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ENVIRONMENTAL HEALTH RISK ANALYSIS OF SULFUR DIOXIDE (SO_2) INHALATION EXPOSURE IN AMBIENT AIR AMONG THE TIRTONIRMOLO COMMUNITY, BANTUL

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Abstract

Introduction: *Sulfur dioxide (SO_2) is one of the gases that can pollute the ambient air and cause respiratory irritation. This study aims to determine the characterization of health risk and risk management of sulfur dioxide (SO_2) exposure to prevent health impact in the Tirtonirmolo community, Bantul.* ***Methods:*** *This study was a quantitative descriptive research with an Environmental Health Risk Analysis (EHRA) approach. The study subjects were the Tirtonirmolo community in Bantul, with a sample of 110 respondents. The sampling method uses purposive sampling.* ***Results and Discussion:*** *Most respondents are female (74%) with ages over 54 years (52%), and the majority work as housewives (44%). The description of EHRA variables consists of an inhalation rate of 0.83 m^3/hour, exposure time of 22 hours/day, exposure frequency of 354 days/year, and exposure duration for real-time projections of 35 years and 30 years for lifetime projections. The SO_2 measurement results did not exceed the national quality standard, with the highest concentration being on Madukismo Road, with a concentration of 11.72 µg/m^3. The dose-response analysis uses data from the US-EPA, which is 0.026 mg/kg/day. The real-time average intake value is 0.0039 mg/kg/day, and the 30-year lifetime average intake value is 0.0033 mg/kg/day.* ***Conclusion:*** *All respondents from this study had an RQ value<1, both in the RQ for real-time and lifetime. Risk management needs to reduce health risk by using masks when doing outdoor activities and installing Flue Gas Desulfurization (FGD) in factories that emit SO^2 emissions.*

INTRODUCTION

Air pollution is a combination of processes involving the entry of different pollutants gases or particulate matter from anthropogenic sources, such as industrial and motor vehicles activity (1). Air pollution caused the deaths of 7 million people annually (2). Sulfur dioxide (SO_2) is a chemical substance in gas patterns that can pollute the ambient air and become a part of ambient air pollutant. Sulfur dioxides have sharp odor characteristics and are not flammable in the air. SO_2 as a pollutant results from various human activities such as power generation, combustion, mining, and metal processing (3). Around 272 cities in China have concentrations of SO_2 as an air pollutant of 10 g/m^3; an average increase in such concentrations can result in a mortality rate of 0.59% (4). By 2020, the concentration level of SO_2 in the Madukismo region in April 2020 was 9.7 µg/Nm^3. In the same year, the concentration level of SO_2, in November, increased to 115.3 µg /Nm^3 (5).

The high concentrations of SO_2 can cause various health problems for exposed humans. SO_2 is a gas or pollutant that irritates the respiratory system (6). SO_2 has several effects, such as eye irritation and inflammation of the breathing system, that can trigger cough or mucous secretion, thus triggering the onset of asthma or chronic bronchitis (7). According to Kasihan II Health Center data, in 2022, there were 1,158 people with acute pharyngitis complaints in the Tirtonirmolo region, Bantul district. The number has increased from the previous year, with 232 cases of acute pharyngitis by 2021.

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An Environmental Health Risk Analysis (EHRA) should be performed based on the previously presented data to determine whether exposure to risk agents, particularly SO_2, has an impact on public health. EHRA is a method of calculating or estimating a population risk by considering the characteristics of risk agents (8). The EHRA method is used to assess the various hazards that have occurred, the current threats, and the risks that will happen in the future.

A preliminary study was conducted on March 28, 2023, to observe the potential for SO_2 contamination in Tirtonirmolo, Bantul Regency. Based on observations, several chimneys from a sugar factory lead upwards and are actively used for industrial activities. Short interviews were conducted with residents who live around the factory within a radius of 100 meters. Through short interviews, it can be seen that quite a few residents have complained about the strong-smelling air around the factory. Residents think this happens because of the air coming out of the chimney. The traffic density factor can also affect SO_2 pollution. During the preliminary study, the traffic density level was relatively moderate but busy, especially for motorbikes, cars, and trucks. Therefore, the EHRA method determines the potential risk of SO_2 in ambient air and its impact on public health.

METHODS

The method of study used is a descriptive quantitative using the EHRA approach. This study performs risk estimates due to exposure to SO_2 inhalation in ambient air among Tirtonirmolo, Bantul Regency community.

This study was conducted in August-October 2023 using a purposive sampling technique with an EHRA checklist. The sample study consists of a sample of the subject and an object sample. The subject sample of study was the Tirtonirmolo community, Bantul, which has potential exposure risk to SO_2. The inclusion criteria for the study are communities that have been residing at the research site for approximately one year and are at a distance of ±150-300 meters from the sugar plant and ±1-10 meters from the main road of the study site and are over 19 years old. The total population was 23, 241 respondents. Based on the Slovin formula, the number of sample subjects used was 110 respondents. The object sample of the study is ambient air with SO_2 parameters. The object sample was taken using SNI 7119-7:2017, which tests the SO_2 levels with the pararosanilin method using spectroscopic photometers (9). The object study site was conducted in three sites, specifically on Jogonalan Road (II), Mrisi Road (II), and Maduksimo Rad (III). The Center for Environmental Health Engineering and Disease Control of Yogyakarta used the Indonesian National Standard (SNI) 19-7119.6-2005 to determine where to collect ambient air samples (10). The research location meets SNI's requirements for an ambient air quality observation point, including a high pollutant concentration, in a densely populated region, and the site location can represent all study locations so that they can be monitored and assessed.

This study used a dose-response via inhalation exposure. The dose-response value is the reference dose or Reference of Concentration (RfC). The RfC value for this study is available in the Integrated Risk Information (IRIS) list issued by the Environmental Protection Agency (EPA) of 0.026 mg/kg/day, which affects respiratory tract disorders.

The instruments in this study are a checklist sheet for measuring characteristics of respondents (gender, age, occupation, and health complaints), weight scales for anthropometric data, EHRA variables (SO_2 concentration, exposure frequency, exposure time, exposure duration) and informed consent for approval. The data collection technique in this study is filling out checklist sheets with respondents and making direct observations in the field. Data analysis was carried out using univariate analysis to find out the data distribution of environmental health risk analysis variables consisting of hazard identification, dose-response analysis, exposure analysis, and risk characterization. The variables of inhalation intake rate, exposure time, exposure frequency, and exposure duration use the median value because these data were not normally distributed, whereas, for the weight variable it uses the mean. After the univariate analysis, the EHRA approach was used to determine the level of risk of SO_2 exposure. The EHRA method consists of four stages: hazard identification, dose-response analysis, exposure analysis, and risk characterization.

Equations (a) and (b) illustrate the formula for estimating the noncarcinogenic risk of inhalation routes (11-14).

$$Ink = \frac{C \times R \times tE \times fE \times Dt}{Wb \times tavg} \quad \text{(a)}$$

Description :

I_{nk} : Non-carcinogenic intake, mg/kg/hari

C : Risk agent level, mg/M³ for air medium

R : Intake rate or consumption, m³/hour for inhalation

t_E : Exposure time

f_E : Exposure frequency

D_t : Exposure duration, years (*real time* or projection, 30 years for residential default values)

W_b : Body weight, kg

t_{avg} : Average time period (30 years x 365 days/year for non-carcinogenic substances)

Risk characterization includes determining the amount of risk for both non-carcinogenic and carcinogenic consequences. The formula for determining risk categorization is as follows:

$$RQ = \frac{\text{Ink}}{RfD \text{ atau } RfC} \quad \text{(b)}$$

Description :

RQ = Risk Quotient

RfC = Reference of Concentration for SO_2 exposures is 0.026 mg/kg/day , its deriving formula for Asian population (11-12).

The Risk Quotient (RQ) represents the risk characteristics. Chronic SO_2 are not safe for the human if RQ > 1 and must be controlled. If RQ ≤ 1, it means safe category (it is not risk for human). RQ using duration exposure value will be shared into two categories, real-time and lifetime. Duration exposure is real-time exposure and refers to the actual exposure experienced at a given moment or within a short time frame and lifetime exposure refers to the cumulative exposure over an individual's entire lifetime. Risk management should be performed if the risk characterization results show RQ > 1. This study was approved by the Ethical Committee of Universitas Ahmad Dahlan, Number 012306099.

RESULTS

The characteristics of respondents in this study are presented to show the variety and distribution of research respondents, including gender, age, and occupation. Based on Table 1, after carrying out a normality test on the respondent's age variable, it can be seen that the data are normally distributed so that *the cut-off point* for this variable refers to the mean as data centering for data categorized display. The majority of respondents with an age of less than or equal to 54 years amounted to 57 respondents or 52%, the majority of respondents' gender was female, 67% or 74 respondents out of a total of 110 respondents, and the majority of respondents' occupation was housewife with 48 respondents or 44% from 110 respondents. Apart from that, 57 respondents or 52%, experienced health complaints with various complaints such us shortness of breath, chest pain, squeaking sound when breathing, high blood pressure, diagnosed lung disease, prolonged cough, and history of respiratory illness.

Table 1. Characteristics of Respondents Based on Gender, Age, and Occupation in Tirtonirmolo Community, Bantul

Respondent Characteristics	Frequency (n)	Percentage (%)
Sex		
Woman	74	67
Man	36	33
Total	**110**	**100**
Age		
≥54 years old	53	48
≤54 years old	57	52
Total	**110**	**100**
Work		
Mother House Ladder	48	44
Laborer	16	15
Trader	24	22
Pension	3	3
Farmer	1	1
Self-employed	2	2
No Work	16	15
Total	**110**	**100**
Health Complaints		
Hard to breathe	8	8
Chest Feels Pain	11	11
Shrinking sound when breathing	1	1
High blood pressure	23	26
Diagnosed with lung disease	1	1
Prolonged cough	9	9
History of respiratory disease	4	4
No health complaints	53	48
Total	**110**	**100**

Based on Table 2, it can be illustrated that the intake or inhalation rate uses the value set by the EPA (US Environmental Protection Agency) through IRIS (Integrated Risk Information System), namely 0.830 m^3/ hour. The duration of exposure uses the median because the data is not normally distributed, so the *cut-off value* is 22 hours/day and is still in the safe category. Mark The respondents' exposure frequency in this study was 365 days/year. The duration of exposure with median data is 35 years. A total of 59 respondents (54%) had a duration of exposure above or equal to 35 years. Body weight data is usually distributed with an average as a benchmark of 59 kg.

Table 2. Description of the EHRA Variables based on Inhalation Rate, Exposure Time, Exposure Duration, and Body Weight of Respondents in Tirtonirmolo Community, Bantul

EHRA Variables	Frequency (n)	Percentage (%)
Inhalation Rate (m^3/hour) adults = 0.83 (18)		
Exposure Time (Hours/day)		
≥22	62	56
<22	48	44
Total	**110**	**100**
Exposure Frequency (days/year)		
≥365	109	99
<365	1	1
Total	**110**	**100**

EHRA Variables	Frequency (n)	Percentage (%)
Exposure Duration (years)		
≥35	59	54
<35	51	46
Total	**110**	**100**
Body Weight (Kg)		
≥59	61	54
<59	49	46
Total	**110**	**100**

The first step in EHRA is to hazard identification. At this stage, collection and testing are carried out to measure how many SO_2 levels are in the research location, as presented in Table 3. Results measurement SO_2 concentrations in Table 3 show that concentration SO_2 reached an average of 11.19 μg/m³ at the research location, and the highest concentration was on Madukismo Road at 11.72 μg/m³. All study sampling sites showed that SO_2 concentrations still below quality standards, it can be categorized as safe. The quality standard used is regulation of Minister of Health Number 2 of 2023 concerning Implementing Regulations of Government Regulation Number 66 of 2014 concerning Environmental Health, with the quality standard for SO_2 in ambient air measuring one hour is 150 μg/Nm³.

Table 3. Concentration of SO_2 in the Gas Tirtonirmolo Community, Bantul

Location	Time	Variable	N (μg/m³)*	N (mg/m³)	Quality standards (μg/m³)**
Jogonalan Road	09.00-10.00 AM	Sulfur Dioxide (SO_2)	11.46	0.01146	150 (0.15 mg/m³)
Mrisi Road			10.40	0.0104	
Madukismo Road			11.72	0.01172	
Average			11.19	0.01119	

**) conversion value : 1 μg/m³ = 0.001 mg/m³*

***) Regulation of Ministry of Health in Republic Indonesia, Number 2, 2023 (39)*

Table 4. Frequency Distribution of Intake Values and Characterization of SO_2 Real-Time and Lifetime (10-30 years) Exposure Risk in the Tirtonirmolo Community, Bantul

Variable	Frequency (n)	Percentage (%)
Intake (I) Real-time & Lifetime		
Real-time intake (mg/kg/day)		
≥ 0.0039	55	50
< 0.0039	55	50
Total	**110**	**100**
Intakes lifetime 10 year (mg/kg/ day)		
≥ 0.00110	55	50
< 0.00110	55	50
Total	**110**	**100**
Intakes lifetime 15 years (mg/kg/ day)		
≥ 0.00166	55	50
< 0.00166	55	50
Total	**110**	**100**
Intakes lifetime 20 years (mg/kg/ day)		
≥ 0.00221	55	50
< 0.00221	55	50
Total	**110**	**100**
Intakes lifetime 25 years (mg/kg/ day)		
≥ 0.00276	55	50
< 0.00276	55	50
Total	**110**	**100**
Intakes lifetime 30 years (mg/kg/ day)		
≥ 0.00331	55	50
< 0.00331	55	50
Total	**110**	**100**
Real-time and Lifetime Risk Characterization (RQ)		
Real-time RQ		
≥ 1	0	0
< 1	110	100
Total	**110**	**100**
RQ lifetime 10 -30 year		
≥ 1	0	0
< 1	110	100
Total	**110**	**100**

Table 4 presents the results of calculations to measure the amount of intake and characteristics of SO_2 exposure received by respondents. This study's average value was 0.0043 mg/kg/day. The median value of SO_2 intake of respondents in this study was 0.0039 mg/kg/day, which was used as a benchmark in the data distribution for this study. The duration of lifetime exposure consists of 10 years, 15 years, 20 years, 25 years, and 30 years, and the highest lifetime intake is 30 years, with a value of 0.00331 for 55 respondents (50%). Meanwhile, for characterization (RQ) real-time and lifetime are still < 1 for 110 respondents (100%).

Table 5 calculates estimated intake and RQ values using minimum and maximum concentration levels. The minimum intake for estimating real-time exposure duration is obtained through a minimum SO_2 concentration level of 0.104 mg/m³ with an inhalation rate was 0.830 m³/hour, exposure time was 2 hours/day, exposure frequency was 365 days/ years, the duration of exposure for real-time was 35 years, body weight using the mean data was 59 kg. The average time was 10950 days, resulting in an intake value of 0.00033109 mg/kg/day. Based on this intake value, the resulting RQ was 0.0127343, which means RQ < 1. Meanwhile, for the minimum intake for lifetime exposure with a 30-year projection, the intake result was 0.00028379 mg/kg/day with an RQ value of 0.0109151 or RQ < 1. The RQ value obtained was still in the safe category.

Table 5. Description of Estimated Intake Figures and RQ for Minimum and Maximum SO_2 Concentrations in Respondents with Projected Real-time Exposure Duration and Lifetime Exposure Duration (25 Years) in Tirtonirmolo, Bantul

Estimate Minimum Intake									RQ
Period	C (mg/m³)	R (m³/hour)	tE (hour/day)	fE (day/year)	Dt (year)	Wb(kg)	t avg (day)	Intakes (mg/kg/day)	
Real-time	0.0104	0.83	2	365	35	59	10950	0.000341	0.013130
Lifetime	0.0104	0.83	2	365	30	59	10950	0.000293	0.010915
Estimate Maximum Intake									**RQ**
Period	**C (mg/m³)**	**R (m³/hour)**	**tE (hour/day)**	**fE (day/year)**	**Dt (year)**	**Wb(kg)**	**t avg (day)**	**Intakes (mg/kg/day)**	
Real-time	0.01772	0.83	2	365	35	59	10950	0.022698	0.872990
Lifetime	0.01772	0.83	2	365	30	59	10950	0.000330	0.012683

DISCUSSION

The average age in the study includes the elderly category with a range of 46-55 years old (15). The more age increases, the more the possibility is that there is a decline in body organ functions that can accompany the existence of the environment, especially air pollution. Many prospective cohort and daily time-series studies published worldwide have repeatedly proven the detrimental links between long and short-term air pollution exposure and human health (16). Age a man influences toxicity, whereas at age more than 45 years, there is a decline in body organ function. That matter can affect metabolism and the drop of work muscles in humans (17). People in the group who carry on age will experience a decline in ability physiology of the body related face influence something agent risk. Age group more prone to toxicity at relative doses more low (18). So, based on the study results, respondents older than 54 years amounted to 53 respondents (48%) own more risk of experiencing a decline in function respiratory from SO_2 exposure compared to respondents under 54 years amounted to 57 respondents (52%).

The majority of respondents in this study are female. However, existing research posits that men, particularly in the age range studied, tend to be taller and may face increased exposure to air pollution compared to women (19). This discrepancy is partly attributed to anatomical differences, as men generally possess greater lung volume than women (20), making them potentially more susceptible to the inhalation of pollutants such as SO_2 from the ambient air (21). Notably, this study adopts the default intake rate values established by the EPA (US Environmental Protection Agency) through the IRIS (Integrated Risk Information System). Specifically, the inhalation rate for adults is set at 0.830 m^3/hour, as determined by EPA-defined default values that consider the same inhalation marker rate (22), ensuring consistency in the assessment of pollutant exposure (11).

Assess exposure time in this study was still under 24 hours. The long exposure time of up to 24 hours/ day in 30 years is still categorized as safe (23). Thus, long exposure time of 22 hours/ day and a period of 25 years exposure to the front is still categorized as safe. The standard exposure period in the area settlement is 24 hours/ day, exposure in the environment works 8 hours/ day, and disclosure at school is 6 hours/ day. The frequency exposure of respondents in the study amounted to 365 days/year. The default value of frequency exposure is 350 days/year for residential areas (11). Therefore, rate frequency exposure to research exceeds the EHRA guidelines' default value. A high-frequency value can increase the risk of disturbance and health-related exposure to SO_2. Suppose the concentration of detected pollutants is still below standard quality, the frequency of exposure is constant, but can increase the possibility of complaints of respiratory consequences from exposure to material pollutants such as SO_2 (24). However, risk characterization of this study still reported safe category according to the EHRA formula especially Risk Quotient (RQ) ≤ 1.

The majority of respondents in the study reported a duration of exposure of 35 years or more. The term "duration exposure" implies a quantitative measure of this exposure. The statement suggests a positive correlation, where an increase in measured duration of exposure corresponds to an increased mark on the intake value. This inference suggests that a longer duration of exposure corresponds to an increased intake of the specified substance, referred to as the "intake value." Consequently, the statement emphasizes the need for a direct comparison between the measured exposure duration and the corresponding mark intake, and highlights the importance of incorporating considerations of exposure duration into the assessment of substance intake within the study (25). Duration exposure value will be shared into two categories, real-time and lifetime. This study uses duration exposure real-time taken from respondents living on-site.

Meanwhile, lifetime exposure with a period length of 30 years is appropriate according to EHRA guidelines. The average body weight in this study was higher than the default average body weight of 55 kg (11). This study's average body weight value was still below the default value set by the EPA, 70 kg (26). In this study, the overall body weight value of the respondent is inversely proportional to the amount of risk and the intake received by the respondent, so the higher the body weight value of a respondent, the smaller the value of the threat received by a respondent.

Motorized vehicles themselves are one factor in increasing SO_2 because 65% of motor vehicle emissions or exhaust gases containing SO_2 on weekdays are contributed by passenger cars. The increase in motorized vehicles can be directly proportional to the increase in pollutant emissions, one of which is SO_2 by 3.6% (23). Various things, such as air humidity, wind speed, air temperature, etc., can influence the SO_2 concentration in the air. The temperature range influenced most SO_2 concentrations in Shandong, China, from 2014 to 2019 during the day (27). It was also stated that increasing industrial areas, rainfall, wind speed, emissions, duration of sunlight, and the rate of urbanization could influence the level of SO_2 concentration in the ambient air.

Traffic volume has a relevant relationship with ambient air quality. The influence of motorized vehicles as a source of mobile pollutants is generally dominated by transportation activity, but passenger transportation can have a significant impact if traffic volume becomes dense (28). The motorized vehicles passing through the research location at the time the air sampling was carried out were considered quite thick. However, further research is needed by calculating the number of vehicles passing at each point of the research location to see the correlation with the increase in SO_2 concentration.

The dose-response analysis is a stage in EHRA that helps determine the relationship between the dose size or level of exposure to a chemical and its adverse effects on human health. The dose response at this stage determines whether a chemical or risk agent can cause adverse effects on the health level of the population at risk (29). Reference Concentration (RfC), is a term used to assess risk through inhalation, where the concentration level refers to the air quality level. RfC is generally expressed in milligrams per kilogram of body weight per day (mg/kg/day).

SO_2 is included in substances with a non-carcinogenic risk so that secondary data can be used for dose response in the form of a reference dose or RfC. The RfC value used in this study was taken from the value set by the US-EPA for SO_2 inhalation exposure, 0.0026 mg/kg/day (12). Risk characterization calculations are carried out by dividing the intake value by the reference dose value or RfC (30). These reference dose-response values were based on those available in the 1990 EPA/NAAQS (12). The calculation results were used to determine whether community respondents in Tirtonirmolo, Bantul Regency, who took part in this study, had a risk of non-carcinogenic health disorders due to SO_2 exposure. A person is categorized as "safe" if they have an RQ calculation result of less than one or RQ<1(11). In contrast to the "unsafe" category, someone with an RQ value of more than 1 or RQ>1 can be categorized as "unsafe" and needs risk management. This study's highest real-time projection RQ value was 0.8303 and almost close to 1.

The results of calculating estimated intake using minimum and maximum SO_2 concentration values in real-time and lifetime projections in this study show that the Tirtonirmolo, Bantul Regency community is still in the "safe" category because all risk are characterized by real-time and lifetime RQ values of less than 1. Previous study reported contrary because concentration of CO gas for real-time and lifetime projections at X Street is "unsafe" category, RQ value > 1 for 16 respondents (real-time) and 82 respondents (life-time) projection exposure. The resulting data can be caused by differences in exposure duration, which can affect the RQ calculation results. The higher exposure duration is similar to the value of the duration a person is exposed to a risk agent. This can increase a person's risk of experiencing health problems, especially respiratory system disorders. In the lifetime projection for the next 30 years, you will be included in the "unsafe" category if you are continuously exposed to risk agents, so you must manage risk (13). According to epidemiological study, exposure to air pollution increases the risk of cardiovascular disorders, metabolic syndrome, and decreased lung function (31-32).

Risk management is carried out to reduce the risk from exposure to risk agents in populations or individuals at risk (33). In China's policy to reduce SO_2 concentrations in ambient air, the authorities have established several regulations related to the environment (34). Several health efforts can be made to minimize the risks and impacts of SO_2 exposure in ambient air. In the Regulation of the Indonesian Minister of Health Number 1077 of 2011 concerning Guidelines for Cleaning Air in Home Spaces (7), efforts include providing the house with natural ventilation or mechanical ventilation so that there is an exchange between air inside the house and outside the house, using environmentally friendly household fuel, such as Liquid Petroleum Gas (LPG) or electricity, and reducing or stopping smoking activities at home.

The changes that people can make to reduce SO_2 exposure are increasing the use of masks when carrying out activities, especially when doing activities outdoors. Respondents in this study who had the habit of using masks when doing outdoor activities were rated relatively high. The number of respondents who practice using masks is 68 (62%). Companies also have a role in SO_2 exposure, so monitoring exhaust gases produced from the ongoing production process is necessary. Monitoring is carried out regularly at specific periods to ensure that the exhaust gas produced is within safe limits for the surrounding environment. If air quality pollution exceeds the threshold limit, counseling and education on air pollution control are carried out daily regarding its impact on potential respiratory problems if exposed.

Sugar factories around the research location can reduce the exhaust gas produced by making improvements in the production process from input to output, including: selecting inputs in the form of environmentally friendly raw materials and fuel, energy-saving production processes in the use of water and electricity, controlling waste produced, as well as the choice of means of transportation within and outside the company using emission-free vehicles. This can be interpreted as meaning that companies as air pollution agents are expected to be willing and able to implement resource efficiency and clean production in all their production lines as well as end-of-pipe (waste) management so that it can reduce SO_2 waste gas.

The implementation of clean production activities has been regulated in the Decree of the Minister of Industry No 250/M/ SK/10/1994 concerning Guidelines for Preparing Environmental Control in the Industrial sector and Decree No 251/M/SK10/1994 concerning the Establishment of an Environmental Management Unit steering team and Environmental Monitoring Efforts. The principle of clean production in SME centers can be carried out through the following five steps: 1) elimination to prevent waste accumulation at the source, 2) to reduce the waste produced, 3) reuse by utilizing waste in other forms, 4) recycle by recycling efforts waste, and 5) recovery in the form of efforts to utilize goods that still have economic value (35).

Installation and use of Flue Gas Desulfurization (FGD) facilities can be an alternative technology used to reduce SO_2 concentration levels in ambient air. This study stated that, by using this facility, the SO_2 removal efficiency level increased by more than 95% (36). The SO_2 reduction method using FGD technology has succeeded in reducing SO_2 emissions and can even comply with CAR 2014 of Malaysian law (37). This FGD facility has several advantages compared to other methods, namely a high level of desulfurization efficiency, the ability to regenerate sorbents, and reduced waste handling (38).

Achieving sustainable control of air pollution, particularly in areas affected by elevated SO_2 concentrations, demands a collaborative approach across government, society, and industries. The primary cause of increased SO_2 emissions stems from industrial processes, notably the combustion of sulfur-containing fuels and raw materials. To mitigate this, planting trees around factories can serve as a practical measure to absorb pollutants and enhance air quality. Additionally, comprehensive policies supported by investments are essential, focusing on environmentally friendly transportation models, energy-efficient homes, and improved industrial management practices. Prioritizing public transportation as an alternative to minimize SO_2 concentrations requires proactive preparation and cooperation from local governments, involving investments in cleaner technologies, expanding transit networks, and ensuring accessibility (14). This collective effort is crucial in curbing significant sources of pollution, promoting a sustainable reduction in SO_2 emissions, and ultimately fostering a healthier environment.

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CONCLUSION

This study shows that all respondents from this study have an RQ value < 1 for real-time and lifetime in the safe category. Risk management can still be carried out to reduce the amount of risk received if exposed to SO_2 continuously in the long term in the community in Tirtonirmolo, Bantul Regency, frequently using masks when doing outdoor activities and installing Flue Gas Desulfurization (FGD) in industries that emit SO_2. We expect the local government to take various preventive and control measures related to polluted air quality.

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