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Air Pollution Control Analysis at the Tofu Industry Center in Sugihmanik Village, Grobogan Regency

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Abstract

Air pollution in Grobogan Regency, especially particulate parameters, annually shows an average value of 69% of ambient air quality standards with an average concentration of PM2.5 reaching 38 µg/m³, primarily due to industrial activities, transportation, and the burning of fossil fuels. In the Sugihmanik Village Tofu Industrial Centre, Grobogan Regency, there are 30 home-based tofu SMEs that use rice husks as fuel for boiler furnaces, which produce pollutants such as SO_2, NO_2, CO_2, CO, $PM_{2.5}$, PM_{10}, and TSP. The largest tofu factory in Sugihmanik Village uses 400 kg of rice husks daily. The chimney design, which does not comply with the technical standards of Kepdal No. 205 of 1996, further increases the risk of air pollution. Therefore, the design of an air pollution control device and a chimney redesign are required to mitigate these negative effects. After calculating the emission concentrations and comparing them with PermenLH No. 7 of 2007, only total particle parameter close to the quality standard of 350 mg/m³ with a particulate loading emitted from the furnace of 232 mg/s. By using a cyclone as an emission control device, there is a particulate removal efficiency of 53.05%. With the implementation of air pollution control devices, the ambient air concentration of particulates, previously a peak concentration of around 300 µg/m³, can be reduced to around 68.8 µg/m³.

Keywords: *chimney; emissions; tofu industry; air pollution; rice husk*

1. Introduction

Air pollution is a significant global issue and requires special attention because it affects human health and environmental conditions (Santoso *et al*., 2020). Based on data from IQAir, Indonesia is ranked 14th with the worst air quality in 2023. As the fourth most populous country in the world after China, India, and the United States, Indonesia faces a very complex air pollution problem in the Southeast Asia region. The high risk of air pollution is triggered by high urbanization, industrial activities, and agricultural practices such as logging and burning (Amin *et al*., 2025). Dust particles are one of the most dangerous indicators of air pollution, especially those with a diameter of less than 10 micrometers, where these particles can easily enter the respiratory tract and trigger various serious health problems, such as respiratory tract infections, asthma, and cardiovascular disorders (Furizal *et al*., 2024). Particulate matter (PM) levels frequently exceed the limits set by WHO and NAAQS, especially in urban areas and during the bushfire season, causing serious impacts on the health of vulnerable communities. Where in 2023, the average concentration of PM2.5 reached 37.1 µg/m³ or 7.4 times higher than the WHO annual standard.

One of the most dynamic small to medium-scale food processing industries in Indonesia is the tofu industry. This industry is a major source of income and employment for local communities with demand reaching 3.5 million tons per year, tofu is a staple food consumed daily by Indonesians as a source of protein (Ningsih *et al*., 2024). The tofu industry generally has low energy efficiency, resulting in high levels of air pollution (Kurniawati *et al*., 2019). One of the small and medium industries that produces air pollution is the marble industry, which also causes disturbing air pollution. The industry then took preventive measures by modifying processes and also improving environmental safety systems (Iqbal et al., 2022)

Sugihmanik Village is one of the villages in Tanggungharjo District, Grobogan Regency (Figure 1)

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where most of the people work as farmers. In addition to farming, some of the people of Sugihmanik Village also make home-scale tofu industries. Sugihmanik Village is a Tofu Industry Center consisting of 30 Tofu SMEs with an average production capacity of around 150 kg of soybeans/day/SME (Hartini *et al*., 2021). Tofu production itself is a continuous process to obtain quality tofu. The stages consist of soaking, grinding, cooking, coagulating, molding and frying (Hartini *et al*., 2021). Soybean seeds are soaked for approximately 5 hours at room temperature before being ground with the aim of softening the seeds and reducing the anti-trypsin content which contains anti-nutritional genes (Kurniawati *et al*., 2019). Then the soybeans are ground into a pulp and the boiling process is carried out using the hot steam produced from the steam boiler. At the boiling stage, the porridge needs to be cooked for 3-10 minutes to facilitate the coagulation of the protein. After the porridge is filtered, the juice is added with whey, which is the remaining water from the coagulation of tofu that is fermented for 1-2 nights with the aim of solidifying and facilitating the molding process.

Tofu producers at the Sugihmanik Village Tofu Industry Center use biomass fuel, namely corn cobs and rice husks in the soybean porridge cooking process (Hartini *et al*., 2023). Rice husk is the outer skin of rice grains which is separated by the milling process (Umar *et al*., 2024). From the existing conditions, the production process in the tofu industry in Sugihmanik Village produces air pollution as an effect of using rice husks as fuel. Biomass burning produces air pollutants, in the form of carbon dioxide (CO2), carbon monoxide (CO), sulfur dioxide (SO2), nitrogen dioxide (NOx), and particulates (Andini *et al*., 2018). Dust particles (PM) are the main pollutants from burning rice husks and have an impact on human health and the environment. Dust particles are easily inhaled by the human respiratory system, so they can cause health problems, such as asthma, cardiovascular disease, heart disease, and even premature death (Nugraha *et al*., 2024).

The absence of air pollution control devices installed in the chimney of the home-made tofu industry in Sugihmanik Village and the inappropriate design of the chimney in its existing condition are the causes of the high concentration of pollutants produced. The speed, penetration distance, concentration, and volume of pollutants that pollute the air are influenced by the type of pollutant, its properties, toxicity level, and concentration (Santoso *et al*., 2016). Therefore, it is necessary to design air pollution control equipment that is in accordance with the characteristics of the pollutants and redesign the chimney.

The purpose of this study is to inventory emission sources, analyze existing emission conditions and analyze the need for air pollution control in the Tofu Industry Center of Sugihmanik Village. By controlling air pollution at the source of emissions, it is expected to minimize emissions resulting from rice husk burning activities, so as to reduce the incidence of air pollution caused by small and home industries in Sugihmanik Village.

2. Methodology

a. Identification of Rice Husk Burning

The tofu production process that produces emissions is the boiling of soybean porridge. The boiling process utilizes hot steam produced from the combustion of biomass, in the form of rice husks in a steam boiler. Rice husks are obtained from agricultural waste in Sugihmanik Village at a purchase price of IDR 10,000/sack. The combustion process produces pollutants that can pollute the environment. In this research, the analysis of air pollutants only analyzed seven pollutants, including TSP, CO, CO2, SO2, NO2, PM2.5 and PM10. The limitation of the analysis of these pollutants is based on the literature study that was conducted. From several literature sources, it states that the emissions produced from burning rice husks include the seven emission parameters that will be analyzed in this study.

b. Sampling

Some data, both secondary and primary, in this planning were obtained using several different methods, such as interviews, laboratory tests, and related literature studies. 24-hour ambient air measurements for TSP parameters using a medium volume sampler (TFIA Staplex, USA) with an average flow rate of 0.9 m3/min. The sampling location is at the coordinates LS: 07°5’ 51.69’’ S and 110°37’10.5’’ E. The tofu industry emission source map is covered in Figure 2.

Interviews with several tofu factory owners and direct observation of existing conditions. These observations and interviews were conducted to obtain information on the amount of fuel used per day. Identification of the combustion process that causes emissions in the field needs to be ensured.

The concentration of existing emissions was not measured directly considering that there were technical discrepancies related to the existing chimney (the absence of sampling holes and the fulfillment of the 8D/2D chimney rule). Therefore, emissions were estimated by calculating the results of ultimate and proximate tests carried out to determine the amount of Carbon (C), Hydrogen (H), Nitrogen (N), Sulfur (S), water content, and ash content contained in rice husks as fuel in the combustion process. The ultimate analysis uses the CHNS Elemental Composition Analyzer method, while the testing of water content and ash content of rice husks refers to SNI 2354.2:2015 and SNI 01-2354.1:2006.

In this study, the reference regulation used is the Regulation of the Minister of State for the Environment Number 07 of 2007 concerning Emission Quality

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Standards for Stationary Sources for Steam Boilers, which regulates the quality standards for stationary energy emission sources originating from various types of industry, especially in Appendix III: emission quality standards for stationary sources for steam boilers using biomass fuel.

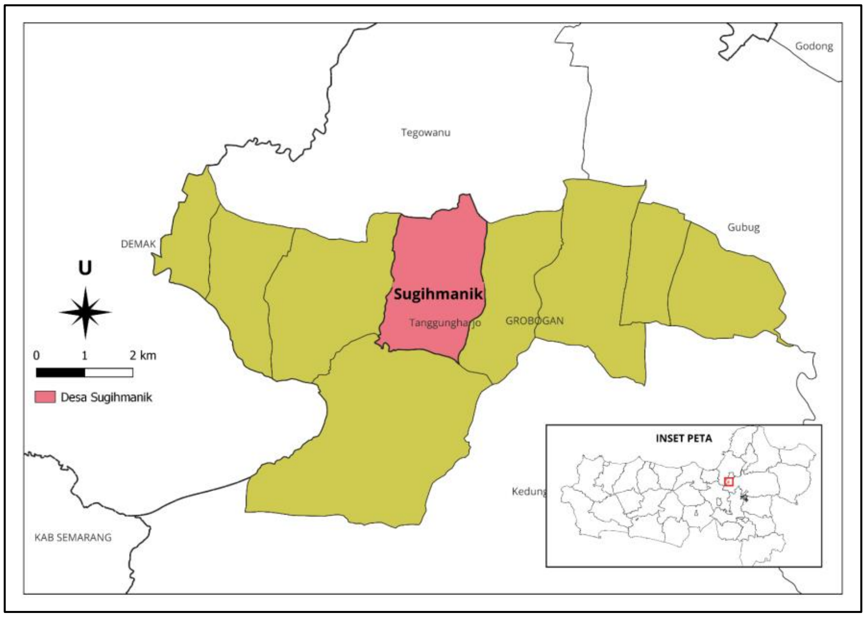

Figure 1. Sugihmanik village administrative map.

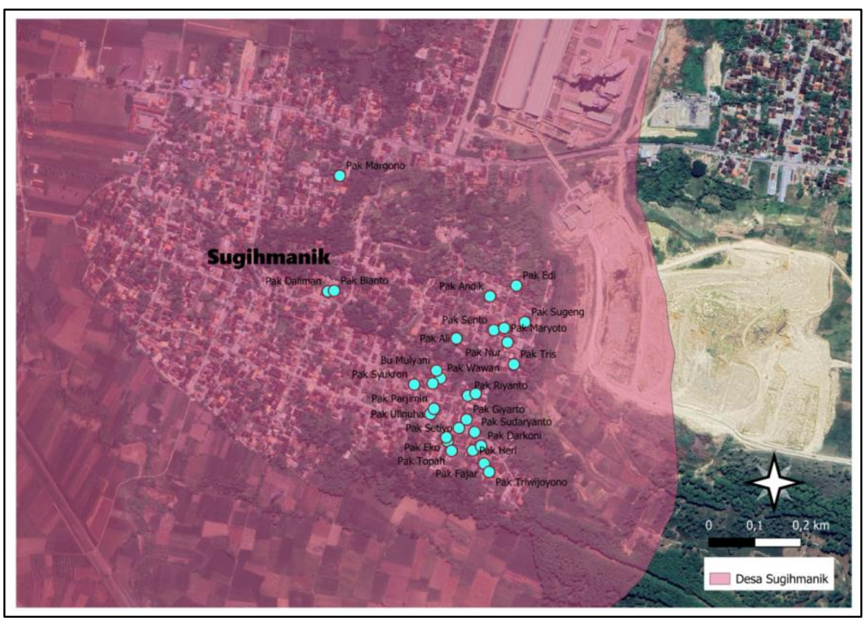

Figure 2. Emission source map.

c. Use of Control Devices

The use of this air pollution control device begins with calculating the mass balance. To calculate the mass balance, it is necessary to know the ultimate and proximate analysis of rice husks so that the mass flow rate can be known from the composition (%) and the amount of fuel used. Flue gas from the boiler is produced by the combustion reaction of rice husks, which contains SO_2,

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NO_2, CO, H_2O from the incoming air, and O_2 from the remaining reaction. The following are some of the reaction equations that occur in the process.

$$S + O_2 \rightarrow SO_2$$
$$NO + \frac{1}{2}O_2 \rightarrow NO_2$$
$$C + O_2 \rightarrow CO_2$$
$$H + \frac{1}{2}O_2 \rightarrow H_2O$$

Emission load is calculated using Equation 1. (KHLK Technical Guidelines, 2013).

$$E = \sum(Fuel \times EF) \quad \text{(mg/s)} \qquad (1)$$

where $Fuel$ is amount of fuel used (kg/day) and EF is emission factor (g/kg)

After the emission load is obtained, calculate the emission concentration (C) in normal condition using Equation 2. (KHLK Technical Guidelines, 2013):

$$C = \frac{E}{V} \qquad \text{(mg/m}^3\text{)} \qquad (2)$$

where E is emission load (mg/s) and V is volumetric flow rate of emissions (m^3/s).

Then an analysis of alternative control devices will be carried out to be used after it is known that the pollutants exceed the quality standards. So that the right air pollution control device is obtained with actual conditions.

The Tofu Industry Center of Sugihmanik Village has a traditional chimney made of stone. From the observation results, the chimney in the Tofu Industry Center of Sugihmanik Village has differences with the applicable technical standards, namely Kepdal Number 205 of 1996 concerning Technical Guidelines for Control. These differences include the height of the chimney, the location of the sampling hole, the diameter, the air speed in the chimney and also the chimney accessories. This increases the risk of ambient air pollution so that a study of the chimney in the Tofu Industry Center of Sugihmanik Village is needed.

d. Emission Distribution Pattern Before and After Control Device

The emission distribution pattern before and after the controller can be modeled using AERMOD 9.6.0 *software*. The analysis of the distribution pattern uses meteorological data, in the form of temperature, humidity, pressure, wind direction, wind speed, cloud cover, radiation, *precipitation* and *ceiling height* obtained from NASA *Power Access Viewer* and *Climate Data Copernicus*, so that the emission distribution pattern produced from the rice husk burning process in the Tofu Industry Center of Sugihmanik Village can be known. In this planning, the pollutants whose distribution will be modeled are pollutants that exceed the quality standards with the assumption that all SMEs carry out production simultaneously and all SMEs have the same controller and chimney. The modeled radius is approximately 1.8 km x 1.8 km around the Tofu Industry Center of Sugihmanik Village using the ambient air *background* in the Tofu Industry Center of Sugihmanik Village.

3. Results and Discussion

a. Existing Condition of Tofu Industry Center in Sugihmanik Village

Sugihmanik Village is one of the villages located in Tanggungharjo District, Grobogan Regency, Central Java. Sugihmanik Village has an area of 1,286.6 Ha (Central Statistics Agency, 2023). Sugihmanik Village has 8 Citizens' Associations (RW) and 37 Neighborhood Associations (RT) with a distance of 2 KM from the Village to the District Capital and 43 KM to the Regency Capital. The development of tofu producers in Sugihmanik Village has a positive impact on improving the economic welfare of the community. Based on the results of a field survey from previous research, there are currently 30 Tofu SMEs spread across the upper area of Sendang Mudal Hamlet, the middle area of Sendang Sari Hamlet, and the lower area of Karang Sari Hamlet. The production capacity of the Sugihmanik Village Tofu Industry Center is 4,000 kg of soybeans per day. The use of rice husks in the process of boiling soybean porridge uses up 400 kg/day.

b. Mass Balance

Mass balance is a process of careful calculation of all incoming, accumulated, and outgoing materials in a certain period of time. The mass balance calculation is based on the results of proximate and ultimate tests. The total fuel used in one day is 400 kg/day or 40 kg/hour which comes from 2 steam boilers. The results of the ultimate and proximate tests can be seen in Table 1 and Table 2.

Table 1 Rice Husk Ultimate Analysis.

Ultimate Analysis	**AR (% wt)**	**Test Methods**
C	38,33%	CHNS Elemental Composisiton Analyzer
H	5,243%	
N	0,70%	
S	0,364%	
O	26,13%	

Source: Analysis report (UPT Integrated Lab. UNDIP, 2024)

Table 2 Rice Husk Proximate Analysis.

Proximate Analysis	**AR (% wt)**	**Test Mehod**
Water content	9,59%	SNI 2354.2:2015
Ash content	19,64%	SNI 01-2354.1:2006

Source: Analysis report (UPT Integrated Lab. UNDIP, 2024)

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From the results of the proximate and ultimate tests and the amount of fuel used, the resulting mass balance can be seen as listed in Table 3.

Table 3 Mass Balance Calculation.

Input		Output	
Component	**Input (kg/hour)**	**Component**	**Output (kg/hour)**
C	7,67	CO_2	28,11
H	1,05	H2O	18,87
N	0,14	N_2 waste	155,85
O	5,23	O~~2~~ waste	9,49
S	0,07	NO_2	0,46
Particulate	-	SO_2	0,15
O_2 air supply	47,43	CO	0,86
N_2 N2 supply	156,13	Ash	3,93
Total	217,72	Total	217,72

c. Emissions Produced from Burning Rice Husks

Emission quantity emission concentrations for gas parameters are estimated from the mass balance, while particulate parameters ($PM_{2.5}$, PM_{10}, TSP) are obtained from emission factors. The emission factor describes the amount of compounds or substances released per unit of dry fuel burned to calculate the gas emissions produced from biomass combustion (Irfan *et al.*, 2014). Table 4 shows the results of the calculation of emission loads, emission concentrations from burning rice husk biomass.

Tabel 4. Results of Emission Load and Emission Concentration from Emission Factor and Flow Rate

Parameters	Mass flow (kg/hr)	Emission Factor* (g/kg)*	Emission Load (mg/s)	Concentration (mg/Nm^3)	Standard (mg/Nm^3)
NO_2	0.92		255.56	276.69	1000
SO_2	0.29		80.56	87.22	800
CO_2	56.22		15616.6	16908.04	-
CO	1.73		480.56	520.29	-
$PM_{2.5}$		19.1	212.22	229.77	-
PM_{10}		10.9	121.11	131.13	-
TSP		20.96	232.89	252.15	350

*Karuppiah and Sumathi, 2021

To determine the quality of emissions produced from combustion, the gas and particulates are compared with the quality standards obtained from a study of quality standards for burning rice husks with reference sources, namely PermenLH No. 7 of 2007 concerning Air Quality Standards for Emissions from Stationary Sources for Steam Boilers

From the results of the comparison of concentration with the quality standard study for burning rice husks, it is known that the one that is closest to the quality standard is the TSP compound, namely having a concentration of 252 mg/Nm^3. Therefore, the emission controller needed is particulate processing.

d. Selection of Alternative Air Pollution Control Tools

In this planning, the processing alternative used is a processing unit for particulates. Determination of processing alternatives to reduce emissions resulting from an activity is considered based on several aspects so that the selected processing alternative is the most effective and efficient processing, namely processing efficiency, capital costs, and operational and maintenance costs.

There are three alternatives for conventional particulate pollution control devices, namely *cyclone*, *wet scrubber* and *fabric filter* or related advanced treatment through pyrolisis process. Based on the scoring using the Likert scale method multiplied by the weight of each parameter (removal efficiency, capital costs, and operational and maintenance costs), looking at the total value, it can be concluded that the best alternative is the cyclone.

e. Design of Air Pollution Control Equipment

Combustion in the furnace is assisted by a blower that has a *flow rate* of 0.5 m3/s. Because the exhaust gas entering the *cyclone* comes from two furnaces, the *flow rate* is multiplied by two to become 1 m^3/s. The planned diameter of the *cyclone body* is 0.66 m, using the design ratio, the detailed dimensions of the cyclone are obtained with a body diameter of 0.66 m, an *inlet height* of 0.33 m, an *inlet width* of 0.13 m, an outlet diameter of 0.33 m, a body length of 0.99 m, a cone length of 1.65 m and an *exit tube* length of 0.33 m. The design results of the *cyclone* assembled with an IDF fan and chimney can be seen in Figure 3.

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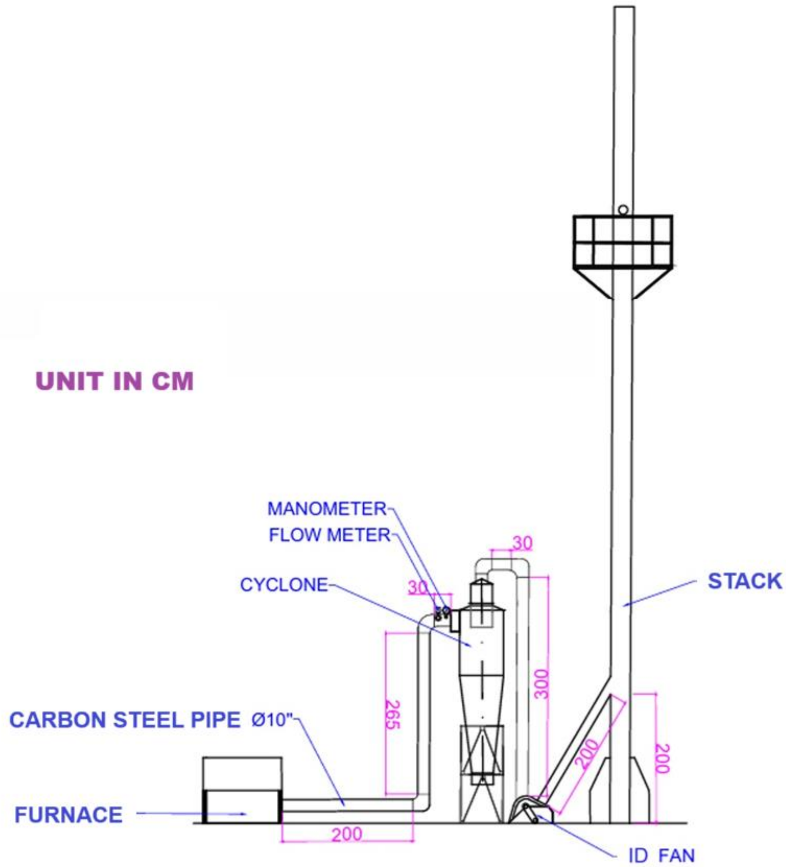

Figure 3 Side View of particulate emission control device.

Then the efficiency calculation of the *cyclone* planning design was carried out and the efficiency of the *cyclone* planning design was obtained as much as 53.05%. The concentration of TSP coming out of the *cyclone* was 285 mg/m3 which had met the quality standards according to PermenLH No. 7 of 2007.

One of the important parameters in a *cyclone* system is pressure drop. Pressure drop in *cyclone* design is an important parameter that affects operational costs, where increasing *pressure drop* increases particle collection efficiency. In *High Efficiency Cyclone*, *pressure drop* ranges from 2-6 in H_2O (Theodore, 2008). Higher efficiency results in greater *pressure drop*. With the existing equation, the amount of *pressure drop* in the *cyclone* is 1014.35 N/m2. After that, the total *pressure drop* of the entire system is calculated and the total *pressure drop* of the system is 1513.69 N/m2.

In the *cyclone* system circuit, a fan is needed that can draw combustion air. The fan used is a *centrifugal fan* with a total *pressure drop* of 2000 Pa and an *airflow* of 4900 m3/h.

f. Chimney/Stack Redesign and Modeling of Emission Dispersion from Burning Rice Husks

The existing chimney at UKM/SMEs Tofu Sugihmanik Village does not meet the design criteria, with a height of 5.25 m in the form of a 40 x 40 cm square made of brick, not in accordance with the provisions of 2-2.5 times the height of the surrounding building (Kepdal Nomor 205 Tahun 1996). The exhaust gas that comes out is indicated to pollute the ambient air which has the potential to cause respiratory problems for local residents. The chimney is also not equipped with a sampling hole. A circular chimney is planned with carbon steel material and is equipped with several accessories, such as sampling holes, stairs and work floors with safety fences, equipment transport tools, and electricity sources.

The height of the tofu factory building in Sugihmanik Village is around 5 meters, therefore the planned height of the chimney is 2.5 times the height of the building, which is 12.5 meters. The diameter of the chimney is determined by dividing the chimney *flow rate* by the air velocity inside it. The speed inside the chimney is determined at 14 m/s with a *flow rate* of 1.00 m^3/s so that the diameter of the chimney is 30 cm.

Dispersion modeling consists of 2 stages, namely the AERMET and AERMOD software applications. AERMET is a program that processes meteorological

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data for use in the AERMOD dispersion model. This planning uses a model with an emission load originating from 30 SMEs of 38.43 g/s. The meteorological period used is one year, starting from January 1, 2023 to December 31, 2023. This model uses a 24-hour *average* pollutant period to be compared with the applicable ambient air quality standards. Wind direction and speed during the period of 2023 can be represented in the form of a wind rose as shown in Figure 4.

The wind rose results showed that the dominant wind direction in the Tofu Industry Center of Sugihmanik Village is from the Northwest with the highest wind speed (shown in blue) of 5.70 – 8.80 m/s.

The results of ambient air measurements (24-hour TSP dust) at the Tofu Industry Center of Sugihmanik Village at coordinates. 07º5'51.69''S dan 110º37'10.5'' E. shows a figure of 68 µg/m3, while the model results at the same point show 100 µg/m^3 (Figure 5A). This result is still below the quality standard for 24-hour TSP particulates, but this result does not necessarily indicate the highest concentration (300 µg/m^3). The distribution of particulate emissions for conditions without the installation of particulate control devices (Figure 5B) shows a high particulate concentration compared to conditions with the installation of particulate control devices (Figure 5C).

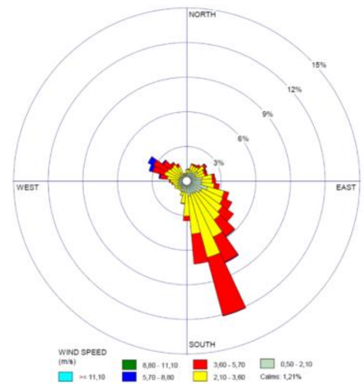
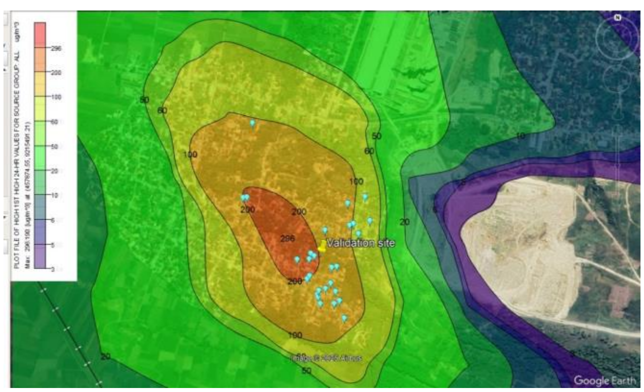
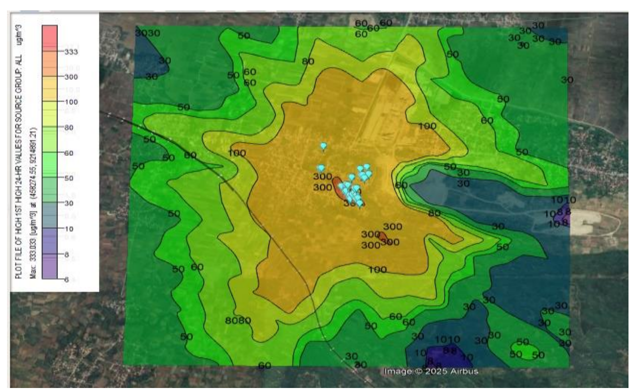


Figure 4 Wind Rose in 2023



(a)



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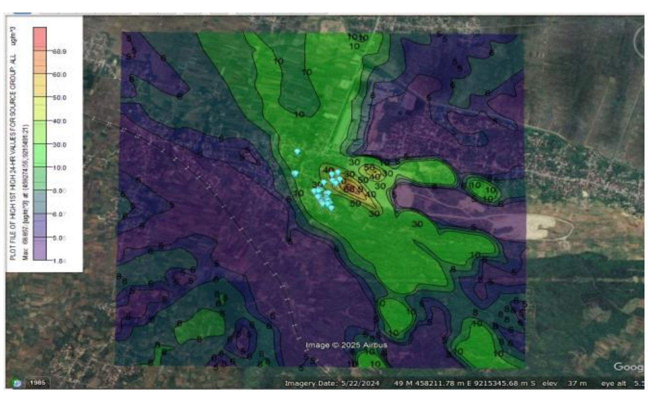

(c)

Figure 5. (a). Measurement validation and model results, (b). Dispersion modeling before implementation of the device, (c). Dispersion modeling after implementation of the device.

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Based on the figure, the highest concentration of particulate emissions that spread in ambient air before the implementation of air pollution control devices around the Tofu Industry Center in Sugihmanik Village was around 300 µg/m3. However, after the implementation of air pollution control devices, the highest concentration of particulate emissions that spread in ambient air was 68.8 µg/m3.

4. Conclusion

The source of emissions from the tofu industry is the process of burning rice husks for steam boilers in the process of melting soybean porridge with a particulate emission load of 232.89 mg/s or 0.84 kg/hour. Other pollutants produced include SO_2, NO_2, CO. Based on the analysis of the need for air pollution control equipment, a cyclone device is needed with dimensions of 0.99 m in length and 0.66 m in diameter. Without the installation of a control device, based on the emission dispersion modeling, it shows the estimated maximum TSP concentration 300 µg/m³ in ambient air in the Sugihmanik area. The existing chimney in the tofu factory in Sugihmanik Village is rectangular in shape made of 40 x 40 cm bricks as high as the roof of the building, so it does not meet the technical standards according to Kepdal Number 205 of 1996. The chimney redesign resulted in a height of 12.5 meters, a diameter of 0.30 meters, a circle made of carbon steel, equipped with a work floor, safety fence, stairs, electricity source, and sampling hole at a height of 8.02–11.88 meters. The Sugihmanik Village Tofu Industry uses a *cyclone* as a control device, with a removal efficiency of 53.05%. Based on the emission dispersion modeling with AERMOD, the maximum ambient air concentration after the application of the air pollution control device is 68.8 µg/m³).

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