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Evaluation of Greenhouse Gas Emission Assessment Resulting from Processing Municipal Organic Waste into Bahan Bakar Jumputan Padat for Co-firing in Power Plants; Case Study: Bagendung Landfill Cilegon City

Teuku Muhammad Ismaldy * and Ratna Purwaningsih

Department of Management and Industrial Engineering, Faculty of Engineering, Diponegoro University, Jl. Prof. Jacub Rais, Tembalang, Semarang City, 50275, Indonesia.

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Abstract

One type of biomass that can be used as fuel for co-firing in power plants is Bahan Bakar Jumputan Padat (BBJP)/Solid Waste Fuel. BBJP is a non-hazardous waste derivative that cannot be recycled. The production process of BBJP is strictly regulated by the Indonesian national standard (SNI) 8966:2021. The definition, characteristics and specifications of BBJP are much closer to Solid Recovered Fuel (SRF) than Refuse Derived Fuel (RDF). The utilization of BBJP reflects the dedication to reducing waste in landfills with a circular economy concept approach as well as the transition of the energy mix in Indonesia. To the present day, the production capacity of BBJP at Bagendung landfill in Cilegon City, Banten Province, has successfully produced 30 tons/day of organic municipal waste with an average BBJP product yield ranging between 11-15 tons/day. This research is intended to assess the Greenhouse Gas emissions (GHG) generated from the processing of municipal waste into BBJP. There are three main processes that produce GHG emissions, namely during bio drying processing, the use of machinery that produces emissions from electricity and the transportation process that produces combustion emissions in diesel fuel. As a result, direct GHG emissions arising from all waste processing activities into BBJP consist of 10 pollutants, namely CH4, N2O, CO, NH3, CO2, NOX, SO2, NVMOC, PM2.5 and ID(1,2,3,c,d)P. CO2 emission is the largest pollutant, accounting for 96.70% of the entire BBJP process.

Keywords: Production BBJP; Greenhouse Gas (GHG); Emissions; Co-firing Power Plant; Waste-to-energy

1 Introduction

Currently, the electricity sector in Indonesia is trying to fulfill the mandate of the National Energy General Plan. The mandate accelerates the achievement of the New Renewable Energy (NRE) mix target of at least 23% by 2025 and 31% by 2030 (1). On the other hand, the waste emergency in Indonesia is an urgent issue that has an impact on various aspects of society. The waste emergency is increasingly faced by the Indonesian people. At least until 2023 there are still 5,981,606.75 tons/year of unmanaged waste or 33.08% of the total waste generation of 18,081,278 tons/year (2). the context of municipal waste treatment, the circular economy offers an approach that integrates technological innovation and management strategies to transform waste into valuable resources.

The circular economy in municipal waste treatment involves transforming waste into valuable resources to create a sustainable and efficient system (3). In dealing with these conditions, one of the quick and practical steps for energy transition in the near future is a strategic initiative by co-firing. Co-firing is the mixing of coal and biomass materials with a certain ratio at the Coal-fired Power Plant (CFPP) installation (4). Until the end of 2023, the achievement of co-firing implementation has been carried out in 43 CFPP locations with energy realization of 1,042.3 GW or equivalent to biomass utilization of 990.8 thousand tons (5). One type of biomass that can be used as fuel for co-firing and has been tested is Bahan Bakar Jumputan Padat (BBJP)/ Solid Waste Fuel. BBJP is a non-hazardous waste derivative that cannot

* Corresponding author: Teuku Muhammad Ismaldy

be recycled. BBJP has no economic value but still has the potential to contain calorific value as energy that can be reused (6). The BBJP is intended as a mixed fuel for power plants that will be combusted simultaneously (co-firing) with coal. In 2023 the total national supply of BBJP for co-firing has reached 1,907.44 tons/day (7).

In order to meet the requirements of the BBJP, PT PLN (Persero) has made a strategic collaboration with the Cilegon City government by producing BBJP from municipal waste. Up to now, the production capacity of BBJP at Bagendung landfill is capable of processing 30 tons of waste per day. The BBJP produced on average ranges between 11-15 tons/day (8). It can be expected that the production of BBJP for co-firing in the future will be required in large-scale quantities and continuously. Waste-to-energy processes such as BBJP require a number of equipment and strict procedures (6). But unfortunately, it is unknown how much the value of emission pollutants and what types of emissions are caused by the entire production of BBJP.

Thus, this research aims to determine the emission footprint and calculate the amount of emission value to evaluate the environmental impact performance of BBJP production. This research contributes by providing comprehensive emission data that is scientific to decision makers regarding the evaluation of environmental impact performance on the application of waste processing into BBJP. In contrast to previous studies that only discussed the waste characteristics test at the landfill, the BBJP co-firing trial at CFPP and the techno-economic assessment of the application of BBJP for co-firing.

2 Material

2.1. SRF, RDF and BBJP: what makes them different?

Some researchers are still ambiguous about the difference between Refuse Derived Fuel (RDF) and Solid Recovered Fuels (SRF). There is no legal definition or universally accepted term between the two terms. Many studies use the terms RDF and SRF with overlapping definitions. Although RDF and SRF are derived from Mechanical-Biological Treatment (MBT), the characteristics, specifications and waste inputs used are clearly different. Conventionally, according to (9) RDF refers to the combustible, high calorific value fraction of inorganic waste (e.g., paper, card, wood, and plastic) generated from MBT treatment of municipal waste or similar commercial/industrial waste. Further, SRF is not the same as RDF which is a non-standardized low-quality fuel, whereas SRF is defined in Europe according to the standard ISO 21640:2021 (10) as the result of MBT treatment produced from non-hazardous waste, containing more organic waste than inorganic waste. Reinforced by (11) claims that there is no common EN or ISO standard for RDF. RDF derivatives that conform to European standards ISO 21640:2021 is classified as SRF. The term BBJP, which is stated in Indonesian National Standard (SNI) 8966: 2021 (6), is not yet popularly recognized by the public.

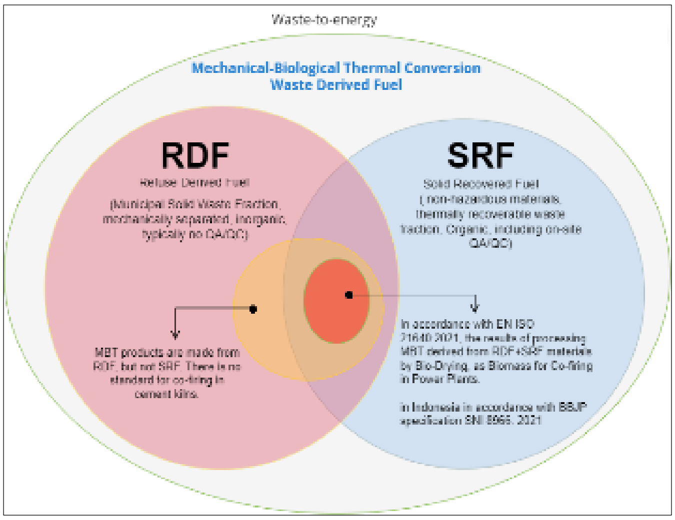

Figure 1 Venn diagram of the relationship between SRF, RDF and BBJP

According to European standards (10), BBJP is considered as SRF resulting from the MBT waste treatment system. Considering the differences between SRF and RDF that have been discussed, the characteristics, classifications and specifications of BBJP are more suitable for SRF than RDF. Thus, as shown in Figure 1 , the definitions and concepts used in this study are that SRF is the same as BBJP.

2.2. Production Process of BBJP

The BBJP production process begins with the arrival of waste from Bagendung landfill in Cilegon city, Banten Province, Indonesia. Every day an average of ±30 tons of wet organic waste from the landfill is transported to the BBJP facility. The waste selection process is done manually. Non-categorized waste will be returned to the landfill. The waste will then be put into the reactor box. This reactor box is used to make it easier to control the bio drying process. Each batch of BBJP production consists of one reactor box with waste composition per layer. The reactor box size dimensions were 1.2m long; 1.2m wide; 1m high.

The volume capacity of each reactor box is 1.3 m3 with a total average full weight of about 620.49 kg and a density value of 449.7 kg/m3. The process of filling the waste into the reactor box is carried out simultaneously with the process of filling the bio activator liquid. Each reactor box will be covered with gunny fabric to maintain temperature and Ph levels. Waste from the bio drying process will decompose. Decomposition is caused by the evaporation of water content in organic waste. This decomposition can cause degradation of wet organic waste weight up to 20% - 30%. So that the average weight of each 1 batch of production in the reactor box shrinks to 496 kg to 434 kg. This bio drying process will take approximately 5-6 days. During the bio drying process, the pH and temperature levels in each reactor box will be monitored. As reported by the BBJP management, on the 6th day the waste temperature had reached an average of 70^0C and the pH level value was 5.3. Then on the 7th day, it will be dismantled and moved to the drying area to be aerated for 1 day.

Then the dried waste will be roughly shredded in a shredding machine. At this stage, the waste will be roughly shredded into a mesh size of 8 or about 2.83 cm. After the waste has been roughly shredded, a screening process is carried out. This sieving process ensures that the waste is free of solids and hard objects and at the same time refines the size of the waste. At this stage, a lot of waste is rejected because the size cannot pass through the 2 cm sieve. The next process is to shred it into a smaller size. The results of the shredding can be up to a diameter size between 0.3-3 mm. The results of this size are in accordance with what is required by SNI 8966: 2021, namely for Fluff-shaped BBJP the minimum size is 0.297 mm and for a maximum size of 2.38 mm. At the final stage, the finely shredded waste will be weighted and then packed in polypropylene plastic sacks. The size of one sack is 50 kg of BBJP and is sewn with a sack sewing machine. Then all sacks are stored and ready to be transported to the Suralaya power plant warehouse.

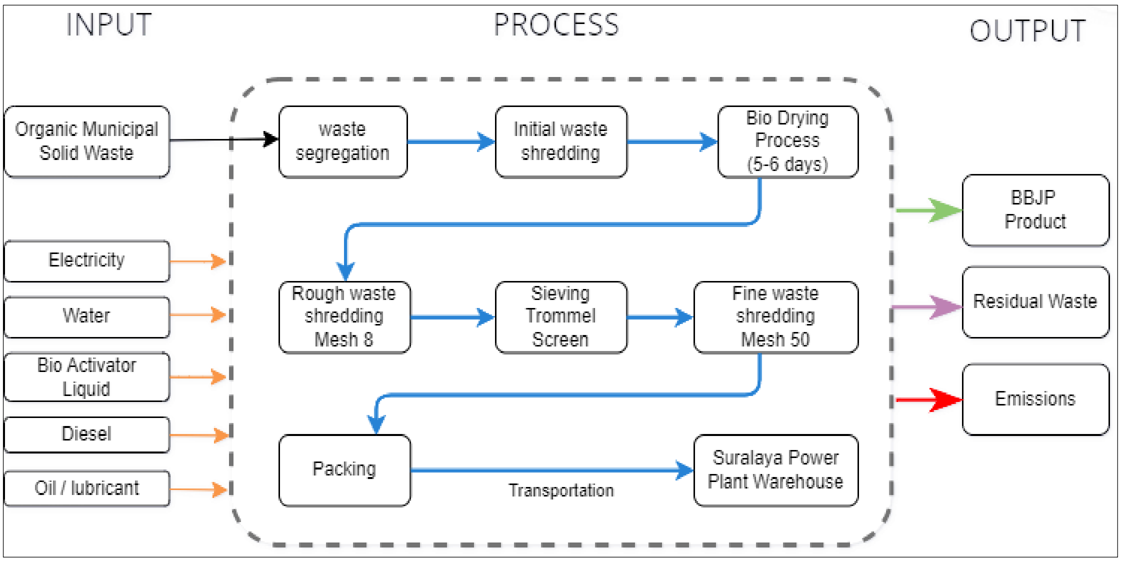

Figure 2 Input, process and output flows of the BBJP production

A step-by-step description of the BBJP production process is shown in Figure 2 Of the total 30 tons/day of organic waste received by the BBJP facility, the production capacity of the BBJP facility is currently only able to maximally produce around 50% or the equivalent of 15 tons of BBJP per day. The remaining 15 tons were lost due to, among other things, decomposition during the bio drying process of up to 30% and another 20% as residue from each processing process.

3 Research methods

3.1. Inventory Data

The research was conducted at the BBJP facility at Bagendung landfill in Cilegon City, Banten Province-Indonesia. The research was conducted in August 2024. Data collection methods were carried out by field observation, interviews, documentation and literature studies. The data used in this study are presented in Table 1.

Table 1 Inventory of BBJP production data required

Process	Description	Material Input	Energy Input
Waste Segregation	Segregation of organic and inorganic waste composition by Conveyor	Conveyor Belt Lubricant Waste raw materials	Electricity consumption
Bio drying process	Biological drying process with the use of chemical solvent	Composition and amount of Bio activator Gunny fabric	water consumption
Rough waste shredding	The rough shredding process reduces the size of the waste to a fuzz size of Mesh 8.	Shredder machine	Electricity consumption
Screening	Sieving process to ensure that the waste is free from harmful materials that could damage the shredder.	Sieving Trommel Screen	Electricity consumption
Fine waste shredding	Shredding waste into fine size Mesh 50	Shredder machine	Electricity consumption
Packaging	Packaging BBJP in 50kg sacks by using a packaging machine	Packaging machine Polypropylene plastic sacks	Electricity consumption
Transportation	Transportation of BBJP finished products from Bagendung landfill in Cilegon to Suralaya power plant warehouse by truck.	Type of truck Type of fuel Distance travelled	Fuel consumption

3.2. Emission Calculation

3.2.1 Bio Drying Emission

Bio drying is an aerobic process and most of the Degradable Organic Carbon (DOC) content the waste material that can be converted to carbon dioxide (CO2). Estimates of the formation of CH4 released to the atmosphere range from less than 1% to several percent of the initial carbon content in the material. Bio drying can also produce N2O emissions. The estimated range of emissions varies from less than 0.5% to 5% of the initial nitrogen content of the waste. Estimated CH4 and N2O emissions from biological treatment can be calculated using the Tier-1 method given in Equation 1 and Equation 2 (12) as follows:

$$Emission\ CH_4 = \sum_i (M_i\ x\ FE_i) x 10^{-3} - R \quad (1)$$

$$Emission\ N_2O = \sum_i (M_i\ x\ FE_i) x 10^{-3} \quad (2)$$

Where,

CH_4 : The total CH4 emissions in the inventory year (kg CH4)
N_2O : The total N2O emissions in the inventory year (kg N2O)
M_i : Weight of organic waste processed by bio drying (kg)
FE_i : Emission factors for bio drying treatment (kgCH4/kg) and (kgN2O/kg)
R : The total CH4 recovered in the inventory year (kg CH4)

To estimate the formation of CO and NH3 emissions in bio drying processing, a Tier-2 approach can be used in Equation 3 and Equation 4, (13) as follows.

$$Emisi\ CO\ =\ AR_{production} x\ FE \quad (3)$$

$$Emisi\ NH_3\ =\ AR_{production} x\ FE \quad (4)$$

Where,
CO : The total CO emissions generated in the bio drying process (kg CO)
NH_3 : The total NH3 emissions generated in the bio drying process (kg NH3)
FE_i : Emission factor for bio drying treatment (kg CO/kg) and (kg NH3/kg)
$AR_{prod.}$: Weight of organic waste processed by bio drying (kg)

3.2.2 Road Transportation Emission

Data collection for transportation emissions including vehicle type, fuel type, amount of fuel and distance traveled were obtained from observations, interviews and BBJP management's historical data. Transportation emission factors using Tier-1 were obtained from (13). The following Equation 5 calculates vehicle emissions of CO, N2O and NOx based on Tier-2 specific to the Indonesian region as follows.

$$ET_{i,j}\ =\ \sum_k (N_{j,k}\ x\ M_{j,k} x FE_{i,j,k}) \quad (5)$$

Where,
$ET_{j,k}$: Transport Emissions of pollutant i for vehicle technology k (g)
$M_{j,k}$: Total distance traveled by vehicle type j and vehicle technology k (km)
$FE_{i,j,k}$: Emission Factor of pollutant i for vehicle type j and vehicle technology k (g/km) k vehicle technology (g/km)
$N_{j,k}$: Number of Vehicles of vehicle type j and vehicle technology k

For the calculation of estimated SO2 emissions in vehicles according to fuel type m, it is assumed that all sulfur in the fuel is converted completely into SO2, Equation 6 as follows:

$$ET_{SO2,m}\ =\ 2x\ k_{s,m} x FC_m \quad (6)$$

Where,
$ET_{SO2,m}$: Emission from transportation of SO2 pollutant per fuel m (g)
$K_{s,m}$: Sulfur content in fuel type m (g/g fuel)
FC_m : Average fuel consumption for fuel m (g)

3.2.3 Electricity Emission

Electricity emission at each stage of the BBJP production process are calculated through secondary data that has been collected and from emission factors obtained from various literatures. Emission factors for low-voltage networks using Indonesia's region-specific tier-2. The following Equation 7 calculates Greenhouse Gas (GHG) emissions in the form of multiplication between activity data and emission factors (13).

$$GHG\ Emissions\ =\ Activity\ Data\ x\ Emission\ Factor \quad (7)$$

Activity Data is defined as the amount of electrical power consumption in hours for each unit of machinery. The unit of activity can be the volume produced or the volume consumed. The Electricity Emission Factor is a coefficient that shows the number of emissions from electricity consumption.

3.2.4 Emission Factor

Emission factors is a coefficient that measure the emission or release of pollutant per unit of activity (14). Local emission factors that are not available are replaced with emission factors from other regions or default values determined by the Intergovernmental Panel on Climate Change (IPCC). The emission factor database contains a compilation of factors from different countries and regions. The methodology for selecting emission inventories is based on the level of accuracy (tier), where higher tiers produce more detailed and accurate results in the calculation of emissions. According to (15), there are three commonly used tiers: Tier 1, tier 2 and tier 3. Tier 1 is a method of calculating emissions using a basic calculation formula, while the activity data used is partly sourced from global data sources, production statistics, and uses emission factors provided by the IPCC Guidelines. Tier-2 methods use more detailed calculation formulas, and activity data can come from state and/or local data sources, and can even be obtained from direct measurements. The Tier-3 emission calculation method is the most detailed calculation using a modelling and sampling approach, while the local emission factor modelling approach varies with the diversity of existing conditions so that emissions and pollutants have a lower error factor. The emission factors used in this study are presented in Table 2.

Table 2 Emission factor of BBJP production

Description	Emission Type	Emission Factor Value	Unit	Reference
Bio drying process	CH_4	4.00E-03	kg CH_4/kg	(12)
	N_2O	2.4E-04	kg N_2O/kg	(12)
	CO_2	0.56	kg CO/Mg	(13)
	NH_3	0.66	kg NH_3/Mg	(13)
Transportation Heavy-Duty Vehicle, Diesel Rigid <= 7,5t, Euro-2	CO	0.806	g/km	(13)
	NMVOC	0.166	g/km	(13)
	NO_x	4.919	g/km	(13)
	N_2O	0.004	g/km	(13)
	NH_3	0.003	g/km	(13)
	CO_2	448.532	g/km	(13)
	PM2.5	8.96E-02	g/km	(13)
	ID(1,2,3,c,d)P	1.40E-06	g/km	(13)
	SO_2	500	ppm	(16)
Low Voltage Electricity PLN Interconnection System,	CO_2	0.87	kg CO_2/kWh	(17)
	NO_x	1.97E-03	kg NO_x/kWh	(18)
	SO_2	1.01E-02	kg SO_2/kWh	(18)
	CH_4	1.59E-05	kg CH_4/kWh	(19)
	N_2O	8.77E-06	kg N_2O /kWh	(19)

4 Results and discussion

4.1. Bio Drying Process Emission Result Calculation

The ratio of bio activator liquid use is 1 liter of bio activator mixed with water to become 80 liters. So that one time the mixture of bio activator solution can serve around 26 reactor boxes with each reactor box being done three times watering. Each watering requires at least 1 liter, meaning each reactor box consumes 3 liters. The content and composition of the bio activator liquid is shown in Table 3.

Table 3 Composition of Bio activator Liquid

Raw Materials	Composition(kg)
Molasses	0.75
Young coconut water	1.56
Pineapple chunks	2
Yeast	0.5
Rice bran	0.3
water	1

Source: (20)

To produce a BBJP product of 15 tons per day requires an average wet weight of organic and inorganic waste of 17,475.32 kg and 3,358 kg respectively for a total of 20.83 tons. Furthermore, the calculation of CH_4 and N_2O emissions can be proceed using equations 1 and 2, while the calculation for CO and NH3 emissions uses equations 3 and 4, so the overall value of emissions generated from the bio drying process can be obtained as shown in Table 4.

Table 4 Bio drying Emission Value

Emission Type	Emission Factor (kg)	Emission Value (kg)
CH_4	0.004	0.083
N_2O	0.00024	0.005
CO	0.56	11.66
NH_3	0.66	13.75

4.2. Electricity Emission Result Calculation

There are 16 machines in total that are used for BBJP production. The total power required is 84.64 kW to operate all the equipment. Per day producing 15 tons for a duration of 8 working hours, the electricity consumed is 1,292.32 kWh of 3-phase low voltage electricity. Following in Table 5 the results of the calculation of electricity emissions.

Table 5 Total electricity consumption

No	Machinery Equipment	Quantity	Power (kW)	Total consumption (kWh)
1.	Waste segregation conveyor	1	2.2	17.6
2.	Waste paper shredder	1	4	32
3.	Coconut shell shredder	2	5,5	88
4.	Conveyor feeder	2	2,2	35.2
5.	Rough shredder	2	22	352
6.	Conveyor feeder	2	2.2	35.2
7.	Trommel screen sieving	2	15	240
8.	Fine shredder	2	30	480
9.	Sack sewing machine	1	0.1	0.8
10.	Electric forklift	1	1.44	11.5
Total		16	84.64	1,292.32

Having obtained the total kWh value of electricity consumption in 8 operational hours, the value of emissions generated will then be calculated. Calculation of emission values for CO2, NOx and SO2 using Tier-2 in accordance with the emission factors in Table 2. The results of the calculation of electricity emissions for the production of 15 tons of BBJP per day are shown in Table 6.

Table 6 Electricity consumption emission value

Emission Type	Emission Factor (kg/kWh)	Emission Value (kg)
CO_2	0.87	1,124.318
NO_x	0.0019680	2.543
SO_2	0.0100670	13.010
CH_4	0.00001594341	0.0206
N_2O	0.00000876813	0.0113

4.3. Road Transportation Result Calculation

The transportation used to transport BBJP products are Hino transport dump trucks, freight, lorry 7.5-16 metric tons, Euro2. 8 m3 load volume capacity and 10 tons load weight capacity. The fuel used was government-subsidized biodiesel (B30). The following Table 7 describes the types and specifications of trucks used to transport BBJP products to the Suralaya power plant warehouse.

Table 7 Types and specifications of transportation

Transportation Description	Remaks
Vehicle type	Dump Truck Hino Euro 2
Load weight capacity	10 ton
Load volume capacity	8 m^3
Fuel type	Bio Solar (B30) (subsidized)
Fuel density	880 kg/m^3
Sulfur content	500 ppm
Average fuel consumption	151 g/km (0.172 l/km)

The distance for a single trip from the BBJP facility at Bagendung landfill to the Suralaya power plant warehouse is 36 km, so the round trip is 72 km. Two dump trucks operate every day with 1 roundtrip each, so the total distance travelled in a day is 144 km. The average operational time required by one dump truck is 198 minutes or equivalent to 3.3 hours. The average consumption of biodiesel fuel (B30) subsidized by 1 unit of dump truck round trip is 12.47 Liter. BBJP's average production of 15 tons/day is packed in 50 kg sacks, totaling to 300 sacks that are transported every day. With the density of BBJP of 0.970 g/cm3, the maximum carrying capacity of 1 unit dump truck is 7,500 kg or equivalent to 150 sacks. So that the value of tons / distance in a day of delivery is 2,160 tkm. The following Table 8 summarizes the transportation operation scheme per day to transport 15 tons of BBJP.

Table 8 Daily transportation operations

Description	Unit	Delivery 1	Delivery 2	Total
Total load weight	kg	7,500	7,500	15,000
Total load volume	m3	7.73	7.73	15.46
Packaging Quantity	sacks	150	150	300
Fuel consumption	liter	12.47	12.47	24.95
Travel Time	minute	198	198	396
Round Trip Distance	km	72	72	144
Ton/distance	tkm	540	540	2.160

After obtaining the number of vehicle units, total distance travelled and total fuel consumption, the calculation of transportation emissions can be carried out. The calculation of CO, N2O and NOx emissions was carried out using the Tier-2 method and in accordance with Equation 5. The following Table 9 shows the results of the calculation of total transportation emissions.

Table 9 Transportation Emission Value

Total Distance Traveled (Km)	Number of Vehicle Units (no)	Emission Type	Emission Factor	Emission Value (kg)
144	2	CO	0.806	0.23
		NMVOC	0.166	0.048
		NO_x	4.919	1.417
		N_2O	0.004	0.0012
		NH_3	0.003	0.000864
		CO_2	448.532	129.177
		$PM_{2,5}$	8.96E-02	0.026
		$ID_{(1,2,3,c,d)}P$	1.40E-06	4.03E-07

The Sulphur content of each fuel is different. Therefore, the Sulphur content of subsidized biodiesel (B30) refers to its producer (16). Therefore, the calculation of SO2 emissions uses Tier 2 and is carried out in accordance with Equation 6. Sulphur SO2 emission calculation results are shown below in Table 10.

Table 10 Transportation SO2 emission value

Description	Unit	Value
Number of vehicles	Unit	2
Total distance traveled	Km	144
Biodiesel consumption	g/km	151.97
Sulfur content of biodiesel	g/g	0.0005
Total biodiesel consumption per day	g	43,767
SO2 emission value	kg	0.0437668

4.4. Result Analysis

Analysis of greenhouse gas emissions shows that CO2 is the dominant pollutant, accounting for up to 97.7% of total emissions. This indicates that activities related to electricity consumption and transportation have a significant impact on air pollution and climate change. With CO2 emissions from electricity consumption reaching 1,124.32 kg/day and from transportation at 129.18 kg/day, it can be seen that energy use and mobility are major factors in increasing CO2 levels in the atmosphere. The total emissions generated are shown in Figure 3 Emission contribution at each process stage of BBJPFigure 3.

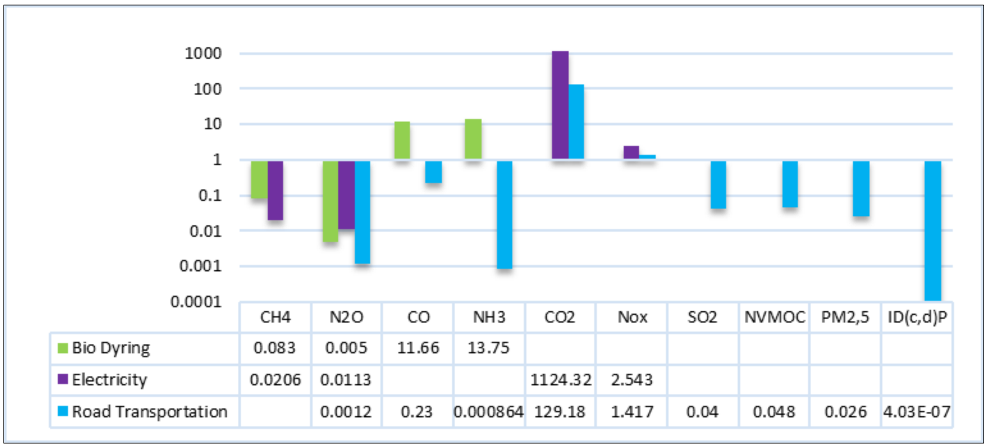

Figure 3 Emission contribution at each process stage of BBJP

On the other hand, emissions of other gases such as CH4 (methane), N2O (nitrous oxide), NVMOC (Non-Methane Volatile Organic Compounds), PM2.5 (fine particulates), and ID(1,2,3,c,d)P have emission values below 1. This shows that although these gases also contribute to pollution, their contribution is much smaller compared to CO2.

5 Conclusion

BBJP production process consists of bio drying process, electricity consumption and transportation. The total emissions generated from the entire 15 tons/day BBJP production activities include CH4, N2O, CO, NH3, CO2, NOX, SO2, NVMOC, PM2.5 and ID(1,2,3,c,d)P. The dominance of CO2 emissions indicates the need for greater attention to the electricity consumption and transportation sectors in an effort to reduce negative environmental impacts. Emission reduction strategies can focus on improving energy efficiency, developing renewable energy sources, and promoting sustainable transportation. While other gaseous emissions are at relatively low levels, it is still important to monitor and manage all types of emissions to maintain environmental quality.

This is mainly due to the fact that most of the national grid system still utilizes fossil fuels, mainly the use of coal rather than using new renewable energy. As well as carbon dioxide pollutant CO2 caused by burning diesel fuel for dump truck transportation. Carbon dioxide pollutant CO2 can cause global warming which will affect the increase of greenhouse gas emissions. Greenhouse gas emissions will lead to an increase in the radiative capacity (w/m2) of the atmosphere which in turn will increase the global average temperature (°C). Increased temperatures ultimately result in damage to human health and ecosystems.

The dominance of CO2 emissions may lead environmental policies to focus on reducing carbon emissions. This could include investing in renewable energy, improving energy efficiency, and developing green transportation. These insights can also be used to raise public awareness about the importance of reducing carbon footprints. The public needs to be informed about how their daily activities contribute to CO2 emissions.

Compliance with ethical standards

Disclosure of Conflict of interest

There are no conflicts of interest.

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