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Life Cycle Assessment Gasification Process of Municipal Solid Waste into Electrical Energy at Putri Cempo Landfill Indonesia

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ABSTRACT

Process of municipal solid waste into the electrical energy of Putri Cempo Landfill with gasification technology as an alternative to significantly reduce the environmental impact related to macro components as chemical constituents of waste. The Life Cycle Assessment (LCA) approach is used to holistically evaluate the environmental impact of the gasification process at the waste power plant (WPP) of Putri Cempo Landfill. This study aims to identify the potential environmental impact and determine the hotspot of the gasification process at the Putri Cempo Landfill WPP. The method used in this study is quantitative descriptive with the LCA method, which includes goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation, where the limitation in this study is gate to gate. The results showed that the largest potential environmental impacts are human carcinogenic toxicity of 41.64738 kg 1.4-DCB, freshwater ecotoxicity of 15.364229 kg 1.4-DCB, and marine ecotoxicity of 11.390976 kg 1,4-DCB. The lowest potential environmental impacts are mineral resource scarcity of 0.000182585 kg Cu eq, stratospheric ozone depletion of 0.041251 kg CFC11 eq, and land use of 0.046136128 m2a crop eq. The hotspot that contributes the greatest environmental impact is the gasifier with a direct gasification system.

1. INTRODUCTION

Waste is a global issue that requires serious attention and effective management. According to data from the Indonesian Ministry of Environment and Forestry (2022), total waste generation in Indonesia reached approximately 5,601,150.78 tons per year. Of this amount, 50.45% was properly managed, while 34.42% remained unmanaged, as reported by the National Waste Management Information System (SIPSN) [1].

The increasing volume of waste is largely driven by population growth and rapid changes in lifestyle and consumption trends [2], which significantly impact daily waste production [3]. Waste itself, particularly biomass waste, has the potential to be converted into electrical energy through various waste-to-energy processes [4]. Consequently, waste represents a promising alternative energy source, alongside other renewable energy options—especially in light of the ongoing depletion of natural resources such as coal, which remains a dominant fuel in electricity generation.

WPP is a form of utilizing waste so that it has more value and reduces waste accumulation in landfill. WPP can also be a solution to the increasing demand for electrical energy, where WPP can become a supplier of national electrical energy needs. One of the existing WPP developments in Indonesia is the WPP of Putri Cempo Landfill. This WPP is located in the Putri Cempo Landfill, Surakarta City. Putri Cempo landfill itself uses an open dumping system and has experienced an overload of landfill waste since 2010 but is still operating today, so the existence of this WPP is an alternative to significantly reduce the environmental impact of landfill waste by converting it into electrical energy. This WPP is the first WPP in the Solo Raya area to use thermal technology in the form of gasification to generate electricity. This WPP has a municipal waste capacity of 540 tones/day and is capable of producing as much as 8 megawatts of electricity per day [5]. The collaboration for the construction of the WPP of Putri Cempo Landfill itself started on December 6 2016 between the Surakarta City Government and PT Solo Citra Metro Plasma Power (SCMPP).

Development of WPP as a form of acceleration in realizing the achievement of the 2030 Sustainable Development Goals (SDGs), especially goals 7, 8, 12, and 13 [6]. WPP is also a form of urban development that is quite complex, but can also have negative impacts in various aspects, one of which is the impact on the environment [7, 8]. This is supported by Khalifa et al. [9] who state that an increase in the demand for electrical energy in cities shows significant economic growth. However, the existence of WPP certainly cannot be separated from the environmental impacts of the WPP process both to the physical environment and society. WPP as a form of waste management has a potential impact on climate change [10].

WPP of Putri Cempo Landfill is a form of implementation of waste management activities and includes the provision of energy which has a potential impact on environmental and community health [11]. This is because the WPP of Putri Cempo Landfill is inseparable from the presence of waste or by-products generated during the production process. Waste products from combustion in WPP include solid residues (bottom ash), fly ash, and charcoal, liquid residues (leachate), and gas residues (odours and emissions or exhaust gases produced during the combustion process) [12]. This is also supported by an interview that was conducted with one of the employees from PT Solo Citra Metro Plasma Power (SCMPP) as the technical implementer of the WPP of Putri Cempo Landfill, where the process of burning waste with thermal technology, both incinerator and gasification, generally causes impacts related to macro components.

Therefore, based on previous statements, the authors wish to examine the potential environmental impacts of the WPP gasification process at Putri Cempo Landfill using the LCA approach. This is considering that the WPP of Putri Cempo Landfill is currently still in a trial period to determine the optimal process and will officially operate using 8 gasifiers (A-H) and 20 engines. An environmental impact study is important to carry out to determine the potential environmental impacts arising from the gasification process and can then be evaluated for improvements and developments in the gasification process in WPP so that environmental impacts that may occur can be minimized. The LCA approach was used in this study to holistically evaluate the environmental impact of the gasification process on the waste-to- electricity management system at the WPP of Putri Cempo Landfill.

This study aims to analyze the potential environmental impacts resulting from the gasification process at the WPP at Putri Cempo Landfill using the LCA approach. It also seeks to identify the environmental hotspots within the gasification process that contribute most significantly to potential environmental impacts. Furthermore, this research is expected to provide valuable information to the public, enhance social acceptance of renewable energy technologies, and offer recommendations for improvement and future development of the WPP at Putri Cempo Landfill.

As a waste processing facility, the WPP at Putri Cempo Landfill is inherently linked to the Second Law of Thermodynamics, which states that energy transformations do not occur spontaneously and are never 100% efficient [13]. Therefore, an in-depth analysis of the environmental impacts associated with the gasification process is essential.

This research contributes to the development of effective waste management strategies and environmental impact mitigation, while promoting the use of eco-friendly technologies for converting waste into electrical energy. It aligns with Presidential Decree No. 35 of 2018, which supports the accelerated development of waste-to-energy installations using environmentally sustainable technologies.

2. METHOD

2.1 Location and time of study

The research was conducted at the WPP which is located in Putri Cempo Landfill, Mojosongo Village, Jebres District, Surakarta City as shown in Figure 1. The location that became the object of this research can be seen in Figure 1, where the research location is located in Surakarta City with coordinates 7°53'61" South Latitude and 110°85'95" East Longitude. The choice of this location was purposive with the study raised in the research being the environmental impact arising from the gasification process of WPP of Putri Cempo Landfill. The research being carried out is ongoing from January to June. The research was carried out employing field observations and interviews, literature studies, design, data collection, environmental impact analysis using SimaPro 9.5 software, and preparation of research results.

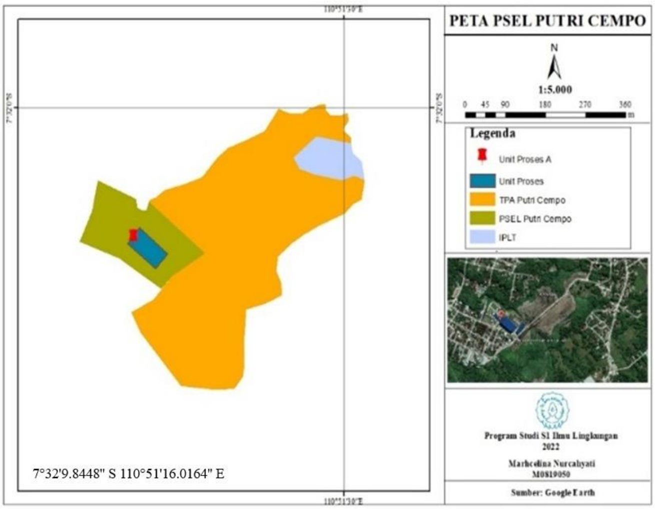

Figure 1. Map PSEL Putri Cempo

2.2 Tool and materials of study

The tools used in this study included 1 set of stationery to record the results of field observations and interviews, 1 item of SimaPro 9.5 software to process data using the LCA method, 1 item of Microsoft Excel to process and record interview data, and 1 unit of mobile phone for documentation and take pictures during research activities. The materials used in this study were interview sheets as materials for recording the results of interviews with informants related to the research.

2.3 Data collection techniques

Data collection is done by collecting the necessary data for further data processing. Data collection in this study was carried out from primary and secondary sources, including data from the WPP management agency for Putri Cempo Landfill, explanations from related parties who supported the research, and several previous research references relevant to this research. The data collection techniques in this study are as follows:

2.3.1 Primary collection technique

The primary data in this study are production data in the gasification process unit, input and output data in the gasification process unit, data on the use of electricity or other energy sources, data on waste produced by partial combustion in the gasification process unit, as well as data on the use of equipment and tool capacity. The primary data in this study is the result of field study activities with observations and interviews conducted regarding the WPP of Putri Cempo Landfill. Observations in this study were carried out by directly observing the stages of the process of producing electrical energy from municipal solid waste in the gasification process at the WPP of Putri Cempo Landfill. Observations in this study were carried out in a systematic and targeted manner to obtain accurate results. Interviews in this study were conducted by collecting data in the form of interactions and direct communication. The parties interviewed in this study were PT Solo Citra Metro Plasma Power (SCMPP) as the manager of WPP of Putri Cempo Landfill, UPT Putri Cempo Landfill, DLH Surakarta, the Person in Charge of Palur Substation, and the community around WPP of Putri Cempo Landfill. Snowball sampling was conducted to interview the community around WPP of Putri Cempo Landfill with the Jatirejo RW 39 community who live within a radius of $\leqslant$ 500 m. The number of target respondents in interviews with the community around the WPP of Putri Cempo Landfill in this study was 30 people. The interviews in this study were conducted in-depth by asking several questions to the informants.

2.3.2 Secondary data collection techniques

For quantitative determination of alanine aminotransferase in vitro (L-Alanine: 2-Oxoglutarate Aminotransferase (ALT) activity, EC 2.6.1.2) in human serum or plasma on Konelab Analyzer. All test results must be interpreted in relation to the clinical context and checked using the Indiko Thermo scientific Auto Analyzer: Photometer (End point & Colorimetric). Secondary data in this study is the result of documentation of literature relevant to this research. Secondary data used as a reference regarding LCA in this study includes 5 14040 of 2004 concerning Life Cycle Assessment (Best Practices of ISO 14040 Series) [14], ISO 14044 of 2006 concerning Environmental Management-Life Cycle Assessment-Requirements and Guidelines, (1404), and Guidelines for Preparing Life Cycle Assessment (LCA) Reports for 2021 [15,16]. This data is used as a reference for writing obtained through literature studies with topics that are appropriate and support research. Literature on secondary data comes from online media, books, scientific articles, and previous research results. Documentation was also carried out by recording results and taking pictures in the field related to the gasification process unit at the WPP of Putri Cempo Landfill.

2.4 Data analysis

Data analysis in this study was carried out in a quantitative descriptive. The approach in this study uses the LCA method to determine the potential environmental impact of the gasification process of WPP of Putri Cempo Landfill which is processed using SimaPro 9.5 software. The following are the stages used to evaluate the environmental impact of the WPP gasification process unit at Putri Cempo Landfill based on ISO 14040/14044 [17, 18] including:

2.4.1 Goal and scope definition

This analysis was carried out by defining the objectives, scope, and limitations of the research. The purpose and scope of this research concern the environmental impact of the gasification process at the WPP of Putri Cempo Landfill with the scope included in the gate-to-gate. This study uses several limitations so that the study can be focused and not get out of the topic discussed, some of these limitations are as follows: The research was conducted on the gasification process of WPP of Putri Cempo Landfill. The data used is a heat and mass balance diagram municipal solid waste gasifier of WPP at Putri Cempo Landfill from PT. SCMPP. Life Cycle Inventory (LCI) and Life Cycle Assessment (LCIA) were carried out by adjusting the database in SimaPro 9.5 software.

2.4.2 Life cycle inventory (LCI)

This analysis is carried out by defining the input and output of each process that is carried out. LCI in this study is the process of collecting data on the number of inputs and outputs in the gasification process unit at WPP of Putri Cempo Landfill. Input is all the use of materials and energy needed for the process, while the output is all the results of the process either in the form of products or in the form of emissions or waste. The input and output data were obtained from field observations, as well as based on literature studies from previous research. The input data will later adapt to the data available in the SimaPro 9.5 software database.

2.4.3 Life cycle impact assessment (LCIA)

This analysis was carried out by identifying the environmental impacts that occurred during the trial of the electricity production gasification process at the WPP of Putri Cempo Landfill. The LCIA stage is carried out by calculating data on the previous LCI to determine the magnitude of the impact on the environment. The LCIA calculation uses SimaPro 9.5 software, the results of which are determined based on the selection of the impact category, classification, characterization, and weighting carried out. The characterization model for the impact category used is the ReCiPe midpoint (H). The midpoint impact category is used to estimate three main impacts consisting of impacts on human health, ecosystem quality and availability of natural resources. The ReCiPe Midpoint (H) method was chosen because of its ability to integrate various environmental impact categories in one standardized framework, making it easier to interpret results and identify environmental hotspots in the gasification process. In addition, this method complies with the ISO 14040/14044 standard and has been widely used in LCA studies related to waste and energy management.

2.4.4 Interpretation

This analysis was carried out in the gasification process carried out by WPP of Putri Cempo Landfill. This analysis was conducted to determine the largest environmental impact and highlight the phases in the WPP gasification process that have the greatest potential impact. Interpretation is done by analyzing the results of the SimaPro 9.5 software. Apart from that, a comparison was also made with the actual conditions to find out what were the direct and indirect impacts that were carried out by the WPP of Putri Cempo Landfill.

3. RESULT

3.1 Goal and scope definition

This study uses the LCA method, where the life cycle assessment begins by determining the purpose and scope of the research. The purpose of this study is supported by determining the boundaries and scope of the research itself. The purpose of conducting this research using LCA is as follows identify the potential environmental impacts arising from the gasification process at the Putri Cempo Landfill WPP and determine the hotspots or processes that have the greatest potential environmental impact on the WPP gasification process of Putri Cempo Landfill. The scope of this research is gate-to-gate, or it only includes the process from the Putri Cempo Landfill WPP. This research covers only units in the process or gate of the PSEL TPA Putri Cempo electrical product system as the system boundaries. The scope of this research includes the components of the product system. Functions of the product system, Gasifier, Cyclone and High Temperature Filter Element, High Exchanger, Mist Eliminator, Fine Filters, Gas Blower, Pleated Filter, Engines Genset and Condensate Evaporator.

The limitation of this study was carried out by evaluating the life cycle of the product system at the WPP process stage of Putri Cempo Landfill only in the form of gasification, which initially started from processing biochar briquettes to become a product in the form of electricity.

This research employs functional units, specifically 1000 kWh, to evaluate the potential environmental impact of the product system under investigation. The functional unit used in this research is the dirty electrical energy produced by PSEL TPA Putri Cempo from each gasifier, which requires 1800 kg of biochar briquettes per hour before being used for internal needs or distributed to the community through PT. PLN (Persero) Palur Main Substation.

The reference flow in this research, 1000 kWh, is based on the total gross electrical energy output produced by each PSEL gasifier at Putri Cempo TPA per hour, as reported by the H&M BD MSW Gasifier owned by PT. SCMPP.

3.2 Life cycle inventory (LCI)

This inventory stage is carried out by collecting secondary data in the electrical product system at the Putri Cempo Landfill WPP for each process stage included in the research system boundaries. Inventory is also carried out by checking the units used so that all input and output units are the same and can be quantified and data quality checks are carried out during the data collection process to provide evidence that the data quality requirements comply with ISO 14040 2006 and ISO 14044 2006 standards. The inventory stage of this research also validated the data that had been collected. Data validation in the WPP process of Putri Cempo Landfill is carried out by accessing data quality based on ISO 14044 of 2006, where data quality requirements must meet the scope of time, geography, technology, precision, completeness, representativeness, consistency, reproducibility, data sources, and information uncertainty. Summary of total inventory data input per unit of product for each PSEL process unit at Putri Cempo TPA The results can be seen in Figure 2.

The gasification process unit in Figure 2 utilizes municipal solid waste in the form of biochar briquettes as its primary raw material. Other inputs include ambient air, oxygen, water from wells, and distilled water from condensate. The output in this process is producer gas and moisture content, which is the main product in the form of syngas to be converted into electricity, which is channeled in the next process to the cyclone and high-temperature filter element. Other outputs in this process are emissions and waste, which include ash and charcoal, heat coming out of the process system, and combustion water from the gasifier.

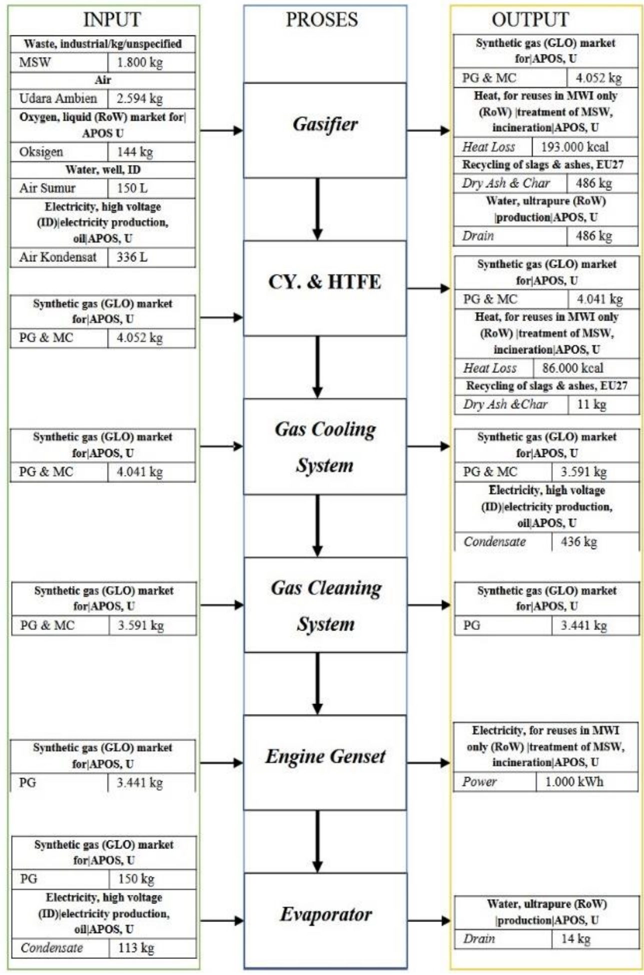

Figure 2. PSEL gasification process flow at Putri Cempo TPA

MSW: Municipal Solid Waste, CY: Cyclone, HTFE: High Temperature Filter Element, PG: Producer Gas, MC: Moisture Content

3.3 Life cycle impact assessment (LCIA)

The impact assessment stage provides a complete system view of the environmental and resource issues of one or more production systems. LCIA result sets provide information regarding the inputs and outputs of product systems and information on environmental issues. Impact analysis in this study was carried out using a midpoint impact analysis or problem- oriented approach which can be categorized into three main impacts oriented toward environmental damage (endpoint impact categories) consist of human health, ecosystem damage, and natural resource depletion. Assessment of impact category elements, category indicators, and characterization models in this method are elements that must be justified and consistent with the objectives and scope of LCA and reflect environmental issues related to the product system being studied. The stages of the gate-to-gate environmental impact assessment of the WPP gasification process of Putri Cempo Landfill in this study used the ReCiPe method as follows:

The environmental impact assessment process produces a value that arises from the impact category on the unit process of the Putri Cempo Landfill WPP electrical product system in each unit then calculated and the results of these calculations can be seen in Table 1.

Table 1 shows the impact categories for all process units, where human carcinogenic toxicity has the highest value, namely 41.64738 kg 1.4-DCB. The impact category with the second highest value is freshwater ecotoxicity, which is 15.364229 kg 1,4-DCB. The impact category with the third highest value is marine ecotoxicity, which is 11.390976 kg 1,4-DCB. The lowest value for all process units is indicated by the mineral resource scarcity impact category, which is 0.000182585 kg Cu eq. The second and third lowest values are shown by the global warming impact category of 0.041251 kg CO_2 eq and marine eutrophication of 0.046136128 kg N eq.

Table 1. Total impact category results for all process units with the ReCiPe midpoint (H) characterization model

No.	Impact Category	Unit	Total
1	Global warming	kg CO2 eq	0.041251
2	Depletion of stratospheric ozone	kg CFC11 eq	0.06470505
3	Ionising radiation	kg Co-60 eq	1.3704103
4	Formation of ozone and its impact on human health	kg NO2 eq	0.247525
5	Formation of fine particulate matter	kg PM2.5 eq	0.151394
6	Ozone synthesis, terrestrial ecosystem	kg NOX eq	0.301941
7	Soil acidification	kg SO2 eq	0.2433842
8	Eutrophication of freshwater	kg P eq	1.754396
9	Eutrophication in marine environments	kg N eq	0.046136128
10	Ecotoxicity in terrestrial environments	kg 1.4-DCB	1.488113
11	Ecotoxicity in freshwater environments	kg 1.4-DCB	15.364229
12	Marine ecotoxicology	kg 1.4-DCB	11.390976
13	Carcinogenic toxicity in humans	kg 1.4-DCB	41.64738
14	Non-carcinogenic to humans toxicity	kg 1.4-DCB	0.19210286
15	Land use	m2a crop eq	0.1807404
16	Scarcity of mineral resources	kg Cu eq	0.000182585
17	Fossil fuel scarcity	kg oil eq	0.714385
18	Water utilisation	m3	0.14695089

3.4 Life cycle interpretation

Interpretation of the data in this study using the LCA method was based on ISO SNI 14040:2006 and ISO SNI 14044:2006 standards. The results of the impact assessment show that the electric product system process with gasification technology at the Putri Cempo Landfill WPP has the three highest potential environmental impacts, namely human carcinogenic toxicity, freshwater ecotoxicity, and marine ecotoxicity as in Table 1. The gasification process of WPP of Putri Cempo Landfill holistically has the potential for a large environmental impact on human health. The results of the characterization model using the ReCiPe method show that human health is affected by the effects of fine particulate matter formation, ozone formation, human health, human carcinogenic toxicity, human non- carcinogenic toxicity, global warming, and water consumption. These impacts later cause respiratory diseases, various types of cancer, malnutrition, and other diseases [19].

4. DISCUSSION

4.1 Environmental impact

Human health in the WPP gasification process at Putri Cempo Landfill is a huge potential impact. This correlates with the output from the WPP gasification process at Putri Cempo Landfill, one of which is emissions. Emission itself consists of several parameters with their respective characteristics. Emissions from burning waste have a different impact on each parameter, that emissions from burning waste and their relationship to dose response [20]. PSEL construction can have a negative impact on the environment because the process produces waste in the form of smoke and odors as well as other types of waste such as boiler ash and flies due to the combustion process, which can cause air pollution and dioxin and furan substances, which are dangerous for health and the environment [21].

The impacts of burning waste emissions include impacts on human health, either illness or even death, agricultural production, forest destruction, building damage, weather, and ecosystems. The existence of the WPP gasification process for Putri Cempo Landfill is of course also inseparable from the potential impact. This is in line with the statement of several residents of Jatirejo RW 39 who complained about air pollution. The pollution is in the form of smoke coming out of the chimneys of the gasification process and you can see particles from the combustion products flying, especially when there is wind towards the local community. The wind speed factor greatly determines the concentration of pollutants that arrive due to the influence of distribution and mixing (dilution) [22]. The greater the wind speed, the narrower the pollutant distribution pattern and the more pollutant concentration values at the distribution centre [23].

Breathing problems were also felt by several residents of Jatirejo RW 39, especially those who lived around the Putri Cempo Landfill WPP with a radius of <100 meters. Air pollution can trigger diseases such as respiratory tract infections, thus increasing the risk of lung disease including acute respiratory infection, especially the lack of public knowledge about the impact of air pollution on respiratory diseases [24]. The mechanism for the entry of pollutants such as dust from the air into the human body so that it accumulates in the lungs consists of three ways, namely inhalation (enters through the respiratory system) ingestion (enters through the digestive system), and skin penetration (enters through the skin pores) [25].

Apart from emissions, some residents also said that there was noise from the gasification process of the WPP of Putri Cempo Landfill. The noise only occurs during the clearing of the trial process, especially at night. The existence of air and noise pollution that occurs in the Jatirejo RW 39 community environment is coupled with the existence of a plastic seed processing factory owned by the community which still uses conventional combustion techniques, so the impact of air pollution and noise cannot be avoided. Therefore, it is necessary to make efforts to control the pollutants that will be released into the environment. Prajogo [20] states that controlling air pollution can be done by modifying the level of distribution, controlling emissions by changing processes, and using air pollution control devices such as mechanical separators in the form of gravity settlers or cyclones, fabric filters, electrostatic precipitator, and wet scrubber.

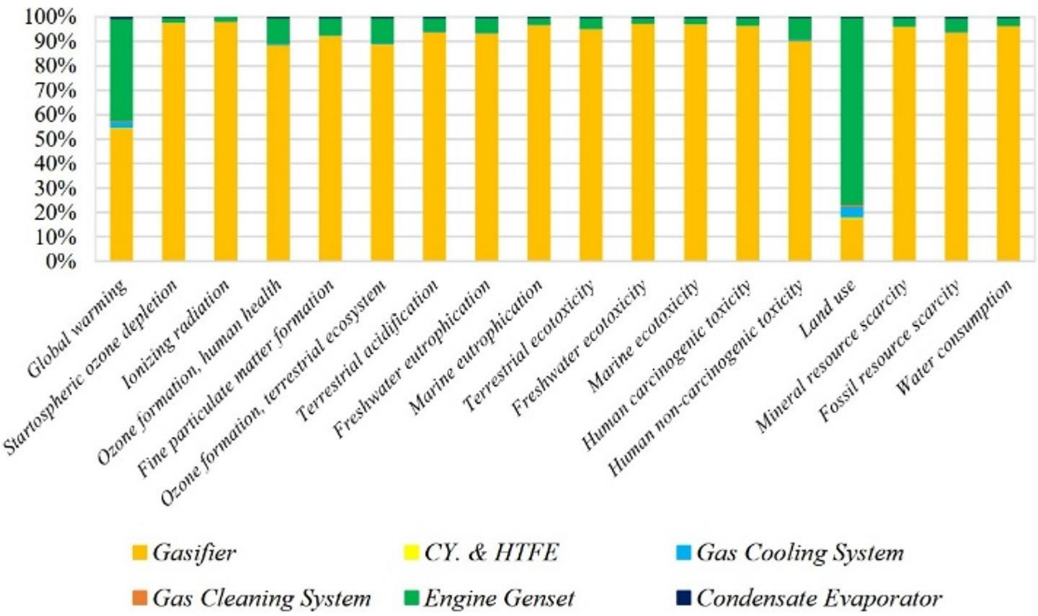

Figure 3. Impact assessment results from the gasification process using the ReCiPe midpoint (H) characterization model

The impact assessment results in Figure 3 show the results if the WPP gasification process for Putri Cempo Landfill does not have the potential for a significant impact on the depletion of natural resources. This is because the natural resource input used in the WPP gasification process for Putri Cempo Landfill is 150 litres of well water per hour. Most of the people of Jatirejo RW 39 themselves use water from arterial wells which are assistance from the Government. The community hopes that the existence of WPP Landfill Putri Cempo in the future will not cause problems related to water and water sources. The results of the study by Romdloni [26] show that the Internet of Things (IoT) can be used as an effort to prevent, protect and control water at the source, especially the distribution of water for consumption to the house connection through a risk management approach to ensure the achievement of quality, quantity, continuity, and affordability.

The construction of the WPP Landfill Putri Cempo is expected to have a positive impact on many aspects, especially regarding the abiotic, biotic and sociocultural aspects of the community. The positive impact of WPP Landfill Putri Cempo on abiotic aspects is reduced water, air and soil pollution due to waste. This is according to Mahyudin [27] because the abiotic environment is an important aspect that needs to be considered in waste management, so that water pollution, air and odour pollution, soil pollution, disease vector habitat, and decreased aesthetics or environmental beauty can be minimized. The positive impact of WPP of Landfill Putri Cempo on the biotic aspect is increased plant productivity. Leachate from unmanaged waste can contaminate the soil which causes a decrease in the biological capacity of the soil including the microorganisms in it, and can reduce the level of soil fertility which affects the biotic elements above the soil such as plants [28].

WPP of Landfill Putri Cempo aside from reducing the environmental impact of landfill waste at Putri Cempo Landfill, it can create clean and affordable energy for the community and reduce greenhouse gases. The existence of this WPP in terms of the sociocultural aspects of the community is expected to be able to add decent jobs and economic growth to the surrounding community, especially the Jatirejo RW 39 community. In addition, there are still opportunities for scavengers to sort waste because a special place will be provided at Putri Cempo Landfill for dropping waste and waste sorting. Such behaviour needs to be encouraged by a culture of consumption and production that is responsible for the waste produced by households in society. Good waste management is waste management with the principles of integrated waste management, where the waste management is adapted to local communities and decision-making is based on development goals [11]. There is a culture of the community around the Putri Cempo Landfill WPP that is good at waste management such as doing 3R (Reduce, Reuse, and Recycle) which can reduce environmental and public health impacts.

4.2 Potential major environmental impact

4.2.1 Human carcinogenic toxicity

The results of the impact assessment indicate that the electrical product system process, which uses gasification technology at the Putri Cempo TPA PSEL, has the highest potential environmental impact, specifically human carcinogenic toxicity. This means that in the PSEL gasification process at the Putri Cempo TPA, there is a potential impact of emissions of hazardous materials, especially those that are carcinogenic, into the air, water, and soil, which can be absorbed and accepted by humans, causing human health problems. The potential impact of human carcinogenic toxicity is also related to the gasification process, which uses partial combustion to produce synthetic gas, which is later converted into electrical energy. This incomplete combustion process can lead to the production of carcinogenic chemical compounds, such as dioxins and furans. Power plants and waste burning can produce toxic compounds known as polycyclic aromatic hydrocarbons (PAHs), a group of carcinogenic or mutagenic compounds, particularly benzo[a]pyrene with a size of 10 micrometres (PM10) [29]. This is in line with the opinion of ICEL (2017), which states that the construction of PSEL will produce dioxin and furan emissions, which have an impact on environmental air pollution and pose risks to public health aspects. Dioxin/furan is an aromatic benzene compound containing oxygen and chlorine that is formed at a temperature regime between 200 and 700ºC with maximum formation at 315℃ [11, 30].

The mechanism of human carcinogenic toxicity is the delivery or movement of toxicants towards humans; toxic reactions with molecules in humans; dysfunction, toxic effects, and cell damage in humans; as well as cell repair that can occur at the molecular, cellular, and tissue levels. The level of carcinogenic toxicity in humans has several different toxic effects for each individual; this is influenced by physical properties and chemical activity in the body, dose and dose-time relationship, route of exposure of the toxicant into the body, species, age, gender, and ease of exposure to the toxicant. The body's absorption, metabolic ability, distribution within the body, excretion process, health condition or medical history, nutritional status, and the presence of other chemicals in the body all play a significant role in determining the level of carcinogenic toxicity [31].

Heavy metals also cannot be separated from PSEL installation facilities, where the metals arsenic, cadmium, chromium, and nickel are classified as group 1 carcinogens by the International Agency for Research Cancer. The metal substances mentioned above cause oxidative stress, DNA damage, and cell death processes, thereby increasing the risk of cancer and cancer-related diseases, but phytochelatin molecules and antioxidant phytochemical substances are very helpful for preventing cancer caused by heavy metals [32]. Therefore, to control the potential impact of human carcinogenic toxicity, toxicant monitoring is necessary. This can be done by identifying and controlling a toxicant and its effects on the environment, where the stages consist of environmental monitoring, biological monitoring and health surveillance. Apart from that, greenery can provide fresh air and help reduce the effects of pollution, especially air pollution. The community should be able to implement health promotion programs that have been provided in the context of continuous disease prevention to build clean and healthy living habits to achieve optimal health [33].

4.2.2 Freshwater ecotoxicity

The impact assessment results indicate that the electrical product system process, which uses gasification technology at the PSEL TPA Putri Cempo, has the highest potential environmental impact, specifically freshwater ecotoxicity. This implies that the emission of hazardous materials into the air, water, and soil could potentially impact concentrations in freshwater ecosystems, leading to environmental health issues. Moreover, this impact category carries the potential to harm freshwater ecosystems, thereby disrupting the lives of other living creatures. The impact of freshwater ecotoxicity is related to heavy metals, which are considered very important and toxic pollutants in the environment [34].

Some metals, such as Cd and Pb, have very toxic properties and their effects on the environment and living organisms. Toxicity caused by heavy metal pollution in freshwater ecosystems, where high levels of heavy metals have been found in sediments and biota of ponds as well as lakes, rivers and wetlands. Freshwater toxicity is also influenced by acid rain resulting from dissolved hydrogen sulphide, sulphur dioxide, and nitrogen oxides, thereby contributing to changes in soil and freshwater acidity. This results in an increase in the bioavailability of many heavy metals in freshwater biota. The mechanism of freshwater ecotoxicity is the delivery or movement of toxicants to water bodies such as rivers, lakes, reservoirs, ditches, etc., then some metals are deposited by gas exchange on the water surface. The chemical composition of fresh water influences heavy metal speciation, wherein turbid river water most of the heavy metals are bound to the organic and inorganic particles in it [35].

The people of Jatirejo are concerned about the potential impact of freshwater ecotoxicity, particularly the potential for wastewater discharge from the gasification process to pollute the surrounding river water. However, it is worth noting that PSEL TPA Putri Cempo already has an IPAL in place. Therefore, to control the potential impact of freshwater ecotoxicity, wastewater can be treated first and then released into rivers so that it meets quality standards in accordance with Minister of Environment and Forestry Regulation No. P.68/Menlhk/Setjen/Kum.1/8/2016 concerning Domestic Wastewater Quality Standards. A form of environmentally friendly PSEL if exhaust emissions and liquid waste meet national quality standards, so the installation needs to be equipped with a pre-treatment plant to reduce water content and air pollution [36].

4.2.3 Freshwater ecotoxicity

The impact assessment results indicate that the electrical product system process at PSEL TPA Putri Cempo, which uses gasification technology, has the highest potential environmental impact, specifically in the area of marine ecotoxicity. This implies that the emission of hazardous materials into the air, water, and land could potentially impact concentrations in seawater ecosystems, leading to environmental health issues. Moreover, this impact category carries the potential to harm the seawater ecosystem, thereby disrupting the lives of other living creatures. The impact of marine ecotoxicity is related to heavy metals, where rivers provide a large contribution of metals to the marine environment. This makes marine ecosystems a provider of containers for many metals and their compounds, so that aquatic microorganisms can be affected by toxicity levels and are also responsible for environmental biodegradation [37].

The toxicity of seawater itself shows the level of bioaccumulation of metals, which depends on the total amount of bioavailability of each metal in the environmental media and the route of absorption, storage, and excretion mechanisms. Furthermore, these metals enhance the potential of living organisms that are either passively exposed to water or directly absorb them, with some metals absorbed as free ions and others as inorganic complexes [35].

The main factors that influence the release of metal ions from metal oxides are the pH and specific surface of the material, where the presence of heavy metals in seawater can increase the level of oxidative stress in marine organisms, reduce the resilience of marine ecosystems, and the effects of climate change [38].

The chemical composition of seawater itself can influence heavy metal speciation, such as pH, turbidity and dissolved organic matter, so that phytoremediation and biomonitoring of heavy metal concentrations in biota can be carried out. The goal is to detect toxicological threats posed to aquatic organisms and also risks to human health through several species of aquatic biota consumed. One of them is that macroalgae or seaweed have good absorption capacity for all substances in the aquatic environment, including the heavy metal mercury (Hg), where the ability to accumulate mercury in red and brown macroalgae species makes it potential as a bioaccumulator [39]. Phytoremediation is an in-situ remediation technology that is ecologically and economically sound by using plants to clean up pollution in the environment.

4.3 Hotspots of the WPP gasification process at Putri Cempo Landfill

The results of the impact assessment that has been carried out show that the processing unit which is the hotspot of the WPP gasification process at Putri Cempo Landfill is the gasifier. This hotspot determination is carried out after an impact assessment to find out which process unit has the greatest environmental impact as shown in Figure 4. Simple gasification technology by combustion is traditionally included in waste power plants, but full gasification technology uses a gasifier to produce chemical components as a generator. The gasifier is the hotspot for the WPP electricity product system at Putri Cempo Landfill with gasification technology because in this process there are the most inputs that are entered and output that is issued, both in the form of products, waste and emissions as shown in Figure 5. This affects the inventory carried out in this study. The process that has the next greatest potential environmental impact is the generator engine and then the gas cooling system.

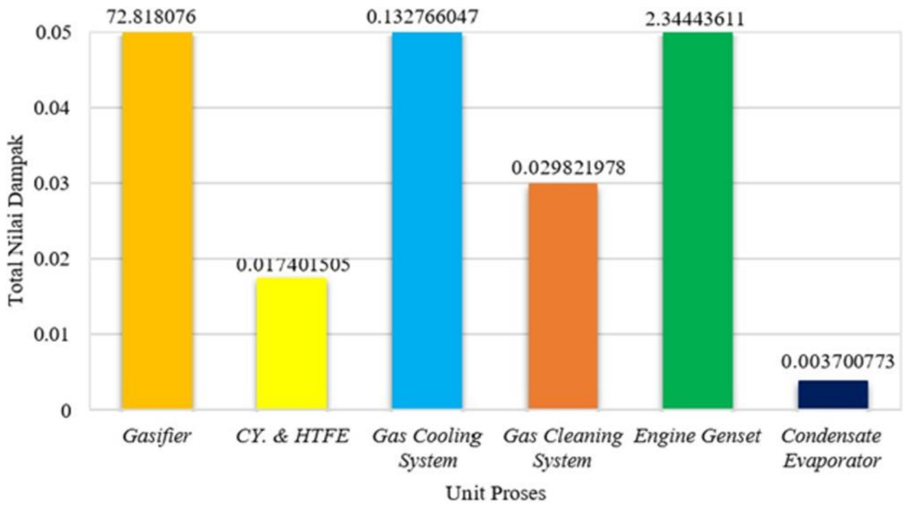

Figure 4. Hotspots of the WPP gasification process at Putri Cempo Landfill

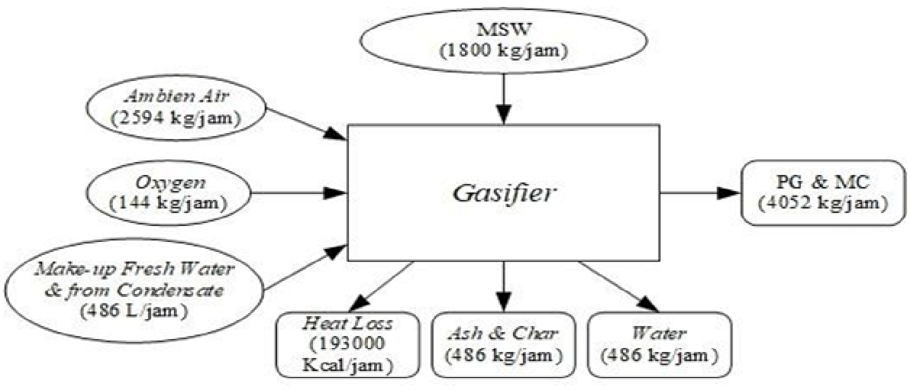

Figure 5. The flow of the gasification process unit WPP of Putri Cempo Landfill

The main input required for the WPP gasification process for Putri Cempo Landfill is urban waste, also known as MSW the waste used in the Putri Cempo Landfill WPP consists of old urban waste which is the waste heap at Putri Cempo Landfill and new urban waste which is the generation of urban waste from the people of Surakarta City. Before being burned in the gasifier through the direct gasification system process to be converted into syngas, this waste needs to be processed into feedstock beforehand. The characteristics of this feedstock will later affect the amount and quality of the syngas produced. Each waste-to-energy technology requires a different feedstock and process so that it can be adapted to the existing urban waste characteristics. This is because each gasification unit has certain characteristics depending on the biomass feed which affects the performance of the unit, so it is necessary to test the tool so that the best operating conditions can be determined [40].

The WPP raw materials come from old waste piles at Putri

Cempo Landfill and new urban waste generation, which will later be processed to become feedstock for the manufacture of biochar briquettes as the main material for the gasification process. Municipal waste processing at the Putri Cempo Landfill WPP is carried out by making feedstock in the form of biochar briquettes. The pre-treatment carried out at the Putri Cempo Landfill WPP was divided into two, namely the old MSW pre-treatment and the new MSW pre-treatment. Feedstock production starts with sorting waste, both old waste from landfill waste and new waste from urban waste generation. The old waste that has been sorted is then put into the rotary dryer, while the new waste needs to be given a bio-activator with the principle of permutation and then dried by bio-drying using the help of sunlight. Furthermore, the dry waste is placed in feedstock storage before being chopped and printed to become biochar briquettes which will later be used for the gasification process.

The higher the ultimate content in the waste and the lower the proximate content in the waste will produce more syngas, and conversely if the lower the ultimate content in the waste and the higher the proximate content in the waste will produce a smaller amount of syngas. In addition, the waste drying process is also a major consideration, because the faster the drying process can increase the feedstock stock to be converted into biochar briquettes before being partially burned in the gasifier. So that the use of technology or equipment that helps drying can improve the quality of feedstock and syngas later such as the use of rotary dryer technology.

5. CONCLUSION

The biggest (major) potential environmental impacts arising from the WPP gasification process of Putri Cempo Landfill are human carcinogenic toxicity of 41.64738 kg 1.4-DCB, freshwater ecotoxicity of 15.364229 kg 1.4-DCB, and marine ecotoxicity of 11.390976 kg 1, 4-DCB. Meanwhile, the lowest (minor) potential environmental impacts arising from the WPP gasification process of Putri Cempo Landfill are mineral resource scarcity of 0.000182585 kg Cu eq, stratospheric ozone depletion of 0.041251 kg CFC11 eq, and land use of 0.046136128 m2a crop eq. The hotspot for the gasification process that contributes the greatest environmental impact is the gasifier with the direct gasification system because in this process there are the most inputs that are included and the output that is released, both in the form of products, waste and emissions, thus affecting the results of the impact category in the inventory carried out. To reduce this impact, recommendations that can be implemented include optimizing the gasification process by controlling the temperature and combustion time, using advanced waste processing technology such as wastewater treatment plants and electrostatic precipitators, as well as routine monitoring of emissions and environmental quality. In addition, public education about waste sorting and collaboration with the government to implement stricter regulations and provide incentives for environmentally friendly technology are also needed. With these steps, gasification efficiency can be increased and environmental impacts minimized, supporting more sustainable PLTSa operations.

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