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Utilization of Bagasse as a Substitute for Coal Fuel in Steam Boilers

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Abstract: Biomass utilization is believed to bring environmental and socio-economic benefits—PT X coal in a steam boiler. The research method used is a mix of quantitative and qualitative. The concentration of particulates that coal produces is higher than that of sugar cane bagasse. The NOx parameter values produced by bagasse and coal showed insignificant results. Meanwhile, coal boilers with higher temperatures produced higher NOx than NOx from biomass. The distribution concentration of SOx in bagasse biomass is higher than coal SOx emissions. A total of 26 communities agreed to change the use of coal to bagasse biomass. Utilization of bagasse biomass provides income of up to 94,000,000,000. Using bagasse as steam boiler fuel has a more positive impact than coal.

Keywords: Concentration and distribution of emissions; Potential cost efficiency; Public perception

Introduction

Along with the rapid economic growth rate, the country has entered an unprecedented process of rapid urbanization and extensive development and construction, especially growth in the industrial sector (Fang et al., 2021). Sustainable development in developing and poor countries remains a global challenge due to the trade-off between development and environmental conservation (Ge et al., 2023). Energy consumption has an essential relationship with economic growth but also reduces environmental quality (L. Wang et al., 2024; Y. Wang et al., 2024). Energy efficiency is closely related to energy supply and demand, economic development, and environmental pollution, but the key to achieving energy and environmental efficiency remains the influence of regional policies (Hsieh, 2022). Sustainable energy and its implementation will help countries reduce CO_2 emissions long-term and influence economic growth, including private investment in sustainable energy projects (Rasoulinezhad et al., 2022). One example of an energy transition policy implemented in Europe is the coal transition agenda, by strengthening climate policies and environmentally friendly development to anticipate the climate crisis (Loewen, 2022).

One of the industry's problems is using coal as the primary energy source. This also causes depletion of energy resources, increased greenhouse gas emissions, climate change, a polluted environment, and increased health risks (Chew et al., 2021). Global food demand continues to grow, so the natural resources needed to produce it have become limited, coupled with environmental degradation (Adelodun et al., 2021). The role of coal has encouraged industry and employment, but the use of coal has significant disadvantages, namely air pollution and its impact on human health (Clay et al., 2024). The most important contribution of PM10 comes from the transportation and loading of coal after crushing, while PM10 levels from crushing dissipate in smaller areas (Srivastava et al., 2021).

Using biomass as fuel can reduce industry dependence on coal and its carbon footprint. However, implementing coal substitution with biomass is not

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simple and requires a deep understanding of various aspects, including technical, economic, and environmental. Biomass as an alternative fuel is attracting attention as a potential replacement solution for coal. Biomass is increasingly being developed as a renewable and environmentally friendly alternative to fossil fuels due to its carbon neutral characteristics, rational development, and use of bioenergy to create environmentally friendly energy and achieve carbon neutrality (Du et al., 2024; Ma et al., 2023; J. Wang et al., 2023; Xing et al., 2023). Biomass residue is one of Indonesia's green energy focuses, as outlined in Government Regulation 79 of 2014 concerning National Energy Development. The potential of biomass as a fuel substitute is one type of renewable energy that is the best choice from the perspective of reducing greenhouse gases (Lu et al., 2022; Miedema et al., 2017). Compared with theoretical predictions, the interaction between coal and biomass shows excellent effects when coal is mixed with different biomass (Yi et al., 2023). Biomass fuel pellets have low emissions and considerable residential conversion potential (Boman et al., 2003).

Another example is wood biomass energy; GHG emissions produced by burning wood are 1.30–1.41 kg-CO_2 eq·kWh^{-1}, which is greater than GHG emissions from coal-fired power plants (Ono et al., 2023). Rice husks contain valuable biomaterials with broad applications in various fields (Kordi et al., 2024). The calorific value of coal and biomass determines combustion efficiency, where 5300 cal/gr of coal produces heat that lasts longer than 3800 cal/gr and 4500 cal/gr (Kurniansyah et al., 2023). The calorific value obtained from rice husk bio briquettes ranges from 2,700 – 4,400 cal/g, while rice husk as fuel feed in gasification furnaces using gasification technology because it has a relatively high calorific value of 14.8 MJ/kg (Dewi et al., 2020; Gumirat et al., 2021). The potential of rice husk biomass, on the other hand, has a negative impact. Volumes of rice husks from milling plants were found scattered in rural agricultural areas in the San Martin region, Peru, where people are exposed every day to polluting gas emissions resulting from burning this waste, which causes respiratory and lung diseases (Arévalo et al., 2017; de Almeida et al., 2022). Based on research at industrial locations, the highest concentration of emissions produced is located in the nearest settlement to the industrial area, between 200 m and 500 m (Ismahani et al., 2023; Sasmita et al., 2021; Tama et al., 2023). Changes in distance from the emission source can impact the emission concentration level, where the further the distance from the emission source, the emission concentration tends to decrease (Ismahani et al., 2023; Tama et al., 2023).

Apart from rice husks, there is biomass that has the potential to be used as an alternative fuel in steam boilers, namely bagasse. In research in the sugar industry in Zimbabwe, bagasse biomass of 2.3 million tons per year can produce 193.1 tons of steam per hour to power the factory. Moreover, it has excess steam of 81.93 tons per hour (Mtunzi et al., 2017). The bagasse biomass tested had a calorific value of 2947 kCal/kg (Destalia et al., 2024). The 25% bagasse and 75% coal ratio provide the fastest and most efficient highest temperature (Kurniansyah et al., 2023).

In line with the sustainable development goal of reducing carbon emissions, this research examines one of PT PT X's programs on environmental control. The target that encourages PT The amount of coal fuel used by PT X is 6.25 tons/hour with a boiler capacity of 9 tons/hour.

The United States government considers that biomass energy improves environmental quality, so it has policies that must encourage the use of biomass and investment in biomass energy (Pata et al., 2023). One of the main limitations of urban biomass use is that cities must have sufficient production potential to meet their own energy needs (Calvo-Saad et al., 2023). The agricultural potential in Mojokerto Regency is also a driving factor in PT X.

Method

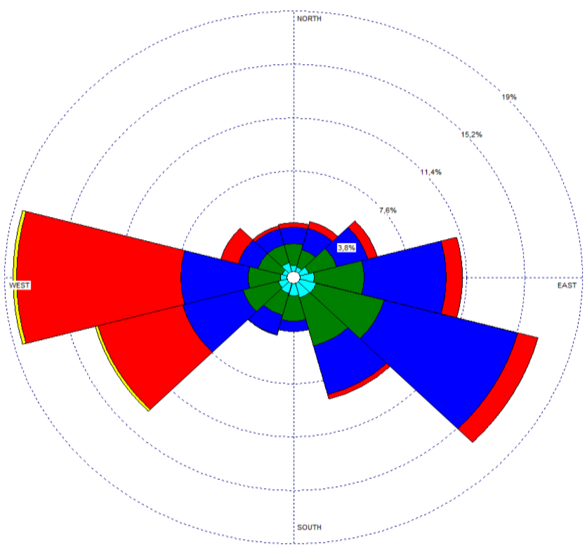

Figure 1. Wind rose

This research examines one of PT X's programs on environmental control. The target that encourages PT X. Meteorological data uses primary data from Copernicus for ten years (2021) with parameters including wind direction and speed, air temperature, solar radiation, air humidity, air pressure, and rainfall. Wind speed at the activity location based on the Beaufort scale is dominated by the calm class at 0.1%, light air at 3.8%, light breeze at 11.4%, gentle breeze at 15.2%, and moderate breeze at 19%. The wind direction blows from the west, but the dominant wind intensity and speed blows to the west of the activity location. Wind direction is dominated by winds blowing from west to east, as in the following image.

Meteorological data processing uses AERMET View with output results in Wind Rose, surface data (.sfc), and profile data (.pfl). Data processing in the form of emission test results using AERMOD View. The emission distribution pattern is presented in isopleth form. Data input procedure in the AERMOD software program View data processing in the New Project Wizard (Coordinate System), Control Pathway input, Source Pathway input, Receptor Pathway input, Output Pathway input, and Terrain input (Elevation, chimney height, temperature, flow rate, emission rate, emission load, chimney diameter). In the model output, the distribution of pollutant concentrations in the research area can be seen in the form of a maximum concentration range, which will be compared with the applicable air quality standards, namely Appendix VII PP Number 22 of 2021 and Based on Minister of Environment Regulation No. 7 of 2007 Appendix III concerning Quality Standards for Stationary Source Emissions For steam boilers that use other biomass fuels.

Table 1. Initial Baseline of Affected Areas

Parameter	Unit	Measurable Rate Hamlet	Hamlet Y	Quality standards
Carbon Monoxide (CO)	μg/m³	770	1530	22600
Nitrogen Oxides (NOx)	μg/m³	29.5	24.1	92.3
Nitrogen Dioxide (NO_2)	μg/m³	17.2	12.9	-
Sulfur Dioxide (SO_2)	μg/m³	<4.3	<4.3	262
Hydrogen Sulfide (H_2S)	μg/m³	<3.39	<3.39	42
Ammonia (NH_3)	μg/m³	50	66.4	1360
Oxidant (Ox)	μg/m³	11.5	19.9	200
Dust (PP)	μg/m³	0.0697	0.0411	0.26
Black Lead (Pb)	μg/m³	0.000103	0.00015	0.06
Total Hydrocarbons (HC)	μg/m³	<31.3	<31.3	160

Table 2. The Composition of Eucalyptus Biomass Fuel

Component	Heavy composition	Mass Weight (Kg/mol)	Composition (Kg)	Composition (Kmol)
C	63.40%	12	82420	6868.333333
H_2	3.50%	2	4550	2275
N_2	1.60%	28	2080	74.28571429
S	1.30%	32	1690	52.8125
O_2	13.70%	32	17810	556.5625
Ash	16.50%		21450	
Total	100.00%		130000	9827

Result and Discussion

Sugarcane Bagasse Fuel Composition (Bagasse)

Sugarcane bagasse is waste produced from extracting sugar water from sugarcane stalks. It is one of the plantation commodities that has a strategic role in the Indonesian economy (Dwiyaniti et al., 2020). Bagasse is a fuel with varying composition, consistency, and calorific value (Harnowo et al., 2021). In research in the sugar industry in Zimbabwe, bagasse biomass of 2.3 million tons per year produced 193.1 tons of steam per hour to drive the factory and had excess steam of 81.93 tons per hour (Mtunzi et al., 2017).

Bagasse biomass is planned as an alternative to coal in the production boiler unit. The scheduled biomass is 130 tons/day or 130,000 kg/day. The composition of eucalyptus biomass fuel is as follows (Table 2).

Mass Balance

Based on the calculation above, the Mass Balance in kg of the fuel combustion process's input and output is as follows.

Table 3. The Mass Balance in kg of the Fuel Combustion Process's Input and Output

Component	Inputs	Outputs
C	82420	
H	4550	
N	1039472	1037392
S	1690	
O	315157	52526
Ash	21450	21450
CO_2		302207
SO_2		3380
NO_2		6834
H2O		40950
Total	1464739	1464739

To calculate emission concentrations, several data are needed, including:

Chimney Diameter (D)	= 2.2 m (measurable)
Cross-sectional area (A)	= 3,799 m² ($A = \pi r^2$)
Flow Speed (V)	= 18.83 m/s (measurable)
Flow Rate (Q)	= 69.95 m³/s ($Q = A \times V$)
Emission Rate (E)	=Convert Kg/day to Kg/s (1/86400)

Emission Concentration (C) = E/Q

So, the emission concentration according to the Stationary Source Emission Quality Standards for Sugarcane Bagasse Fuel Steam Boilers is as follows (Table 4).

Table 4. The Stationary Source Emission Quality Standards for Sugarcane Bagasse Fuel Steam Boilers

Parameter	Emission Rate (Kg/s)	Emission Concentration (mg/m³)	Efficiency	The calculation results* (mg/m³)	Quality Standard** (mg/m³)
SO_2	0.0391	546.81	0.00	546.81	600
NO_2	0.0791	1105.64	0.00	1105.64	800
PM	0.4740	6624.83	0.99	66.25	250
H_2O		40950			
Total	1464739	1464739			

*Based on Mass Balance calculations
**Based on Minister of Environment Regulation No. 7 of 2007 Appendix III concerning Quality Standards for Stationary Source Emissions for Steam Boilers Using Other Biomass Fuels

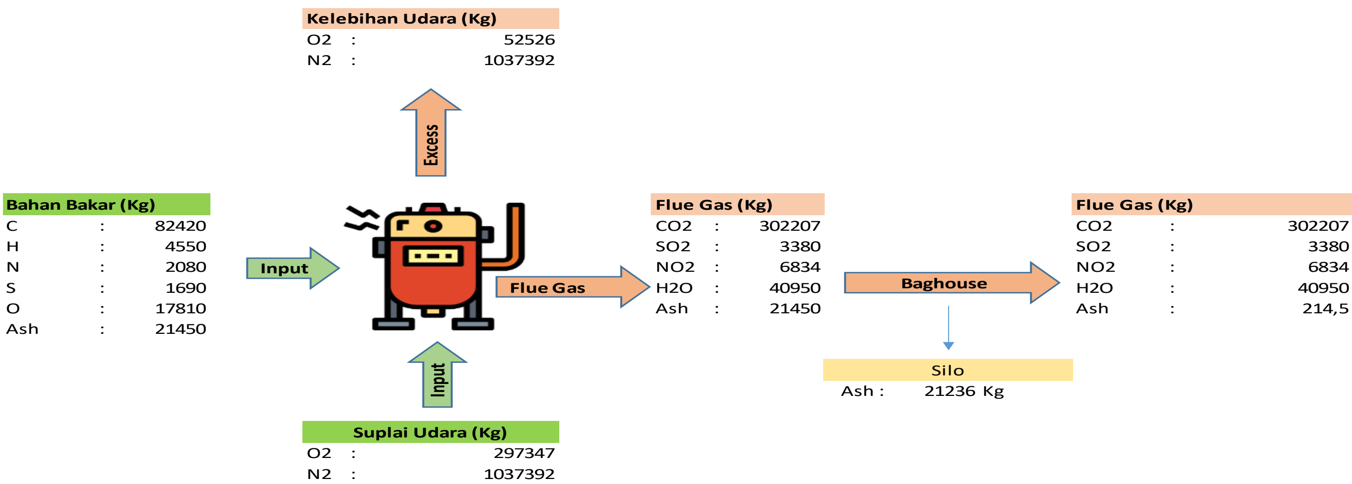

Figure 2. Mass illustration of sugarcane bagasse steam fuel

Coal Fuel

Coal Composition

Mass balance and stoichiometry calculations of coal combustion are as follows:

Table 5. The Composition of Coal Fuel

Component	Heavy composition	Mass Weight (Kg/mol)	Composition (Kg)	Composition (Kmol)
C	57.75%	12	124740	10395
H_2	6.39%	2	13802,4	6901.2
N_2	0.95%	28	2052	73,28571429
S	0.60%	32	1296	40,5
O_2	28.07%	32	60631.2	1894,725
Ash	6.24%		13478.4	
Total	100.00%		216000	19305
C	57.75%	12	124740	10395
H_2	6.39%	2	13802.4	6901.2
N_2	0.95%	28	2052	73,28571429
S	0.60%	32	1296	40.5

Note: *Coal composition

Mass Balance

Table 6. Mass Balance

Component	Inputs	Outputs
C	124740	
H	13802	
N	1775782	1773730
S	1296	
O	538855	89809
Ash	13478	13478
CO_2		457380
SO_2		2592
NO_2		6742
H_2O		124222
Total	2467953	2467953

From the calculation results, the mass balance of input and output of the coal combustion process can be seen in table 6. To calculate emission concentrations, several data are required, including:

Chimney Diameter (D) = 2.2 m (measurable)
Cross-sectional area (A) = 3.799 m^2 ($A= \pi r^2$)
Flow Speed (V) = 18.83 m/s (measurable)
Flow Rate (Q) = 69.95 m^3/s (Q=A×V)
Emission Rate (E) = Convert Kg/day to Kg/s (1/86400)

Thus, the emission concentration according to the Regulation of the Minister of Environment No. 7 of 2007, Attachment IV concerning Emission Quality Standards for Stationary Sources for Coal-Fired Steam Boilers can be seen in Table 7. For an illustration of the mass balance, see Figure 3.

Table 7. Coal Boiler Emission Concentration

Parameter	Emission Rate (Kg/s)	Emission Concentration (mg/m^3)	Efficiency	The calculation results* (mg/m^3)	Quality Standard** (mg/m^3)	Parameter
SO_2	0.03	419.33	0.00	419.33	20.50	750
NO_2	0.08	1090.76	0.00	1090.76	120.00	825
Partikulat	1.44	20096.39	0.99	200.96	28.50	230

*Based on Mass balance calculations
**Based on monitoring results, July 2021
***Based on PermenLH No. 7 of 2021 Attachment IV

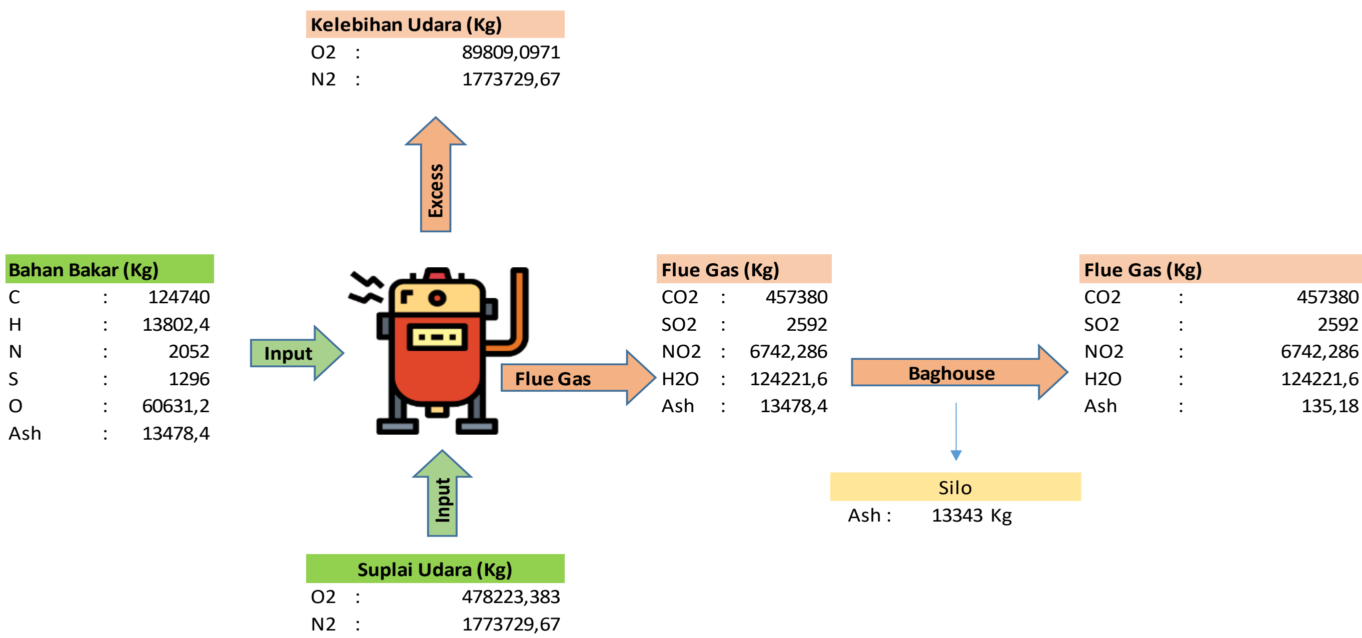

Figure 3. Coals mass balance

Dispersion Simulation of Emission Sources for Production and Utility Activities Fueled by Bagasse Biomass

The results of the dispersion simulation showed that the increase in emission concentration in the air resulted from PT X. The highest increase in emission concentration in the ambient air was to the west of the PT X Simulation of emission distribution dispersion, as presented in the Figure 4.

Emission concentration refers to the amount of particles or chemicals released into the air from a pollution source, such as a boiler chimney, measured in milligrams per cubic meter (mg/m^3) or micrograms per cubic meter (μg/m^3). The results of the simulation of emissions dispersion from the bagasse-fired boiler chimney show that the increase in emission concentrations in the air due to PT X's activities are as follows: SO_2 at 83.3 μg/m^3, NO_2 at 176 μg/m^3, and particulates at 14.8 μg/m^3. The highest increase in ambient air emission concentrations is located west of PT X's research site at a distance of 350 meters, including PT X's factory premises, rice fields, and residential areas. At the farthest distance of approximately 5000 meters, the minimum emission concentrations of bagasse biomass are 20 μg/m^3 for SO_2, 30 μg/m^3 for NO_2, and three μg/m3 for particulates. Changes in distance from the emission source can impact the emission concentration level, where the further the distance from the emission source, the emission concentration tends to decrease (Ismahani & Anurogo, 2022; Tama et al., 2023). The simulation results of bagasse dispersion found that the maximum concentration distance was 350 m from the chimney. This is in line with other research. The highest concentration of the distribution of emissions produced is located in the nearest settlement from the industrial area between 200 m to 500 m (Ismahani & Anurogo, 2022; Sasmita et al., 2021; Tama et al., 2023). The distribution pattern produced by the chimneys in this modeling simulation is by the dominant wind direction from west to east.

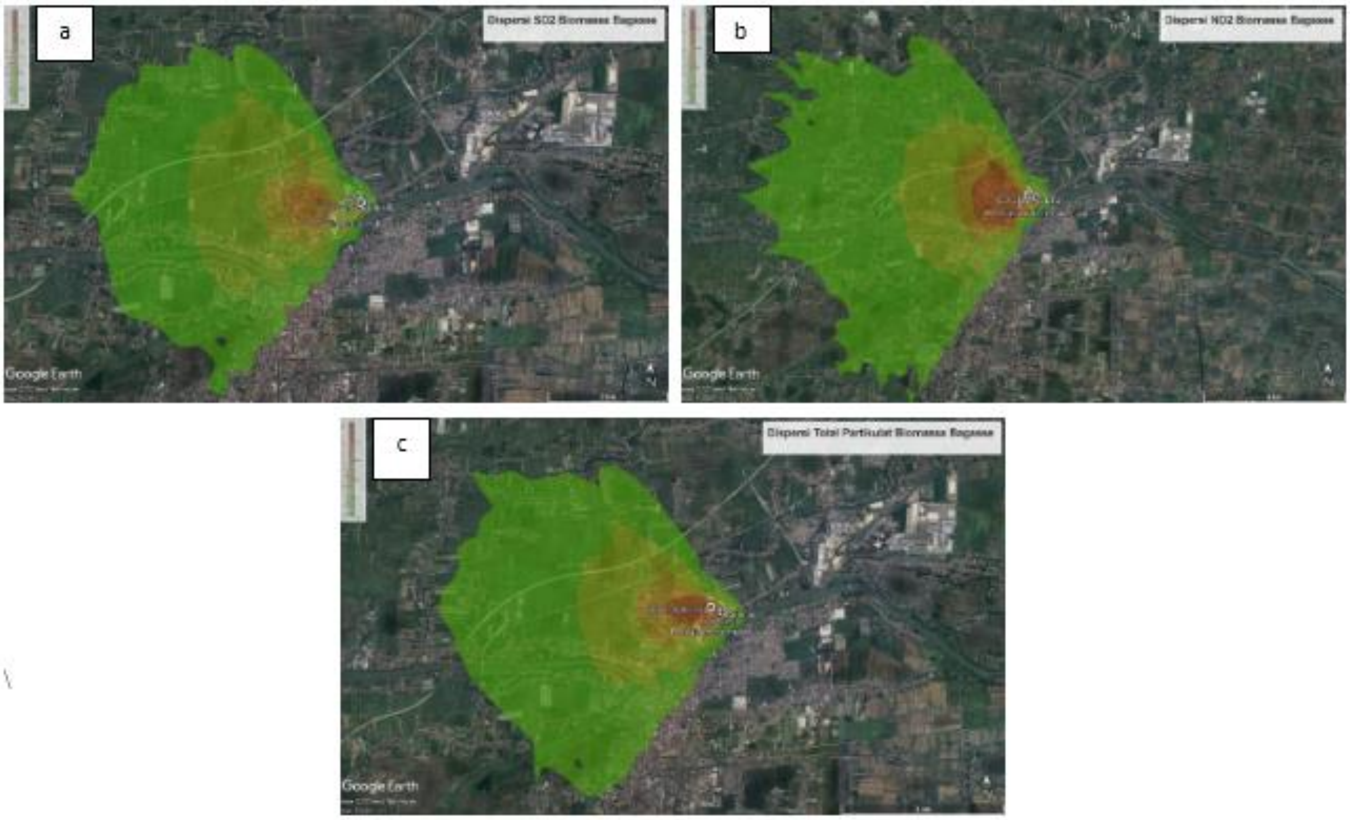

Figure 4. Distribution of (a) Bagasse SO_2 emissions; (b) Bagasse NO_2 emissions; and (c) Bagasse particulate emissions

Table 8. The Results of the Simulation of Emissions Dispersion from the Bagasse-Fired Boiler Chimney

Parameter	Maximum Concentration Increase (ug/m^3)	Coordinate		Distance from Emission Source		Type of Affected Area
		South latitude	East longitude	Distance (m)	Direction	
SO_2	83.3	7°25'56.78"S	112°25'35.73"E	350	West	Settlement
NO_2	176	7°25'55.68"S	112°26'36.63"E	350	West	Settlement
PM	14.8	7°25'54.79"S	112°25'38.74"E	350	West	Settlement

Based on the AERMOD simulation results for coal fuel, the maximum concentration was found at a distance of 535 m to the west. The maximum emission concentrations for coal were 2.06 μg/m^3 for SO_2, 172 μg/m^3 for NO_2, and 31.5 μg/m^3 for particulates. In another study, emissions from a coal-fired boiler showed that SO_2 concentrations increased from $1x10^{-45}$ ppm to $1.9x10^{-5}$ ppm at distances from 2,000 m to 42,000 m (Amrullah et al., 2021). The farthest concentration in the emission model for PT X's coal boiler was approximately 1000 m for SO_2 at 0.5 μg/m^3, approximately 5000 m for NO_2 at 50 μg/m^3, and approximately 5000 m for particulates at seven μg/m^3. The dispersion simulation results for bagasse showed that the maximum concentration distance was 350 m from the chimney.

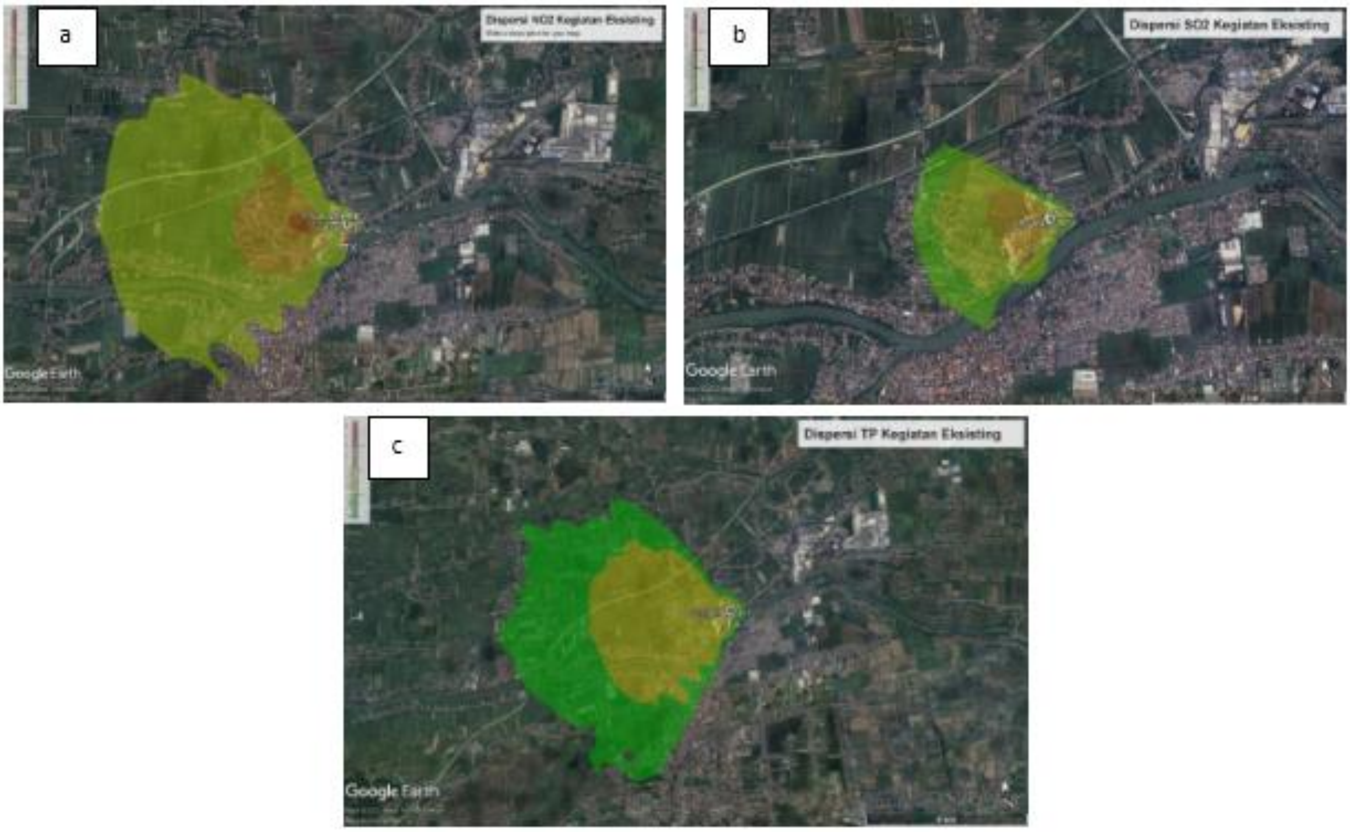

Figure 5. Simulation of (a) NO_2 dispersion of coal fuel; (b) Simulation of SO_2 dispersion of coal fuel; and (c) Simulation of TP dispersion of coal fuel

The content of coal and bagasse affects the concentrations produced in this modeling. Bagasse is a fuel with varying composition, consistency, and calorific value, depending on the climate, type of soil where the sugarcane is grown, sugarcane variety, and harvesting method (Harnowo et al., 2021). The emission concentrations produced by the coal and bagasse biomass-fired boiler chimney at PT X are also influenced by an emission control device as a bag house filter, with a particulate reduction efficiency of up to 99%. In contrast, PT X does not yet have emission control devices for SO_2 and NO_2. Emission control devices are mandatory for biomass boilers to reduce pollution from large-scale bagasse biomass combustion (Zhang et al., 2020). The emission concentrations produced by coal and bagasse biomass-fired boiler chimneys can vary depending on boiler type, operational conditions, and emission control technology. Previous research on industries in China has shown that industrial coal consumption does not have a significant impact in the short term. However, in the long term, coal consumption plays a vital role in reducing carbon emissions, with every 1% increase in coal consumption leading to a 1.057% increase in carbon emissions (Jiang et al., 2023).

42% of PT X respondents know that PT X uses coal as a fuel for steam boilers. The interview results indicated that respondents agree with replacing coal with bagasse as fuel at PT X. This aligns with the research by Hermiati et al. (2016), which found that bagasse can be an energy source like bioethanol. Also, bagasse can be an alternative to increasingly limited fossil fuels. The rising cost of fossil fuels has led to numerous studies seeking alternative fuel sources, with bagasse emerging as a viable solution.

Conclusion

The maximum concentration value of emissions from using bagasse as PT X boiler fuel, among other SO_2 parameters, is 83.3 μg/m^3, NO_2 is 176 μg/m^3, and particulates are 14.8 μg/m^3. Compared with the quality standards set by the government, the simulation of bagasse concentration using AERMOD has met the set quality standards. Compared to the concentration of particulates produced by coal, bagasse produces far fewer particulates than coal. The use of bagasse can bring sustainability to PT X.

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Author Contributions
M.B.B. conceptualized the research idea, methodological, design, data analysis, funding acquisition, writing-original draft, planning and execution. A.S., and D.A.C. guided, directed, helped the process of processing and analyzing data, provided ideas and suggestions in writing research, wrote-reviewed and edited, surprevised.

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Conflicts of Interest
All authors declare that there is no conflicts of interest.

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