchange membrane (PEM) permeability (Rahimnejad et al., 2015; Sharma and Li, 2010). In other cases, circuit connection is also important to note, since it can increase the voltage output to 344.11% times greater than a single reactor (Utomo et al., 2017).

2.1. Process in the Anode

The anode chamber is an important component of SMFCs. Microorganisms that play a role in substrate degradation and electron production attach to the electrodes in the anode chamber. The process occurs at the anode under anaerobic conditions. The presence of oxygen in the anode chamber can inhibit the generation of electricity by microorganisms. In addition to the electrodes and microorganisms, there are also substrates and mediators in the anode chamber. The general reactions that occur at the anode are expressed in Equation (1).

$$Biodegradable\ organics \xrightarrow[Anaerobic\ environment]{Active\ microorganism} CO_2 + H^+ + e^- \qquad (1)$$

The microorganisms present in the anode act as catalysts capable of breaking the substrate into simpler molecules. This active biocatalyst is able to oxidize the substrate and produce electrons and protons. The resulting protons are forwarded to the cathode via the PEM, whereas the electrons are forwarded to the external path (Antonopoulou et al., 2010; Du et al., 2007; Ghasemi et al., 2013; Rahimnejad et al., 2015; Rahimnejad et al., 2011).

Figure 2. Working mechanism of electrode and separator in SMFCs (Modified from Mohan et al., 2014)

Modification of the material used as an anode influences the performance of the SMFCs reactor. Previous studies showed that the use of different electrode materials at the anode generates different amounts of electrical energy; thus, it can affect the overall performance of the SMFCs reactor. Materials that are widely used are graphite carbon in different shapes, including: fiber brush, cloth, rod, paper, and felt because they have a high conductivity and a large surface area (Cercado-Quezada et al., 2010; Ghasemi et al., 2013; Li et al., 2019; Sharma and Li, 2010; Xin et al., 2019).

2.2. Process in the Cathode

The cathode and anode chambers in the MFC work continuously to generate electrical energy that can be utilized. Protons move from the anode chamber to the cathode chamber through the PEM, which refines the electric current.

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (2)$$

Radical oxygen produced in the anode chamber (Equation (2)) moves to the cathode chamber and forms water that spreads on the cathode with the help of a catalyst. Equilibrium can be reached on the basis of equation (2) by connecting the cathode and the anode with external cable connections. The performance of MFCs on the cathode is different from that on the anode. The concentration and type of electron receiver, availability of protons, performance of the catalyst, electrode structure, and capability of the catalyst affect the performance of the cathode. The availability, strong oxidation potential, and nontoxic end products of oxygen make it a suitable electron acceptor for the cathode chamber some cathodes are configured by placing one side of the cathode in direct contact with the cathode chamber and the other side in direct contact with free air.

2.3. Process in ~~Electrode~~ Separator or Membrane

~~2.4. In general,~~ SMFCs consists of anode and cathode chamber separated by cationic membrane or proton exchange membrane, porous ceramic, clayware membrane (Yousefi et al., 2017), and

Formatted: Justified, Indent: Left: -0.63 cm, Line spacing: Double electrode distance (by configuring the placement of electrodes) (Moqsud et al., 2017). Biopotential that occurs due to the metabolic activity of microorganisms and the condition of electron acceptors can induce bioelectricity in SMFCs. The proton exchange membrane (PEM) or other separators in SMFCs, which physically separates the cathode and anode chamber, also prevents the transfer of dissolved oxygen contained in the cathode chamber to the anode chamber so that the anaerobic conditions in the anode chamber can be maintained (Ghasemi et al., 2013). The separators or PEM can facilitate the transfer of protons produced in the anode chamber without the transfer of substrate and oxygen to the cathode chamber. The following may occur when the PEM is not applied in SMFCs: the displacement of oxygen and substrate can result in decreased coulombic efficiency (CE) and microorganism activity, which has a dramatic effect on the system performance and stability. The highly cost PEM / CEM makes many researchers looking for alternative separator substitution. Porous clay, such as novel porous clay earthenware (NCE), could produce higher power output compared to the use of PEM as electrode separator (Daud et al., 2020). Therefore, the higher the thickness of the porous clay, the lower the power generation produced by SMFCs. The difference of the thickness can change the hydraulic pressure and also the transport of fluid through the SMFCs system. The flow of ions will be slower when the thicker clay membrane is applied (Jimenez et al., 2017).~~SMFCs consist of anode and cathode chamber separated by proton exchange membrane (PEM). Biopotential that occurs due to the metabolic activity of microorganisms and the condition of electron acceptors can induce the generation of bioelectricity in SMFCs. The PEM or other separator in SMFCs, which physically separates the cathode and anode chamber, also prevents the transfer of dissolved oxygen contained in the cathode chamber to the anode chamber so that the anaerobic conditions in the anode chamber can be maintained. The separators or PEM can facilitate the~~

transfer of protons produced in the anode chamber without the transfer of substrate and oxygen to the cathode chamber. The following may occur when the PEM is not used in SMFCs: the displacement of oxygen and substrate can result in decreased coulombic efficiency (CE) and microorganism activity, which in turn has an effect on the performance of the reactor and stability of the system.

3. Factors Affecting the Performance of SMFCs

Electricity generated by SMFCs is influenced by various factors, such as electrode material and type of membrane used, salinity and alkalinity, type of waste, and composting factors, such as pH and C/N ratio. Moqsud et al. (2013) stated that SMFCs with a good performance has a low internal resistance and a high electromotive force. Table 1 shows some of the optimizations that have been made to increase the amount of electricity generated by SMFCs.

Table 1 Recent studies related to improvement of MFCs performances treating solid wastes

3.1 Substrate

Substrates or materials used as organic sources for SMFCs can use various types of wastes that contain high organic matter such as kitchen and bamboo wastes. The voltage generated by kitchen waste rapidly increases in the initial phase and gradually becomes constant at the voltage of 620 mV. Conversely, in bamboo waste, the voltage generated gradually increases to 540 mV. This finding is expected because some fruits in kitchen waste contain large amounts of glucose. An adequate supply of glucose activates bacteria and produces a higher voltage (Moqsud et al., 2014). Utomo et al. (2017) used sludge originating from a communal waste treatment plant that has a different age. They observed that the stress generated at the anode with fresh sludge material has a higher value than that with stored sludge material. Xin et al. (2019) determine the effect of the complex compound (glucose, sodium acetate, and food waste hydrolysate) used in MFC on the production of electrical energy. The electrical density produced by the MFC reactor with a food waste hydrolysate substrate was higher than that with glucose and sodium acetate. Wang et al. (2013a) obtained a higher power output using different substrates. With an adequate supply of glucose, complex substrates rich in monosaccharides, organic acids, and other micro-molecules can be directly utilized as SMFCs substrates so that bacteria become more active and generate higher stresses (Pant et al., 2010; Wang et al., 2019a). Similar results were obtained by Jia et al. (2013) and Li et al. (2018), that is, SMFCs can produce a larger amount of energy with substrates in the form of mixed carbon rather than single type of carbon.

In different studies, biogas slurry is used as a substrate for MFC (BS-MFC). Biogas slurry as waste from biogas technology that has been widely applied is considered to cause new problems. Biogas slurry is rich in monosaccharides, organic acids, and other micro-molecules that can be directly utilized as MFC substrates (Pant et al., 2010; Wang et al., 2019a). Wang et al. (2019a) found that microbial acclimation was achieved on the 10^{th} day at 150.4 ± 14.6 mV. The second cycle, which was conducted with the addition of substrates, showed a voltage of 622.7 ± 30.3 mV on the 20^{th} day, indicating that biofilms were formed at the anode. The accumulation of electrical voltage in these three cycles reaches its maximum value and is stable for a sufficiently long period of time. However, the BS-MFC hydrolysis reaction and the long operational period lead to a high level of energy demand and a low average CE production of 4.1% (Wang et al., 2019a).

In different studies, rice husk, soybean residue, coffee residue, and leaves were used as substrate. The choice of substrate is based on the nature of each substrate that is rich in cellulose and biopolymers and is an ideal source of organic matter and the abundance of substrates. Rice husk can increase hydraulic conductivity and porosity on SMFCs reactors. Therefore, substrate composition can affect the community of microorganisms that grow at the anode, as well as the output of electrical energy (Wang et al., 2015). The addition of bio-enzymes to the substrate increases the power density by up to 8.5 times and can decrease the internal resistance by 31% (Wang et al., 2015; Wang et al., 2013b). SMFCs that use solid waste tend to have high levels of chemical oxygen demand (COD). In the study conducted by Samudro et al. (2018), they determined that leaf waste, which had a COD content of 16.567 mg COD/L, had a higher COD removal efficiency of up to 87.67% and a more stable power density of 4.71 mW/m^2 compared with canteen and mixed wastes. However, in this study, high levels of COD do not lead to a high COD removal efficiency and a high-power density output. The optimum COD levels can lead to high power densities.

In addition to the type of waste or organic solid waste used, the degree of alkalinity (Moqsud et al., 2013) and the amount of waste used as substrate also determine the amount of electrical energy that can be generated (Samudro et al., 2018). Large amounts of waste can provide substrates and nutrients for microorganisms that will increase specific energy. The addition of alkaline materials can also increase the electrical power output of SMFCs. The addition of fly ash, for example, produced a maximum electric power per cathode surface area of 54.4 mW/m^2. This value is two times greater than that of SMFCs without added fly ash (Moqsud et al., 2013). In different studies, rice husk, soybean residue, coffee residue, and leaves were used as substrate. The choice of substrate is based on the nature of each substrate that is rich in cellulose and biopolymers and is an ideal source of organic matter and the abundance of substrates. Rice husk can increase hydraulic conductivity and porosity on SMFCs reactors. Therefore, substrate composition can affect the community of microorganisms that grow at the anode, as well as the output of electrical energy (Wang et al., 2015).

Another composting factor that is considered to affect the performance of the reactor is the water content in the SMFCs material used. The power density produced by the SMFCs reactor is measured to be high in the substrate, which has a high water content. The maximum measured power density is 17.71 mW/m^2 with a water content of 60%, with four times the mixing frequency, and a C/N ratio of 30:1. The same study showed that the range of water content that allows the reactor to operate at its optimum is 40% to 60%. Another study showed that the ideal water content for SMFC was 60%; meanwhile, at a water content of 40%, the fermentation process and microorganism activity were inhibited (Wang et al., 2013a; Wang et al., 2017). Before the research was conducted, the macro- and micronutrient content, C/N ratio, and water content were determined in advance to ensure that the process of generating electrical energy and making compost runs optimally (Ganjar et al., 2018; Wang et al., 2015). The C/N ratio of 31:1, water content of 60%, and pH of 6–8 are known to ensure optimum performance, indicating that SMFCs can be integrated into the composting process. The addition of bio-enzymes to the substrate increases the power density by up to 8.5 times and can decrease the internal resistance by 31% (Wang et al., 2015; Wang et al., 2013b). SMFCs that use solid waste tend to have high levels of chemical oxygen demand (COD). In the study conducted by Samudro et al. (2018), they determined that leaf waste, which had a COD content of 16.567 mg COD/L, had a higher COD removal efficiency of up to 87.67% and a more stable power density of 4.71 mW/m^2 compared with canteen and mixed wastes. However, in this study, high levels of COD do not lead to a high COD removal efficiency and a high power density output. The optimum COD levels can lead to high power densities.

The biggest limitation of microbial process in solid phase ecosystem is substrate / mass transfer rate (Rahimnejad et al., 2011). Transfer resistance would be higher since the absence of sufficient solution homogenized the distribution of substrate to microorganism and also the electrons to electrode. Reducing electrode distance may increase the rate of electron transfer, but some other problems occur such as the increasing of oxygen penetration and active surface electrode which lead to the decreasing power output (Sharma and Li, 2010). Water content is the other critical point to note when working with SMFCs. Ideally, 60% of distributed moisture will make the process occur in a good condition (Wang et al., 2015). As many SMFCs reactor working in gravitational direction of electrodes, anode chamber will be flooded and exceeded 60% of moisture content soon after the process is working. The use of Xanthan 80 SF can significantly improve the performance of the SMFCs reactor because the nature of Xanthan 80 SF is able to maintain moisture in the compost and prevent the effects of gravity so that water does not accumulate at the bottom of the reactor. Therefore, cathode chamber will dry and decrease the proton transfer rate which make a lower power production. In this case, drainage and circulation system may be useful for maintaining the power production. This finding is expected because the moisture in the compost is reduced, which in turn inhibits the compost decomposition process and decreases the microbial activity, thereby inhibiting ion transfer and energy production. These results indicate that the use of Xanthan 80 SF can increase the amount of electricity generated and extend the period of electrical energy release (Wang et al., 2017; Samudro et al., 2018). Li et al. (2019) tried to solve the transfer rate problem by using biochar amendment in soil which has limited water content. Biochar could increase electron transfer rate and kinetics because of the presence of electroactive surface. The addition of biochar also can support microbial colonization and increase the rate of biodegradation process. Therefore, knowing the optimization of biochar mass that will be used is important since biochar may decrease the electrical conductivity because of its ability to adsorb ions in soils.

3.2 Environmental Factors

In addition to the type of waste or organic solid waste used, the degree of alkalinity (Moqsud et al., 2013) and the amount of waste used as substrate also determine the amount of electrical energy that can be generated (Samudro et al., 2018). Large amounts of waste can provide substrates and nutrients for microorganisms that will increase specific energy. The addition of alkaline materials can also increase the electrical power output of SMFCs. The addition of fly ash, for example, produced a maximum electric power per cathode surface area of 54.4 mW/m^2. This value is two times greater than that of SMFCs without fly ash addition (Moqsud et al., 2013).

The pH plays a vital role in maintaining the performance of solid-phase microbial fuel cells. The pH can activate several reactions and affect microorganisms' performance in consuming substrates, thus produce bioelectricity (Jadhav and Ghangrekar, 2009). Higher electricity production can occur in a neutral pH range because of exoelectrogens like neutral environmental conditions (He et al., 2009). Low pH condition which is very likely to occur in the anode chamber, can cause the soluble metals to be precipitated, thereby covering the cathode's layer and inhibiting the transfer of electrons to the cathode, and protons to the membrane/separator (Makinen et al., 2013). An increase in the cathode chamber's pH and a decrease in the anode chamber's pH or pH splitting can occur when a separator or PEM in SMFCs is available. This risk might occur since the membrane/separator cannot effectively transfer the protons to the cathode chamber and electrons to the electrode (Rahimnejad et al., 2015). The biggest SMFCs issue is the mass transfer, including the transfer of protons and electrons in a solid-state system (Chiu et al., 2016). Mixing is essential to ensure the uniformity of mass transfer, thus prevent the pH splitting between anode and cathode chamber (Nastro et al., 2017).

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3.23.3 The presence of a separator or PEM in SMFCs can also cause pH splitting, that is, an increase in pH in the cathode chamber and a decrease in pH in the anode chamber (Rahimnejad et al., 2015). Thus, Electrode and System Configuration

In a study conducted by Moqsud et al. (2013), the use of bamboo charcoal with iron wire as an anode material produces the highest electrical voltage compared with carbon fiber alone and carbon fiber with iron wire. The electrical voltage generated in the reactor with bamboo charcoal electrodes with iron wire reaches 420 mV, whereas that in the reactor with carbon fiber with iron wire reaches 260 mV after 3 days of research. This study showed that the addition of iron wire slightly increases the electrical voltage. The maximum power density of 394 mW/m^2 is achieved in reactors with carbon fiber electrode material. This value is higher than that achieved in reactors with bamboo charcoal, which only reaches 8 mW/m^2 (Moqsud et al., 2013). This finding can be attributed to the fact that the contact of biomass with electrodes is higher in carbon fiber than that in bamboo charcoal. Although bamboo charcoal is inexpensive and environmentally friendly, it is less recommended for use as cathode material because its wavy shape causes low biomass contact. In addition, the performance of MFCs in generating electrical energy will be improved if the surface area of the electrodes is increased with respect to the reactor volume (Nastro et al., 2017). In another study, a double anode with graphene material is used because

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graphene is considered to have a larger surface area than carbon graphite (Samudro et al., 2018). Meanwhile, carbon felt was interesting to be used as an electrode because it is porous and has a large surface area, which are suitable for microorganism growth, adhesion, and reduced impedance activation (Kim et al., 2011).

~~The presence of a separator or PEM in SMFCs can also cause pH splitting, that is, an increase in pH in the cathode chamber and a decrease in pH in the anode chamber (Rahimnejad et al., 2015). Thus, v~~Various studies are conducted to determine the type of separator that supports the optimization of the SMFC reactor so that the electrical energy generated can reach the optimum value (Li et al., 2018; Mohan and Chandrasekhar, 2011; Wang et al., 2015). Moqsud et al. (2013) said that the voltage generated by the SMFCs reactor with cellophane separator has the highest value compared with that by the SMFCs reactor with filter paper and PEM. Cellophane is considered to have a lower electrical resistance value than filter paper and PEM. The dry surface of PEM is considered to be the cause of its higher resistance value than cellophane and filter paper. Filter paper is considered to be more permeable than PEM and cellophane. Meanwhile, cellophane is more easily damaged; thus, its quality is low and it cannot be reused. In another study, a single-chamber reactor was used so it did not need a membrane separator or other separator material (Moqsud et al., 2014). However, it is also known that the application of PEM can increase the internal resistance. Novel porous clay Thus, various studies have been conducted to make different reactor configurations to suppress the MFC internal resistance values, for example, single-chamber MFCs, up-flow MFCs, and stacked MFCs (Rahimnejad et al., 2015; Rahimnejad et al., 2012; Rahimnejad et al., 2011).

The distance between the electrodes in a single-chamber SMFCs can also affect the amount of electrical energy generated (Miran et al., 2016; Oh et al., 2010; Mohan et al., 2010). Sandwiched electrodes producing the lowest electrical power output compared to a system which have a distance between the electrodes. The shorter the distance of electrodes (assuming the electrode is located in the middle of the reactor) could produce greater electricity because of the active surface area ensures a high electrical gradient since protons can move to the cathode easily (Mohan and Chandrasekhar, 2011). Therefore, the distance of electrodes can significantly reduce the electricity since the protons need to move further to the cathode. This condition means that determining the optimal distance is essential when working with single chamber SMFCs. Even though the distance between the electrodes must be kept small, sandwiched electrodes and PEM can increase the likelihood of substrate transfer from the anode to the cathode and oxygen transfer from the air to the cathode (Hassan et al., 2014; Palanisamy et al., 2019; Peighambardoust et al., 2010).

~~3.3~~3.4 Microorganisms

Microorganisms involved in the process are also considered an important factor that improve the performance of the reactor. The substrate in the SMFCs is not the only factor influencing the type of dominant microorganisms that exist in the anode. The dominant microorganisms at the anode can also be influenced by the inoculum and the conditions when the reactor is operating (Parot et al., 2009). In another study, Reiche and Kirkwood (2012) stated that SMFCs reactors with mixed culture biocatalysts obtained from three different types of compost produce a maximum electric power density of 12.3 mW/m^2. Mixed culture biocatalysts obtained from three different types of compost were considered to be able to enrich the substrate and exoelectrogenic activity. The efficiency of electron transfer that occurs in SMFCs can be influenced by the selection of biocatalysts to be used. Ion and substrate transport through solid media is an important factor that influences the performance of SMFCs. If those transport is slow, then the electrochemical reactions are reduced. Therefore, transport system in SMFCs becoming critical since water content is limited. In that case, maintaining water content in optimum condition (around 60 – 80%) is necessary (Oliot et al., 2016; Wang et al., 2017).

Wang et al. (2019a) stated that the type of inoculum can determine the rate of substrate decomposition and affect the generation of electrical energy. In this research the dominant genus identified on the anode biofilm was the genus *Pseudomonas* (5%). *Pseudomonas* can produce chemical intermediaries that can transfer electrons to electrodes. In addition, *Hydrogenophaga* (5%) was the dominant genus identified on biofilms derived from household wastewater. The genus consumes H_2 in the anode chamber, thereby inhibiting the generation of electricity by SMFCs with biogas slurry as substrate. In addition to the analysis of the genus level, it is known that four genera of hydrolytic bacteria can break down cellulose, protein, and starch chains into organic micro-molecules, thereby increasing sugar degradation and volatile fatty acids in SMFCs with biogas slurry as substrate. The diversity of the genus of microorganisms contained in SMFCs influences the performance of the reactor because of the different roles of each microorganism in degrading the substrate (Lu et al., 2019; Reiche and Kirkwood, 2012; Wang et al., 2015; Wang et al., 2019b; Zhi et al., 2014

4. Integration of SMFCs with Other Solid Waste Treatment

Solid phase microbial fuel cells (SMFCs) seems to have many potentials when compare to other solid waste treatment. This technology only needs relatively small energy input for supporting chemical reaction in cathode. Moreover, air-cathode MFCs does not need a supply oxygen since it is provided by its system configuration. SMFCs produce a less sludge as an anaerobic power generation system and convert organic matter into direct electricity and biohydrogen. The processed organic matter could be a mature compost and fertilizer. The used electrode could be a soil conditioner, to increase the fertility of soil. It is also producing a less emissions such as CH_4, CO_2, NH_3, N_2O. The same characteristics can be seen in the anaerobic digestion which has the same processing stage as SMFCs. Aerobic composting needs a lot of energy for aeration and mixing and only produce compost with excessive amount of leachate. This type of composting also produces a significant amount of odor and VOC which interfere the environment. While incineration has many benefits for treating solid waste, it also generates dioxin and furan (especially when is working with plastic-based material), CO_2 and N_2O. If the incineration is not controlled properly, the emission and byproduct (fly and bottom ash / slag) may harmful for the environment.

Table 2 Comparison of SMFCs with other conventional solid waste treatment

Typically, maximum energy generated from MFCs treating food and organic waste (in the form of liquid fraction/hydrolysate) is around 0.28 – 0.78 MJ/kg COD (Xin et al., 2018; Xiao and He, 2014). The total energy can be higher until it reaches 2.48 MJ/kg of COD when MFCs are fed by anaerobic sewage sludge and 3.52 MJ/kg of COD by food waste hydrolysate (Wang et al., 2013b; Xin et al., 2019). That energy values may lower, especially when it is compared with other waste to energy (WtE) technology such as incineration which can result in energy values ranging from 3.60 MJ/kg to 6.00 MJ/kg of food waste (Carmona-Cabello et al., 2018; Chen and Christensen, 2010). Although the MFCs energy generation seems promising since only 8 to 12 SMFCs systems might achieve the same energy output as combustion, the energy generation sustainability is doubted compare to thermal processing technologies such as incineration. The condition will be more challenging when SMFCs is implemented to process the solid fraction of municipal waste. The maximum electricity generation from solid-phase MFCs is relatively small and amounted to 0.072 MJ/kg of food waste, as reported by Moqsud et al. (2014). This condition is related to its mass transfer limitation, which resulted in the low electricity generation of SMFCs. Therefore, those values are still on a laboratory scale (none SMFCs in larger scale), which is still in doubt that the process efficiency will be much lower than a pilot or even industrial scale. At the pilot / industrial scale, MFCs reactor must be constructed in a minimum dimension to ensure the power per unit area of the electrode or reactor volume is lower, making the energy generation higher. An ideal substrate supply rate can also be provided in smaller sized reactors (Greenman and Ieropoulos, 2017). This limitation might be solved by integrating other waste processing technologies. ~~Typically, energy generated from MFCs treating food and organic waste (in the form of liquid fraction / hydrolysate) is around 0.28 – 0.78 MJ/kg COD (Xin et al., 2018; Xiao and He, 2014). The total energy can be higher until reached 2.48 MJ/kg COD when MFCs is fed by anaerobic sewage sludge and 3.52 MJ/kg COD by food waste hydrolysate (Wang et al., 2013b; Xin et al., 2019). That energy values are promising, especially when it is compared with other waste to energy (WtE) technology such as incineration which can provide energy values ranging from 3.60 MJ/kg to 4.96 MJ/kg of food waste (Carmona-Cabello et al., 2018). However, the condition will be more challenging when SMFCs is implemented to process the solid fraction of municipal waste. The electricity generation from solid-phase MFCs~~

is relatively small, amounted of 0.072 MJ/kg of food waste as reported by Moqsud et al. (2014). This is related to its mass transfer limitation which resulted to the low electricity generation of SMFCs. Therefore, those values are still in a laboratory scale which is still in doubt that the process efficiency will be much lower than a pilot or even industrial scale. This limitation might be solved by integrating other waste processing technologies.

Dark fermentation (DF) is a technology commonly used to recover bio-hydrogen from high cellulose content materials. Through fermentation reactions, cellulose is hydrolyzed to hexoses and produces acetate and hydrogen gas (Wang et al., 2011). However, the DF system is only able to recover one third of the total theoretical energy that could be recovered. The combination of microbial fuel cells and microbial electrolysis cells (MFC-MEC) to treat DF effluent could increase bioenergy production. MFC could support MEC's energy needs for converting substrate into H_2, as well as direct electricity for the system as a whole (Chookaew et al., 2014). Increased power density in MFCs also resulted from the use of dark fermentation effluents where the maximum power density increased to 4 times more significant based on research conducted by Varanasi et al. (2017). The combination of DF-SLS (Solid Liquid Separation)-MFC can also be used to treat cellulose waste such as swine manure and rice bran. As a post-treatment of DF and SLS, MFC can improve the energy recovery process in the form of bio-electricity. MFC efficiency will also increase due to higher degradable COD available from DF and SLS processes (Schievano et al., 2016). The potential for utilizing integrative technology might be explored more intensely to get better system durability and sustainability.

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Xin et al. (2018) showed that the amount of electric power generated by MFCs is greater than by anaerobic digester (AD). This finding can be attributed to the fact that the AD process requires a longer residence time than the MFCs technology, thereby affecting the size of the reactor used. The MFCs reactor can be 5.5 times smaller than the AD reactor. The MFCs application is considered to be more practical, more environmentally friendly, and more economically feasible in terms of electricity conversion and production costs than AD. The MFCs is expected to become a solution for processing food waste that ensures the rapid recovery of resources and electricity sources by not producing any other waste. Strengthening Xin et al. (2018) proposed scheme, Antonopoulou et al. (2019) also proposed a food waste management system, using an integrated biochemical process. Food waste is grinded and heated (as waste pre-processing system) then carbonaceous COD is extracted to produce two fractions of product, liquid and solid fraction. The liquid fraction is processed using MFCs continuously and the solid fraction is processed using anaerobic digester. This scheme is considered to be applied in pilot scale because it produces more energy recovery value of 12.32 MJ/kg of total solids (TS), or almost comparable to the maximum net calorific value using various types of combustion, amounting to 18.09 - 18.38 MJ/kg TS. The total energy produced from MFCs and anaerobic digester are still positive, especially to cover the pre-processing energy needs of 8 MJ/kg TS (Antonopoulou et al., 2019; Wang et al., 2013b; Xin et al., 2018). This energy balance can still be reduced if it uses cheap and energy-friendly drying technology such as bio-drying or low-cost decanters to reduce the excessive amount of water content in the food waste (Velis et al., 2009). In case of integration with aerobic composting, the leachate can be processed using MFCs for further substrate conversion. The generated energy could be used as self-supporting system for aerating the compost pile. In other hand, MFCs itself can be directly treat the organic fraction of solid waste without the help of anaerobic and aerobic composting. However, this option is not feasible since the energy generated is lower and need further investigation to enhance the productivity of electricity. Figure 3 shows the proposed mechanism for integrating other solid waste treatment with SMFCs.

Figure 3. SMFCs and other solid waste treatment achieving sustainable energy production (modified from Antonopoulou et al. (2019) and Xin et al. (2018)

5. Conclusions

SMFCs are an alternative technology of generating electricity that is environmentally friendly and sustainable. Various studies have been conducted to determine the optimum configuration of the MFC reactor and its development potential to generate electrical energy. The various factors that affect the performance of SMFC reactors, such as substrates, electrodes, microorganisms involved, and reactor configuration, need to be further investigated. The presence of separator and electrode distance used in the SMFC reactor are important to determine since it is related to the electron and proton transfer. Mass transfer process is also important in a solid phase, ensuring the microorganism can breakdown the substrate properly. Therefore, this limitation may be further studied, and finding the best configuration system may enhanced the electricity generated by the SMFCs. Integrating this technology with other solid waste processing system could be possible and reliable, since SMFCs itself has many limitation. The proposed system is combining the preprocessing system, anaerobic digestion, composting, and also SMFCs in a sequential system. After solid waste processed by using pretreatment technology, solid waste is sending to composter, both in anaerobic or aerobic composting system. Then, the leachate, slurry or hydrolysate from the process may be treated by using SMFCs. The direct electricity can be used as alternative energy sources for other treatment needs. SMFCs also could be used as a single solid waste treatment, but the efficiency may be lower than the proposed system instead and not feasible for field application.

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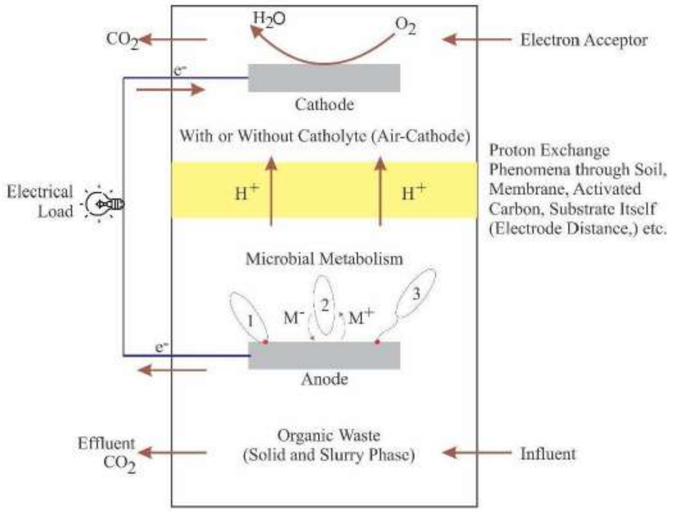

Figure 1. Schematic illustration of the SMFC process (Modified from Nastro et al., 2017 and Logroño et al., 2015)

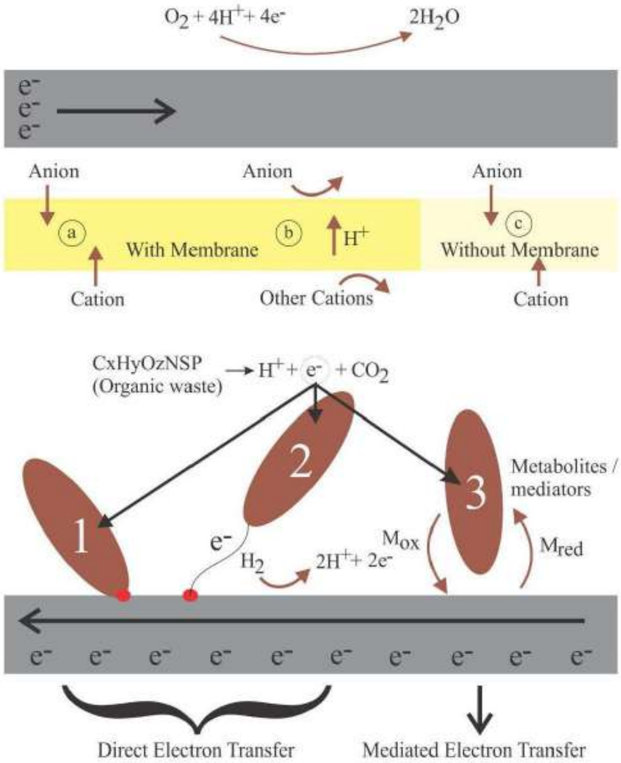

Figure 2. Working mechanism of electrode and separator in SMFCs (Modified from Mohan et al., 2014)

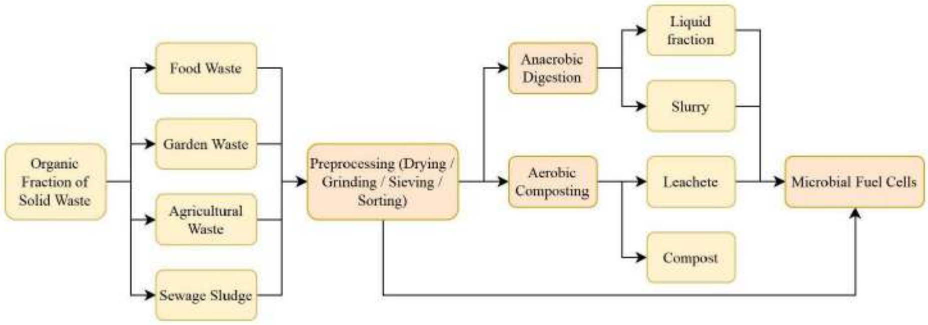

Figure 3. SMFCs and other solid waste treatment achieving sustainable energy production (modified from Antonopoulou et al. (2019) and Xin et al. (2018)

Table
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Table 1 Recent studies related to improvement of MFCs performances treating wastes

Substrate	Electrode		Separator	Bacteria	Operating Phase	System Configuration	Maximum Power Density	References
	Anode	Cathode						
Household food waste (glucose) hydrolysate	Graphite granules	MnO_2	Nd	Mixed anaerobic microbial culture	Liquid	Single chamber	11,800 mW/m^3 per anode working volume	Antonopoulou et al. (2019)
Organic fraction of municipal waste	Graphite plates	Graphite plates	Membraneless	*Lactobacillaceae*, *Bacillaceae*, *Clostridia*, and *Pseudomonadaceae*, with *Pseudomonas aeruginosa*	Solid	Single chamber	1.75 mW/m^2 per anode specific surface area	Florio et al. (2019)
Food waste hydrolysate	Carbon brush	Plain carbon cloth	Nd	*Moheibacter*, *Azospirillum*, *Geobacter*, *Petrimonas*, *Alicycliphilus*, *Rhodococcus*, *Pseudomonas*	Liquid	Single chamber	173 mW/m^2 per total working surface area	Xin et al. (2018)
Vegetable and fruit residues	Carbon fiber	Ceramic disk	Nd	Nd	Solid	Single chamber	Nd	Nastro et al. (2017)
Municipal solid waste	Carbon felt, stainless steel, carbon paper, and carbon plate		Oxygen and $K_3Fe(CN)_6$	Nd	Solid	Dual chamber	1,817 mW/m^2 per anode specific surface area	Chiu et al. (2016)
Mix of apples, lettuce, green beans, and soil	Carbon felt	MnO_2	Nd	*Gammaproteobacteria* and *Bacilli*	Solid	Single chamber	5.29 mW/m^2 per anode specific surface area	Khudzari et al. (2016)

Substrate	Electrode		Separator	Bacteria	Operating Phase	System Configuration	Maximum Power Density	References
	Anode	Cathode						
(potting mix)								
Dewatered sludge	Graphite fiber	Titanium wire	PEM (Nafion 117, Dupont Company)	Electricigens, the common fermentation bacterial colonies	Solid	Dual chamber	5,600 mW/m^3 per anode working volume	Yu et al. (2015)
Kitchen and yard wastes	Carbon fiber	Carbon fiber	Nd		Solid	Single chamber	39.2 mW/m^2 per anode specific surface area	Moqsud et al. (2015)
Vegetable and fruit wastes	Carbon fiber		Soil-activated carbon	Mixed anaerobic microbial culture	Solid	Single chamber	Nd	Logroño et al. (2015)
Rice husks, soybean residue, coffee residue, and leaf mold	Carbon felt		Nd	Nd	Solid	Single chamber	4.6 mW/m^2 per anode specific surface area	Wang et al. (2015)
Wastes from compost facility	Tin-coated copper mesh	Coil spring	Soil-activated carbon	Mixed anaerobic microbial culture	Solid	Single chamber	47.6 mW/m^2 per anode specific surface area	Karluvalı et al. (2015)
Kitchen garbage and bamboo waste (glucose)	Carbon fiber	Carbon fiber	Soil-activated carbon	Mixed anaerobic microbial culture	Solid	Single chamber	60 mW/m^2 per anode specific surface area	Moqsud et al. (2014)
Food waste hydrolysate	Brushes	Carbon cloth	Nd	Mixed anaerobic microbial culture	Liquid	Single chamber	~556 mW/m^2 per anode specific surface area	Jia et al. (2013)

Substrate	Electrode		Separator	Bacteria	Operating Phase	System Configuration	Maximum Power Density	References
	Anode	Cathode						
Grass cuttings, leaf mold, rice bran, oil cake, and chicken droppings	Carbon fiber	Carbon fiber	Filter paper, cellophane, and PEM	Nd	Solid	Dual chamber	394 mW/m^2 per cathode specific surface area	Moqsud et al. (2013)
Sewage sludge	Carbon felt and rod	Carbon felt and rod	Proton exchange membrane	Mixed anaerobic microbial culture	Solid	Single chamber	38.1 W/m^3 per anode working volume	Wang et al. (2013b)
Rice hull, bean residue, and ground coffee wastes	Carbon felt	Carbon felt	Nd	Nd	Solid	Single chamber	264.7 mW/m^2 per anode specific surface area	Wang et al. (2013a)

Nd: Not defined

Table 2 Comparison of SMFCs with other conventional solid waste treatment

Solid Waste Treatment	Energy Input	Products	Byproducts	Emissions	References
Solid Phase Microbial Fuel Cells	Half aeration in cathode and ignored when working in air-cathode Mixing (if necessary)	- Electricity - Soil conditioner - Compost - Fertilizer (in slurry phase) - Biohydrogen	Less sludge	CH_4, CO_2, NH_3, N_2O	Li et al., (2020)
Aerobic Composting	Full aeration Mixing	Compost	Leachate	Odor, CO_2, CH_4, VOC, NH_3, N_2O	Rincon et al., (2019) Smith and Aber, (2018) Bernstad and la Cour Jansen (2012)
Anaerobic Digestion	Mixing (if necessary)	- Fertilizer - Biogas - Soil conditioner - Non-direct electricity (from heat) - Compost	Less sludge	CH_4, CO_2, NH_3, N_2O	Santos et al., (2020) Rincon et al., (2019)
Incineration	Full aeration	- Heat/steam - Electricity	Ash and slag	Dioxin and furan (if the waste contains plastic-based material), CO_2, N_2O	Assi et al., (2020)

*Declaration of Interest Statement

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Waste Valorization using Solid-pPhase Microbial Fuel Cells (SMFCs): Recent Trends and Status

Abstract

This review article discusses the the use ofuse of solid waste processed in solid--phase microbial fuel cells (SMFCs) as a source of electrical energy source. MFCs are usually typically operated in the liquid phase because of the ease of the ion transfer process is efficient in liquid media. Nevertheless, some researchers say have considered that the potential for MFCs in the solid phases (particularly for treating solid waste). -This hasis also quite promiseing if several important factors are optimized, such as the type and amount of substrate, microorganism community, system configuration, and type and number of electrodes, whichare optimized, thereby increasesing the amount of electricity generated. The critical factors that affectsing the SMFCs performance is the efficiency of electron and proton transfer through solid media. However, this limitation may be overcome by electrode system enhancements and regular substrate mixing. In the other ha Tnd, the integration of SMFCs with other conventional solid waste treatments could be used to produce sustainable green energy. Although SMFCs produce relatively small amounts of energy compared with than other waste--to--energy treatments, SMFCs are is still quite promising to achieve zero zero-emission treatment. Therefore, this article is expected to addresses the challenges and also fills the gaps in in SMFCs research and development.

Keywords: anaerobic digestion, compost, mass transfer, microbial fuel cells, solid-phase

1. Introduction

1

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The increaseing of municipal solid waste generation is an issue faced by almost nearly all countries in the world, due to an increasethe expansion of in industrial activitiesy and global development. In developing countries, almost 90% of municipal waste is transported directly to landfills directly without any intermediate treatment that couldan reduce the solid waste volume of solid waste (Barik and Paul, 2017). This waste management activity even contributes 5% toto the total global greenhouse gas emissions by 5% compared to total world greenhouse gas emissions. Recycling, effective waste treatment, and source-segregation are the main primary strategies in to reduceing emissions and environmental impacts due to increased waste generation (Florio et al., 2019). Waste is considered to still have a -relatively large enough energy content such that, so waste- to- energy is considered a viable one of the alternatives, that is considered (Chiu et al., 2016). Composting and anaerobic digestion are biological treatment technologies that have been used and explored massively extensively in various countries (Yu et al., 2015; Xin et al., 2018). However, conventional composting under aerobic conditions requires more energy for mixing and an air supply, which could -and may produce a huge vast amounts of leachate (Chu et al., 2019). Anaerobic composting, which is commonly known as anaerobic digestion, can be an alternative solution for to converting solid waste into reusable energy and biofuel (Khudzari et al., 2016). Many rRecent works research has shown revealed that anaerobic digestion has many constraints, such as a long residence time, relatively a low purification of biomethane and its conversion to electricity, and many a variety of safety issues, which makes this technology cannot be aan imperfect solution for zero- discharge treatment (Xin et al., 2018).

Recently, microbial fuel cells (MFCs) is were found as to be an alternative treatment for to generateing electricity from waste (waste valorization) without intermediate treatment steps asbecause anaerobic digestion does by utilizesing electrogenic (anodophilic) microorganisms (Xin et al., 2018). Bioelectric The bioelectric energy of MFCs is dependsing on the electron transfer process and biodegradation efficiency of solid waste (Song et al., 2015). Many researchers use the terms term of solid- phase MFCs (SMFCs / SPMFCs) (Logrono et al., 2015; Wang et al., 2015; Mohan et al., 2011for MFCs that convert solid waste into electricity (Logrono et al., 2015; Wang et al., 2015; Mohan et al., 2011)); however, some and a few of themresearchers use the termss of compost MFCs (cMFCs) (Khudzari et al., 2016) orand biogas slurry MFCs (BSMFCs) (Wang et al., 2019a) to name MFCs which converting solid waste into electricity. Solid-phase microbial fuel cells (SMFCs) are one of the developments in MFCs technologiesy that can be applied to solid waste, and These are claimed to be able to accelerate the process of anaerobic waste degradation process, directly harvest electrical energy directly, and produce mature compost from organic compounds (Choudhury et al.b, 2017; Moqsud et al., 2013; Moqsud et al., 2015; Pandey et al., 2016; Santoro et al., 2017). SMFCs areis profitable because it they only requires low-cost materials (Du et al., 2007; He et al., 2017). Moreover, theirits capability to generate electricity directly makes them s it an direct alternative source for renewable energy source, which has attracteding considerable attention from researchers (Do et al., 2018; Escapa et al., 2016; Xia et al., 2018). In addition, solid waste which is used as substrate also makes SMFCs to be an alternative method forto overcomeing the problem of solid waste treatment because it uses the solid waste as a substrate toto provide an environmentally friendly and sustainable source of electricity (Gude, 2016; Yasri et al., 2019). Thereforeus, SMFCs are considered to be capable of addressing multi-sectoral problems sinceas itthey can be integrated with other processing waste treatments, such as aerobic composting or anaerobic digestion (Kadier et al., 2016; Logan, 2009; Trapero et al., 2017; Utomo et al., 2017).

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Over the lpast five years alone (2016–2020 as article in press), 2,499 review articles, 1,193 book chapters, and 1,513 research articles relating to the utilization of MFCs in various treatments have been published based on -were found on sciencedirect.com (beyond other scholarly databases). NeverthelessHowever, there are limited finding articles that discussabout the use of SMFCs for comprehensive solid waste management is quite difficult. Rahimnejad et al. -(2015) explained in detail the application of MFCs to processes at anodes -cathodes processes;, proton transfer processes through cation exchange membranes, anion exchange membranes, or bipolar membranes;, the production of biohydrogen, bioelectricity, and biosensors;, and wastewater treatment. Information about concerning advanced developments in the use and manufacturing process of electrodes and MFC membranes has also beenwas updated discussed by Palanisamy et al. (2019). Meanwhile, Zhang et al. (2016) and Khudzari et al. (2016) used bibliometric methods to measure the extent of global research trends, explicit research, and developments regarding MFCs using the based on the Scopus and Web of Sciences databases, or in several specifically in several journals, which are the main platforms of MFC progress reporting. However, to the authors' -understandingknowledge, there has not been a single any article that summarizinges, discussinges, andor -providinges a detailed descriptions of the development of SMFCs for treating solid waste. The factors that influence the performance optimization of the performance of the SMFCs reactors, as mentioned -previouslybefore, need to be further investigated through various in-depth and comprehensive studies. This review article was written to better understand and analyze the technological basies of SMFCs and their influential factors that influence it,. as well as In addition, potential obstacles are considered that may be encountered in the future in with its further development toward industrial commercialization. Through this article, we can collate the results of recent studies ~~that have been conducted to~~ on the ~~optimize the~~ performance optimization of SMFCs, ~~and its~~ their possible integration and ~~comparation~~comparison with other technologies, ~~as well as~~and the various improvements needed to enhance the results of ~~generating~~ electricity generation using SMFCs are collated throughout this article.

2. Fundamental Process of an SMFC

An SMFC~~s~~ is a technology used to generate ~~environmentally~~ eco-friendly electricity from biomass by utilizing microorganisms (Garita-Meza et al., 2018; Mäkinen et al., 2013; Pushkar et al., 2016). SMFCs employ the bioelectrogenesis capability of microorganisms to utilize organic compounds as electron acceptors to ~~where~~ generate energy ~~is generated in the process~~. This system directly harvests the energy generated ~~by t~~from the microorganisms ~~directly~~ without the need for combustion (Calignano et al., 2015; Minutillo et al., 2018; Nastro et al., 2017). In g~~G~~eneral~~ly~~, the configuration of SMFC~~s~~ ~~configuration~~ systems consists of two chambers: a cathode and an anode ~~chamber~~, which are separated ~~by~~ with specifie~~d~~ membranes. The cathode is a chamber ~~which is~~ full of oxygen~~,~~ where protons ~~will move toward the cathode chamber~~ collect to form water molecules (Logroño et al., 2016a; Moqsud et al., 2013). The two electrode chambers are separated by a mediating membrane ~~as a mediator capable of moving~~ that allows protons to pass from the anode ~~to the cathode,~~ and transferring electrons between the two electrodes~~,~~ ~~and~~ while inhibiting the entry of oxygen into the anode. However, ~~there are also SMFCs that~~some SMFCs do not use membranes and rely only on the distance between ~~the two~~ electrodes (Logroño et al., 2016a; Logroño et al., 2016b; Mohan and Chandrasekhar, 2011). Figure 1 ~~generally~~ illustrates the general processes that occur in ~~the~~ SMFCs.

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Figure 1. Schematic illustration of the SMFCs process (Modified from Nastro et al., 2017 and Logroño et al., 2015)

Chemical energy present in ~~the~~ organic waste will be oxidized by microorganisms in the anode chamber. Microorganisms extract the energy needed to build biomass through the metabolic~~sm~~ process (Palanisamy et al., 2019). The effectiveness of the SMFCs reactors is influenced by several factors, such as the oxygen supply and consumption in the cathode chamber, oxidation of the substrate in the anode chamber, electron transfer from the anode chamber to the anode surface, and the proton exchange membrane (PEM) permeability (Rahimnejad et al., 2015; Sharma and Li, 2010). In other cases, circuit connections ~~is~~are ~~also~~ important ~~to note, since~~ as they~~it can~~ increase the voltage output to 344.11% times ~~greater than~~ more than a single reactor (Utomo et al., 2017).

2.1. Process in the Anode

The anode chamber is an important component of SMFCs. Microorganisms that play a role in substrate degradation and electron production attach to the electrodes in the anode chamber~~.~~, which ~~The process~~ occurs at the anode under anaerobic conditions. The presence of oxygen in the anode chamber ~~can~~ inhibits the generation of electricity by the microorganisms. In addition ~~to the electrodes and microorganisms~~, there are also substrates and mediators in the anode chamber. The general reactions that occur at the anode are as expressed in Equation (1).

$$Biodegradable\ organics \xrightarrow[\text{Anaerobic environment}]{\text{Active microorganism}} CO_2 + H^+ + e^- \quad (1)$$

The microorganisms present in the anode act as catalysts capable of that breaking the substrate into simpler molecules. This active biocatalyst is able to oxidizes the substrate and produces electrons and protons. The resulting protons are forwarded transmitted to the cathode via the PEM, whereas the electrons are forwarded transmitted toalong the external path (Antonopoulou et al., 2010; Du et al., 2007; Ghasemi et al., 2013; Rahimnejad et al., 2015; Rahimnejad et al., 2011).

Figure 2. Working mechanism of the electrodes and separator in SMFCs (Mmodified from Mohan et al., 2014)

Modifications to of the anode material used as an anode influences the performance of the SMFCs reactors. Previous studies have showned that the use of different electrode materials at the anode generates different various amounts of electrical energy; thus, which it can affects the overall performance of the SMFCs reactor. Widely used mMaterials that are widely used areinclude different forms of graphite carbon in different shapes, including: including a fiber brush, cloth, rod, paper, and felt because they each have a a high conductivity and a large surface area (Cercado-Quezada et al., 2010; Ghasemi et al., 2013; Li et al., 2019; Sharma and Li, 2010; Xin et al., 2019).

2.2. Processes in the Cathode

The cathode and anode chambers in the MFC work continuously to generate electrical energy that can be utilized. Protons move from the anode chamber to the cathode chamber through the PEM, which refines the electric current.

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (2)$$

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Radical oxygen produced in the anode chamber (Equation (2)) moves to the cathode chamber ~~and~~ to forms water that spreads on the cathode with the help of a catalyst. Equilibrium can be reached ~~on the basis of~~ based on ~~e~~Equation (2) by connecting the cathode and the anode with external cable connectors~~ions~~. The ~~performance of~~ MFCs performance on the cathode is different from that on the anode. The concentration and type of electron receiver, availability of protons, performance of the catalyst, electrode structure, and capability of the catalyst all affect the cathode performance ~~of the cathode~~. The availability, strong oxidation potential, and nontoxic end products of oxygen make it a suitable electron acceptor for the cathode chamber. S~~s~~ome cathodes are configured by placing one side of the cathode in direct contact with the cathode chamber ~~and~~ while the other side is in direct contact with free air.

2.3. Process in Separator or Membrane

SMFCs consist~~s~~ of an anode and a cathode chamber separated by a cationic membrane or ~~proton exchange membrane~~PEM, a porous ceramic~~,~~ clayware membrane (Yousefi et al., 2017),~~,~~ and electrode distancinge (~~by~~ configureding ~~the~~ placement of electrodes) (Moqsud et al., 2017). Biopotential that occurs due to ~~the~~ metabolic activity of the microorganisms and the condition of electron acceptors can induce bioelectricity in SMFCs. The ~~proton exchange membrane (~~PEM~~)~~ or other separators in SMFCs~~,~~ (which not only physically separate~~s~~ the cathode and anode chamber~~s,~~ but also prevent~~s~~ the transfer of dissolved oxygen contained in the cathode chamber to the anode chamber) ~~so that~~ maintain the anaerobic conditions in the anode chamber ~~can be maintained~~ (Ghasemi et al., 2013). The separators or PEM can facilitate the transfer of protons produced in the anode chamber without the transfer of the substrate ~~and~~ or oxygen to the cathode chamber. ~~The following may occur~~ W~~w~~hen the PEM is not applied in SMFCs, ~~:~~ the displacement of the oxygen

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and substrate can result in a decreased cCoulombic efficiency (CE) and microorganism activity, which has a dramatically eaffects on the system performance and stability. The highly cost of PEM / CEM makes many has shifted attention researchers looking for to alternative separators substitution. Porous clays, such as novel porous clay earthenware (NCE), could produce higher power outputs compared to the use of PEM as aelectrode separator (Daud et al., 2020). Therefore, the higher the thickness of the pPorous clay with a larger thickness, generates lessthe lower the power generation produced byin the SMFCs. The difference of the tThickness differences can change the hydraulic pressure and also the transportation of fluid through the SMFCs system. The flow of ions will also be slower when withthe thicker clay membranes is applied (Jimenez et al., 2017).

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3. Factors Affecting the SMFC Performance of SMFCs

Electricity generated by SMFCs is influenced by various factors, such as the electrode material, and type of membrane used, salinity, and alkalinity, type of waste, and composting factors, such as the pH and C/N ratio. Moqsud et al. (2013) stated that SMFCs with a good performance hayes a low internal resistance and a high electromotive force. Table 1 shows some of the optimizations that have been made to increase the amount of electricity generated by SMFCs.

Table 1 Recent studies related to improvements ofin MFCs performances when treating wastes

3.1 Substrate

Substrates or materials used as organic sources for SMFCs can use various types of wastes that contain high organic matter, such as kitchen and bamboo wastes. The voltage generated by kitchen

Commented [DD6]: Please note that it is unclear what these wastes are or how they are related. Consider "such as from food and bamboo processing" if it does not change the intended meaning. If accepted, please update "kitchen waste" with "food waste" throughout the entire manuscript.

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waste rapidly increases rapidly in the initial phase and gradually becomes constant at stabilizes to thea voltage of 620 mV. Conversely, in bamboo waste, the generated voltage generated gradually increases to 540 mV. This finding is expected because some fruits in kitchen waste contain large significant amounts of glucose. An aAdequate suppliesy of glucose activates bacteria and produces a higher voltage (Moqsud et al., 2014). Utomo et al. (2017) used sludge originating from a communal waste treatment plant that has a of different ages. They observed that the stress generated at the anode with fresh sludge material has a is a higher value than that with stored sludge material. Xin et al. (2019) determined the effects of the complex compounds (glucose, sodium acetate, and food waste hydrolysate) used in MFCs on the when producingtion of electrical energy. The electrical density produced by the MFC reactors with a food waste hydrolysate as a substrate was higher than that with glucose and sodium acetate. Wang et al. (2013a) obtained a higher power outputs using different substrates. With an adequate supply of glucose, complex substrates rich in monosaccharides, organic acids, and other micro-molecules can be used directly utilized as the SMFCs substrates so that bacteria become more active and generate higher stresses (Pant et al., 2010; Wang et al., 2019a). Similar results were obtained by Jia et al. (2013) and Li et al. (2018), that iswhere, SMFCs can produces a larger amount of energy with substrates in the form of mixed carbon rather than a single carbon type of carbon.

In different studies, Bbiogas slurriesy ishave also been used as a substrate for MFCs (BS-MFC). Biogas slurry as waste from biogas technologiesy that has been widely applied and is considered to cause new problems. Biogas slurry is rich in monosaccharides, organic acids, and other micro-molecules that can be directly utilized as MFC substrates (Pant et al., 2010; Wang et al., 2019a). Wang et al. (2019a) found that microbial acclimation was achieved on the 10^{th} day at 150.4 ± 14.6

mV. The second cycle, which was conducted with the by addiingtion of substrates, showed a voltage of 622.7 ± 30.3 mV on the 20th day,. This indicatesing that biofilms were formed at the anode. The accumulation of electrical voltage in these three cycles reaches its maximum value and is stable for a sufficiently long period of time. However, the BS-MFC hydrolysis reaction and the long operational period lead to a high level of energy demand levels and a lower average CE production of 4.1% (Wang et al., 2019a).

In different studies, rRice husk, soybean residue, coffee residue, and leaves were have also been used as substrates. The choice of substrate is based on the nature of each substrate as that ithoses rich in cellulose and biopolymers and isare an ideal sources of organic matter and the abundance of substrates. Rice husk can increase the hydraulic conductivity and porosity onof SMFCs reactors. Therefore, the substrate composition can affect the community of microorganisms that grow at the anode, as well as the output of electrical energy output (Wang et al., 2015). The addition of bio-enzymes to the substrate increases the power density by a factor of up to 8.5 times and can decrease the internal resistance by 31% (Wang et al., 2015; Wang et al., 2013b). SMFCs that use solid waste tend to have higher levels of chemical oxygen demand (COD). AIn the study conducted by Samudro et al. (2018), they determined that leaf waste, which had a COD content of 16.567 mg COD/L, had a higher COD removal efficiency of up to 87.67% and a more stable power density of 4.71 mW/m^2 compared with canteen and mixed wastes. However, in this study, high levels of of COD do not lead to a high COD removal efficiency and or a high-power density output. Thus, Tthere is some optimum COD levels thatcan leads to high power densities.

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The ~~biggest~~ greatest limitation of microbial processes in solid phase ecosystems is the substrate~~-~~/ mass transfer rate (Rahimnejad et al., 2011). Transfer resistance ~~would be~~ is higher ~~since~~ when the absence of a sufficient solution to homogenize~~d~~ the distribution of the substrate to microorganisms ~~and also~~ or~~the~~ electrons to the electrode. Reducing the electrode distance may increase the rate of electron transfer, but some other problems occur in this case, such as ~~the~~ an increased~~ing~~ ~~of~~ oxygen penetration and active surface electrode, which leads to ~~the~~ a decreased~~ing~~ power output (Sharma and Li, 2010). The ~~W~~water content is the other critical point ~~to note~~ when working with SMFCs. Ideally, a 60% ~~of~~ distributed moisture will ~~make~~ allow the process to occur in ~~a~~ good conditions (Wang et al., 2015). As many SMFC~~s~~ reactors ~~working~~ operate in the gravitational direction ~~of~~for electrodes, the anode chamber ~~will be~~is flooded and exceeds~~ed~~ 60% of the moisture content soon after the process ~~is working~~begins. The use of Xanthan 80 SF can significantly improve the performance of the SMFC~~s~~ reactor because it~~the~~ naturally~~e~~ ~~of Xanthan 80 SF is able to~~ maintains moisture in the compost and ~~prevent~~ reduces the effects of gravity so that water does not accumulate at the bottom of the reactor. Therefore, the cathode chamber will dry and decrease the proton transfer rate, which ~~make~~ causes a lower power production. In this case, a drainage and circulation system may be useful ~~for~~ to maintain~~ing~~ the power production. This ~~finding~~ is expected because the moisture in the compost is reduced, which ~~in turn~~ inhibits the compost decomposition process and decreases ~~the~~its microbial activity.~~,~~ ~~thereby~~ This inhibits~~ing~~ ion transfer and energy production. These results indicate that the use of Xanthan 80 SF can increase the amount of electricity generated and extend the period of electrical energy release (Wang et al., 2017; Samudro et al., 2018). Li et al. (2019) tried ~~to~~ solving~~e~~ the transfer rate problem ~~by~~ using biochar amendment in soil, which has a limited water content. Biochar could increase the electron transfer rate and kinetics because of the presence of an electroactive surface. The addition of biochar ~~also~~ can also

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support microbial colonization and increase the rate of biodegradation ~~process~~. Therefore, knowing the optimalization ~~of~~ biochar mass ~~that will be used~~ is important ~~since~~ as biochar may decrease the electrical conductivity ~~because~~ due to ~~of~~ its ability to adsorb ions in soils.

3.2 Environmental Factors

In addition to the type of ~~waste or~~ organic solid waste used, the degree of alkalinity (Moqsud et al., 2013) and the amount of waste used as a substrate also determine the generated ~~amount of~~ electrical energy ~~that can be generated~~ (Samudro et al., 2018). Large amounts of waste can provide substrates and nutrients for microorganisms that will increase the specific energy. The addition of alkaline materials can also increase the electrical power output ~~of~~from SMFCs. The addition of fly ash, for example, produces~~d~~ a maximum electric power per cathode surface area of 54.4 mW/m^2~~.~~, ~~This value~~ which is two times greater than that of SMFCs without fly ash ~~addition~~ (Moqsud et al., 2013).

The pH plays a vital role in maintaining the performance of solid-phase microbial fuel cells. The pH can activate several reactions and affect the microorganisms' performance in consuming substrates~~,~~ ~~thus~~ to produce bioelectricity (Jadhav and Ghangrekar, 2009). Higher electricity production can occur in a neutral pH range because of exoelectrogens, like the neutral environmental conditions (He et al., 2009). A ~~L~~low pH ~~condition which~~ is ~~very~~ likely ~~to occur~~ in the anode chamber, and can cause ~~the~~ soluble metals to ~~be~~ precipitate~~d~~, ~~thereby~~ which covers~~ing~~ the cathode~~'s~~ layer and inhibits~~ing~~ the transfer of electrons to the cathode~~,~~ and protons to the membrane/separator (Makinen et al., 2013). An increase (decrease) of the pH in the cathode (anode) chamber~~'s pH and a decrease in the anode chamber's pH~~ or pH splitting can occur when a separator or PEM in the SMFC~~s~~ is available. This may ~~risk might~~ occur ~~since~~ as the membrane/separator cannot effectively transfer ~~the~~ protons to the cathode chamber and electrons to the electrode (Rahimnejad et al., 2015). The ~~biggest~~ greatest SMFC~~s~~ issue is ~~the~~ mass transfer, including the transfer of protons and electrons in a solid-state system (Chiu et al., 2016). Mixing is essential to ensure ~~the~~ uniformity of the mass transfer, ~~thus~~ which prevents ~~the~~ pH splitting between the anode and cathode chambers (Nastro et al., 2017).

Another composting factor that ~~is considered to~~ may affect the reactor performance ~~of the reactor~~ is the water content in the SMFC~~s~~ material ~~used~~. The power density produced by the SMFC~~s~~ reactor is measured ~~to~~ as beingbe high in the substrate, which has a high- water content. The maximum measured power density is 17.74 mW/m^2 with a water content of 60%, ~~with~~ four times the mixing frequency, and a C/N ratio of 30:1. The ~~range of~~ water content range that allows the reactor to operate at its optimum is 40~~% to~~–60%. Another study showed that the ideal water content for SMFCs was 60%~~;~~, ~~meanwhile~~while~~,~~ ~~at~~ a water content of 40%~~,~~ inhibits the fermentation process and microorganism activity ~~were inhibited~~ (Wang et al., 2013a; Wang et al., 2017). Before the research was conducted, the macro- and micronutrient content, C/N ratio, and water content were determined to ensure that the ~~process of generating~~ electrical energy generation and ~~making~~ compost creation ~~runs~~ are optimall~~y~~ (Ganjar et al., 2018; Wang et al., 2015). The C/N ratio of 31:1, water content of 60%, and pH of 6–8 ~~are known to~~ ensure optimal~~um~~ performance, indicating that SMFCs can be integrated into the composting process.

3.3 Electrode and System Configuration

In aA study conducted by Moqsud et al. (2013), the used of bamboo charcoal with iron wire as anthe anode material and produceds the highest electrical voltage compared with carbon fiber alone andor carbon fiber with iron wire. The electrical voltage generated in the reactor with bamboo charcoal electrodes with iron wire reacheds 420 mV, whereas that in the reactor with carbon fiber withand iron wire reacheds 260 mV after 3 days of research. Theiris study showed that the addition of iron wire slightly increases the electrical voltage. TheA maximum power density of 394 mW/m^2 iswas achieved in reactors with carbon fiber electrode material. This value is higher than that achieved in reactors with bamboo charcoal, which has only reacheds 8 mW/m^2 (Moqsud et al., 2013). This finding can be attributed to the fact that the contact of biomass with electrodes is higher in carbon fiber than that in bamboo charcoal. Although bamboo charcoal is inexpensive and environmentally friendly, it is less not as often recommended for use as a cathode material because its wavy shape causes low biomass contact. In addition, the performance of MFCs in generating electrical energy will be is improved if the surface area of the electrodes is increased with respect to the reactor volume (Nastro et al., 2017). In another study, a double anode with graphene material iswas used because graphene it is considered to have a larger surface area than carbon graphite (Samudro et al., 2018). Meanwhile, carbon felt was interesting to be used as an electrode because it is porous and has a large surface area, which arise suitable for microorganism growth, adhesion, and a reduced impedance activation (Kim et al., 2011).

Various studies are have been conducted to determine the type of separator that supports the the optimization of the SMFC reactor so that in terms of the generated electrical energy generated can reach the optimum value (Li et al., 2018; Mohan and Chandrasekhar, 2011; Wang et al., 2015). Moqsud et al. (2013) said stated that the voltage generated by the SMFCs reactors with a

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cellophane separator has the highest ~~value~~ electrical output compared with ~~that by the~~ SMFCs reactors with filter paper and PEM. Cellophane is considered to have a lower electrical resistance ~~value~~ than filter paper and PEM. The dry surface of PEM is considered to be the cause of its higher resistance ~~value than~~compared with cellophane and filter paper. Filter paper is considered to be more permeable than PEM and cellophane. Meanwhile, cellophane is more easily damaged; thus, its quality is low and it cannot be reused. In another study, a single-chamber reactor was used ~~so it~~ that did not ~~need~~ require a membrane ~~separator~~ or other separator material (Moqsud et al., 2014). However, it is ~~also~~ known that the application of PEM can increase the internal resistance. ~~Novel porous clay~~ Thus, various studies have considered ~~been conducted to make~~ different reactor configurations to suppress the MFC internal resistance ~~values~~, ~~for example~~such as, single-chamber MFCs, up-flow MFCs, and stacked MFCs (Rahimnejad et al., 2015; Rahimnejad et al., 2012; Rahimnejad et al., 2011).

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The distance between ~~the~~ electrodes in a single-chamber SMFCs can also affect the ~~amount~~generated ~~of~~ electrical energy ~~generated~~ (Miran et al., 2016; Oh et al., 2010; Mohan et al., 2010). Sandwiched electrodes produc~~e~~ing the lowest electrical power output compared to a system ~~which~~that ha~~ve~~s a non-zero distance between ~~the~~ electrodes. ~~The~~A shorter ~~the~~ distance ~~of~~between electrodes (assuming the electrode is located in the middle of the reactor) could produce ~~greater~~ more electricity because ~~of~~ the active surface area ensures a ~~high~~ greater electrical gradient ~~since~~ as the protons can more easily move to the cathode ~~easily~~ (Mohan and Chandrasekhar, 2011). Therefore, the distance ~~of~~between electrodes can significantly reduce the generated electricity ~~since~~ as the protons need to move further towards the cathode. This ~~condition~~ means that determining the optimal distance is essential when working with single-chamber SMFCs. Even

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though the distance between ~~the~~ electrodes must be kept small, sandwiched electrodes and PEM can increase the likelihood of substrate transfer from the anode to the cathode and oxygen transfer from ~~the~~ air to the cathode (Hassan et al., 2014; Palanisamy et al., 2019; Peighambardoust et al., 2010).

3.4 Microorganisms

Microorganisms involved in the electricity generation process are also considered an important factor ~~that~~ to improve the reactor performance ~~of the reactor~~. The substrate in ~~the~~ SMFCs is not the only factor that influences~~ing~~ the type of dominant microorganisms that exist in the anode. These ~~dominant~~ microorganisms ~~at the anode~~ can also be influenced by the inoculum and the reactor conditions when ~~the reactor is~~ operational~~ing~~ (Parot et al., 2009). ~~In another study,~~ Reiche and Kirkwood (2012) stated that SMFCs reactors with mixed culture biocatalysts obtained from three different types of compost produce a maximum electric power density of 12.3 mW/m^2. ~~Mixed culture biocatalysts obtained from three different types of~~These compost were considered to be able to enrich the substrate and exoelectrogenic activity. The efficiency of electron transfer ~~that occurs~~ in SMFCs can be influenced by the selection of biocatalysts ~~to be used~~. Ion and substrate transport through solid media is an important factor that influences the performance of SMFCs. If th~~o~~ese transports ~~is~~are slow, then the electrochemical reactions are reduced. Therefore, transport systems in SMFCs become~~ing~~ critical ~~since~~ as the water content is limited. In ~~that~~ this case, maintaining the water content in optimum condition (around 60—80%) is necessary (Oliot et al., 2016; Wang et al., 2017).

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Wang et al. (2019a) ~~stated~~ indicated that the type of inoculum can determine the rate of substrate decomposition and affect the generation of electrical energy. ~~In this research~~ T~~t~~he dominant genus identified on the anode biofilm was the genus *Pseudomonas* (5%), ~~, *Pseudomonas*~~ which can produce chemical intermediaries that can transfer electrons to the electrodes. In addition, *Hydrogenophaga* (5%) was the dominant genus identified on biofilms derived from household wastewater. Thi~~s~~e genus consumes H_2 in the anode chamber~~,~~ ~~thereby~~ and inhibits~~ing~~ the generation of electricity ~~by~~from the SMFCs with biogas slurry as the substrate. In addition to the analysis of the genus ~~level~~, it is known that four genera of hydrolytic bacteria can break down cellulose, protein, and starch chains into organic micro-molecules.~~,~~ ~~thereby~~ This increases~~ing~~ the sugar degradation and volatile fatty acids in SMFCs with biogas slurry as the substrate. The diversity of the ~~genus of~~ microorganisms genus contained in SMFCs influences the performance of the reactor because of their ~~different~~ various roles ~~of each microorganism~~ in degrading the substrate (Lu et al., 2019; Reiche and Kirkwood, 2012; Wang et al., 2015; Wang et al., 2019b; Zhi et al., 2014).

4. Integration of SMFCs with Other Solid Waste Treatment

~~Solid phase microbial fuel cells (~~SMFCs~~)~~ ~~seems~~ appear to have many potential applications ~~when~~ compared ~~to~~ with other solid waste treatments. This technology requires only a ~~needs~~ relatively small energy input ~~for~~ to support the~~ing~~ chemical reactions in the cathode. Moreover, air-cathode MFCs do~~es~~ not need an oxygen supply ~~oxygen since~~ as ~~it~~this is provided by ~~its~~ the system configuration. SMFCs produce ~~a~~ less sludge as an anaerobic power generation system and convert organic matter ~~into~~ directly into electricity and biohydrogen. The processed organic matter could be a mature compost and fertilizer~~.~~, and ~~T~~the used electrode could be a soil conditioner~~,~~ to increase ~~the~~ its fertility ~~of soil~~. ~~It~~ This ~~is~~ also produces~~ing~~ ~~a less~~ fewer emissions, such as CH_4, CO_2, NH_3,

N_2O. The same characteristics can be seen in ~~the~~ anaerobic digestion, which has the same processing stage as SMFCs. ~~A~~Aerobic composting ~~needs~~ requires ~~a lot of~~ significant energy for aeration and mixing and only produces compost with excessive amounts of leachate. This type of composting also produces a significant ~~amount of~~ odor and VOCs, which interfere with the environment. While incineration has many benefits for treating solid waste, it also generates dioxin and furan, (especially when ~~is~~ working with plastic-based materials), CO_2, and N_2O. If the incineration is not ~~controlled~~ properly controlled, the emissions and byproduct (fly and bottom ash /-slag) may be harmful ~~for~~ to the environment.

Table 2 Comparison of SMFCs with other conventional solid waste treatments

Typically, the maximum energy generated from MFCs at treating food and organic waste (in the form of liquid fraction/hydrolysate) has a COD ~~is~~ around 0.28—0.78 MJ/kg ~~COD~~ (Xin et al., 2018; Xiao and He, 2014). The total energy can be higher until it ~~reaches~~ reaching a COD of 2.48 MJ/kg ~~of COD~~ when MFCs are fed by anaerobic sewage sludge and a COD of 3.52 MJ/kg ~~of COD by~~ from food waste hydrolysate (Wang et al., 2013b; Xin et al., 2019). ~~That~~ These energy values may be lower, especially when ~~it is~~ compared with other waste-to-energy (WtE) technology such as incineration ~~which~~ can result in energy values ranging from 3.60 ~~MJ/kg~~ to 6.00 MJ/kg of food waste (Carmona-Cabello et al., 2018; Chen and Christensen, 2010). Although the MFCs energy generation ~~seems~~ is promising ~~since~~ as only 8 to 12 SMFCs systems ~~might~~ may achieve the same energy output as combustion, the energy generation sustainability is doubted compared to thermal processing technologies, such as incineration. The ~~condition~~ situation ~~will be~~ is more challenging when SMFCs ~~is~~ are implemented to process ~~the~~ a solid fraction of municipal waste. The maximum electricity generation from solid-phase MFCs is relatively small and amounted to 0.072 MJ/kg of

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food waste, as reported by Moqsud et al. (2014). This condition is related to its mass transfer limitations, which resulted in thethe low electricity generation of SMFCs. Therefore, theese values are still on aat laboratory scales (none SMFCs inat larger scales)., Thus, which is still in doubt that the process efficiency is suspected to bewill be much lower than a pilot or even industrial scales. At the pilot / industrial scale, MFCs reactors must be constructed in a with minimalum dimensions to ensure the power per unit area of the electrode or reactor volume is lower ,to making increase the energy generation higher. An ideal substrate supply rate can also be provided in smaller sized reactors (Greenman and Ieropoulos, 2017). This limitation might may be solved by integrating other waste processing technologies.

Dark fermentation (DF) is aa technology commonly used approach to recover bio-hydrogen from high cellulose content materials. Through fFermentation reactions, hydrolyze cellulose is hydrolyzed to hexoses and produces acetate and hydrogen gas (Wang et al., 2011). However, the DF system iscan only able to recover one one-third of the total theoretical energy that could be recovered. The combination of MFCsmicrobial fuel cells and microbial electrolysis cells (MFC-MEC) to treat the DF effluent could increase the bioenergy production. The MFC could support the MEC's energy needsdemands for to converting the substrate into H_2, as well as direct electricity for the system as a whole overall (Chookaew et al., 2014). Increased power density in MFCs also resultsed from the use of dark fermentation DF effluents where the maximum power density becomesincreased to 4 times more significant based on research conducted by Varanasi et al. (2017). The combination of the DF-SLS (Ssolid- Lliquid Sseparation)-MFC can also be used to treat cellulose waste, such as swine manure and rice bran. As a post-treatment of DF and SLS, MFCs can improve the energy recovery process in the form of bio-electricity. The MFC efficiency

1

will also increase due to the higher degradable COD as available from DF and SLS processes (Schievano et al., 2016). The potential ~~for~~ to utiliz~~ing~~e integrative technology ~~might~~ could be explored more intensely to ~~get~~ obtain a better system durability and sustainability.

Xin et al. (2018) showed that the amount of electric power generated by MFCs is greater than ~~by~~from anaerobic digesters (ADs). This ~~finding can be~~ is attributed to the fact that the AD process requires a longer residence time than ~~the~~ MFC~~s~~ technologies~~y~~, ~~thereby~~ which affects~~ing~~ the size of the reactor ~~used~~. Thus, ~~T~~the MFC~~s~~ reactor can be 5.5 times smaller than the AD reactor. The MFC~~s~~ application is considered to be more practical, more environmentally friendly, and more economically feasible in terms of electricity conversion and production costs than the AD. The MFC~~s~~ is expected to be~~come~~ a solution for processing food waste that ensures the rapid recovery of resources and electricity ~~sources by~~ while not producing any ~~other~~ additional waste. ~~Strengthening Xin et al. (2018) proposed scheme,~~ Antonopoulou et al. (2019) added to this scheme by~~also~~ proposing~~ed~~ a food waste management system~~,~~ using an integrated biochemical process. Food waste is ~~grinded~~ ground and heated ~~(~~as a waste pre-processing system~~)~~, and ~~then~~ the carbonaceous COD is extracted to produce ~~two fractions of product,~~ liquid and solid product fractions ~~fraction~~. The liquid fraction is continuously processed using MFCs ~~continuously~~ and the solid fraction is processed using the AD~~anaerobic digester~~. This ~~scheme~~ is considered to be applied ~~in~~ at the ~~pilot~~ pilot-scale because it produces more energy recovery ~~value of~~ at 12.32 MJ/kg of total solids (TS), ~~or~~which is nearly ~~almost comparable~~ that of~~to~~ the maximum net calorific value using various types of combustion~~,~~ (amounting to 18.09 ~~-~~–18.38 MJ/kg TS). The total energy produced from MFCs and the AD~~anaerobic digester~~ ~~are~~ is still positive, especially ~~to~~when covering the pre-processing energy needs of 8 MJ/kg TS (Antonopoulou et al., 2019; Wang et al., 2013b; Xin et al., 2018). This energy balance can still be reduced if it uses cheap and energy-friendly drying technologies,~~y~~ such as bio-drying or low-cost decanters, to reduce the excessive ~~amount of~~ water content in ~~the~~ food waste (Velis et al., 2009). ~~In case of~~ When integrating~~ion~~ with aerobic composting, the leachate can be processed using MFCs for further substrate conversion. The generated energy could be used as a self-supporting system ~~for~~ to aerate~~ing~~ the compost pile. ~~I~~On the other hand, MFCs ~~itself~~ themselves can be used to directly treat the organic fraction of solid waste without the help of anaerobic ~~and~~or aerobic composting. However, this option is not feasible ~~since~~ as the energy generated is lower. ~~and~~ This needs further investigation to enhance the productivity of electricity. Figure 3 shows the proposed mechanism ~~for~~ to integrate~~ing~~ other solid waste treatments with SMFCs.

Figure 3. SMFCs and other solid waste treatments to achieve~~ing~~ sustainable energy production (modified from Antonopoulou et al. (2019) and Xin et al. (2018))

5. Conclusions

SMFCs are an alternative technology ofto generateing electricity that is environmentally friendly and sustainable. Various studies have been conducted to determined the optimum configuration of the MFC reactor and its development potential to generate electrical energy. The various factors that affect the performance of SMFC reactors, include the such as substrates, electrodes, microorganisms involved, and reactor configuration, which requireneed to be further investigationsed. The presence of a separator and the electrode distance used in the SMFC reactor are important to determine since it as they isare related to the electron and proton transfer. Mass transfer process is also important in athe solid phase, as it ensuresing the microorganism can properly breakdown the substrate properly. Therefore, this limitation may be further studied, and finding the best configuration system may enhanced the electricity generated by the SMFCs. Integrating this technology with other solid waste processing systems could be possible and reliable, since as SMFCs itself themselves haves many limitations. The proposed system sequentially is combinesing the preprocessing system, anaerobic digestionAD, composting, and also SMFCs in a sequential system. After solid waste is processed by using the pretreatment technology, solid waste it is sentding to the composter, both in anaerobic or aerobic composting system. Then, the leachate, slurry, or hydrolysate from the process may be treated by using SMFCs. The dDirect electricity can be used as an alternative energy sources for other treatment needs. The SMFCs also could also be used as a single solid waste treatment, but the efficiency may be lower than the proposed system instead and not feasible for field applications.

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