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Health Risk Assessment of Pollutant Emissions from Coal-fired Power Plant: A Case Study in Malaysia

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ABSTRACT

Coal-fired power plants (CFPPs) are Malaysia's primary electricity source, but their emissions adversely affect human health, organism growth, climate change, and the environment. The carbon, hydrogen, and sulphur content of coal make it a viable option for electricity generation. However, the by-products from leaching, volatilisation, melting, decomposition, oxidation, hydration, and other chemical reactions significantly negatively impact the environment and human health. This study aims to quantify the emissions from a coal-fired power plant, investigate the interplay between different emissions, simulate the dispersion of emissions, and assess their health impact through a health risk assessment. The results indicate that SO_2 is the primary contributor to emissions and its impact on human health is a concern. The health effects, both chronic and acute, are more pronounced in children than in adults. This study combines real-time emissions data and simulations to assess emissions' health impact, raising awareness about the emissions from coal-fired power plants. Furthermore, the findings can potentially enhance working conditions for employees and promote environmental health.

Keywords: CFPP emissions, air pollution, health risk assessment, hazard Quotient, hazard index

INTRODUCTION

Coal is the most abundant energy source on Earth and is extensively utilised for power generation in numerous countries (Munawer, 2018). In Malaysia, coal-fired power plants (CFPPs) contribute the largest

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share of electricity, accounting for approximately 64%, while gas and hydro technologies contribute 32% and 4%, respectively (Ranjan et al., 2019). However, the utilisation of fossil fuels in thermal power plants has significantly contributed to air pollution, with primary pollutants such as carbon monoxide (CO), sulphur dioxide (SO_2), carbon dioxide (CO_2), and nitrogen oxides (NO_x) (Shekarchian et al., 2011). The adverse effects of these pollutants, particularly CO_2 emissions from coal combustion, have been linked to climate change and related phenomena, resulting in an increased risk of malaria and its associated mortality (Gething et al., 2010).

It is essential to examine the emission levels and composition of various pollutants to provide a comprehensive understanding of the environmental impact of CFPPs. According to a study, CFPPs release significant quantities of carbon dioxide (CO_2), with an annual rate of 17,739 tonnes per thousand households (The IBR Asia Group Sdn. Bhd., 2019). Moreover, it was found that CFPPs emit approximately 5.7 tonnes of NO_X, 1.2 tonnes of particulate matter (PM), and 5.9 metric tonnes of SO_2 per year (The IBR Asia Group Sdn. Bhd., 2019). Additionally, CFPPs release trace amounts of heavy metals like cadmium, arsenic, mercury, and lead (Pb) (The IBR Asia Group Sdn. Bhd., 2019). These emissions contribute to the overall air pollution and environmental degradation of CFPPs. As reported by the Malaysia Ministry of Natural Resources and Environment (2015), CO_2 accounted for 73%, 76%, and 72% of all greenhouse gas emissions in 2000, 2005, and 2011, respectively, with methane (CH_4) and nitrous oxide (N_2O) also contributing to the overall greenhouse gas emissions. Nitrous oxide in the atmosphere rose from 4% in 2000 to 5% in 2011 (Babatunde et al., 2018).

The release of these pollutants from CFPPs poses significant risks to human health and other organisms, as highlighted by reports from the United Nations Environment Program (UNEP). CFPPs are estimated to be responsible for approximately 1400 additional deaths annually due to the lethal doses of air pollutants they produce (Yakubu, 2017). Furthermore, the World Health Organization (WHO) has identified air pollution as a leading cause of approximately 4.2 million premature deaths each year, associating it with various health issues such as cardiovascular diseases, cancer, respiratory illnesses, and neurological disorders. Therefore, this study is crucial for estimating the level of health risk in different age and gender groups (Combes & Franchineau, 2019). CFPPs contribute to 23% of Malaysia's air pollution, making them the second-largest source after transportation (Zubir et al., 2017). Considering these air pollutants' physical and chemical characteristics, they can spread over vast distances, posing significant risks to the environment and human health (Zubir et al., 2017).

Coal combustion yields several harmful gases, including CO_2, CO, SO_2, sulphur trioxide (SO_3), nitrogen dioxide (NO_2) and nitric oxide (NO), which have been associated with various health issues (Badman & Jaffé, 1996; Kelsall et al., 1997; Munawer, 2018). Even in residential settings, coal combustion for heating contributes to environmental and health problems. Recent studies have shown that coal's chemical processing releases two to four times more CO_2 compared to oil, resulting in adverse environmental effects such as global warming and the greenhouse effect (Ren & Patel, 2009). The health problems associated with these gases range from malaria and cardiovascular disease to asthma and other respiratory ailments. Approximately 90% of all global CO_2 emissions in 2011 were attributed to burning fossil fuels, emphasising the significance of addressing emissions from coal combustion (Munawer, 2018).

In addition to CO_2, coal combustion releases sulphur into the environment, leading to air, water, and land pollution. Unregulated coal power plants release twice as much sulphur oxides and particulate matter into the atmosphere annually compared to vehicles, trucks, and factories. The resulting SO_x and PM travel long distances from a power station and decompose into sulphuric acid (H_2SO_4), a key component of acid rain. Besides, inhaling SO_x can also negatively impact human health. The inhalation of SO_x air pollution has been linked to disrupted cardiac rhythms and an increased risk of heart attacks (Peters et al., 1999). Proximity to power plants and high exposure to SO_2 have also been associated with respiratory issues such as suffocation, wheezing, coughing, and decreased lung function (Munawer, 2018).

Moreover, NO_2 generated during coal combustion accumulates in the air and causes cumulative damage to the environment and human health due to its corrosive nature and strong oxidising properties (Levy et al., 1999). Exposure to high levels of NO_2 (>1500 mg/m^3) has been linked to decreased lung function, asthma attacks, and other respiratory problems. The impact of NO_2 on individuals varies, with some being vulnerable even to lower pollutant quantities (Munawer, 2018). Furthermore, coal burning releases millions of tonnes of coal fly ash (CFA) and coal dust annually, which serve as precursors to PM and pose severe health risks (Clancy et al., 2002; Miller & Sullivan, 2007). Air pollution, particularly PM, has been associated with various developmental abnormalities, including congenital malformations, adverse pregnancy outcomes, infant mortality, and genetic anomalies. The detrimental effects of PM on human health include the development of cancers, cardiovascular diseases, and reproductive abnormalities (Munawer, 2018).

According to Mahlia (2002), electricity power plants in Malaysia emit significant amounts of pollutants into the atmosphere, with a considerable portion of the chemical energy being converted into heat inefficiently. While previous studies have shed light on the air emissions from CFPPs, the effects of these emissions on health, particularly in the Johor region, remain understudied. Therefore, this study aims to evaluate the pollution emissions and assess the associated health risks among populations residing near CFPPs due to exposure to air pollutants. The findings of this research will contribute to a better understanding of the health risks faced by different populations in proximity to CFPPs. Not only that, but the research will also serve as a basis for raising awareness among the public and policymakers about the dangers associated with CFPP pollutant emissions and facilitate prompt responses to potential emergencies involving hazardous gas releases.

MATERIALS AND METHODS

Data Collection

The lab equipment within the CFPP offered two sets of historical data: a quarterly year interval historical data taken at four different sampling points from May 2016 to June 2019. The second consists of 30 min intervals of historical data taken at the main stack of the CFPP from January 1, 2016, to December 31, 2018.

Target Population

Multiple neighbourhoods can be found within 10 km of the CFPP site, as Google Earth Pro 7.3 shows. Hazard quotient assessment threat locations were Kampung Sungai Boh and Kampung Sungai Chengkeh for three main reasons: (1) the nearest population area to the CFPP location, (2) the high-density population, and (3) prevailing wind direction.

Google Earth Pro 7.3's ruler tools measure the distance with the camera pointed directly north (Table 1). Meanwhile, the geography of Malaysia's southwestern region is viewed on a topographic map courtesy of Worldwide Elevation Finder/Topographic map/ Altitude map (Figure 1).

Table 1
Location coordinates and distance from the CFPP (source: Google Earth Pro 7.3)

Location	Coordinates	Distance (km)
Coal Fired Power Plant (Emission source)	1°19'58.97"N, 103°32'9.61"E	-
AA4 sampling point in Kg. Chokoh Besar	1°18'58.30"N, 103°30'9.70"E	4.19
Kampung Sungai Boh	1°20'38.81"N, 103°30'54.16"E	2.63
Kampung Sungai Chengkeh	1°20'39.25"N, 103°31'13.72"E	2.10

Figure 1. Topography map of southern-western Johor (source: Worldwide Elevation Finder/ Topographic map)

Sampling and Analysing Methods

The CFPP follows the guidelines established by the Joint Standards Australia/New Zealand Standards Committee EV-007, which include the adoption of the Australian/New Zealand Standard (AS/NZS 3580.9.6:2003 and AS/NZS 3580.9.14:2013) for PM sampling and analysis (Standard Australia Committee and Standard New Zealand Committee, 2015). ISC Method (Inter-Society Committee Methods of Air Sampling and Analysis) is utilised for SO_2 and NO_2 analysis and sampling (Table 2). Sampling and testing for CO concentrations have been done using a technique different from the United States Environmental Protection Agency (USEPA) Method 10. Table 2 provides a summary of the sampling and analysis techniques that were employed.

Table 2
Sampling and analysing methods

Type of gases	Sampling and analysing methods used
Particulate matter (PM_{10})	AS/NZS 3580.9.6:2003
Particulate matter ($PM_{2.5}$)	AS/NZS 3580.9.14:2013
Sulphur dioxide (SO_2)	ISC Method 704
Nitrogen dioxide (NO_2)	ISC Method 408
Carbon monoxide (CO)	USEPA Method 10

Real Time-based Emissions and Regression

In this study, the emissions were recorded over three years with a 1 min interval between each entry. These results were collected and recorded, and the overall emissions were extracted. Moreover, linear regression was used to determine how some emissions impact each other.

Atmospheric Dispersion Model Simulation

The dispersion model is simulated using a free copy of ALOHA, version 5.4.7, downloaded from the EPA's website. The Gaussian Plume dispersion model in ALOHA software solidified the author's decision to utilise it. ALOHA dispersion models have previously been widely used in the field of consequence emissions (Khalid et al., 2019; Malik et al., 2021, 2023).

Health Risk Assessment

After determining the population's exposure to individual air contaminants using air quality modelling, the next step was using air pollution health risk assessment (AP-HRA). Since non-carcinogenic gases are more abundant than carcinogenic gases, Hazard Quotient (HQ) is evaluated here. Acute and chronic AP-HRA estimates have been calculated for four groups, male adult, female adult, male child, and female child, to differentiate non-chemical variables, including respiration and body weight (Das et al., 2018).

$$ADD = \frac{Ca \times IR \times ET \times EF \times ED}{BW \times AT} \quad [1]$$

$$\mathrm{fD} = \mathrm{RfC} \times \frac{20\mathrm{m}^3/\mathrm{day}}{70\mathrm{kg}} \quad [2]$$

$$HQ = \frac{ADD}{RfD} \quad [3]$$

Equations 1, 2 and 3 are the formulas used to calculate HQ. For non-cancer assessment, the average time equals the Exposure duration (ED), converted into days (Das et al., 2018). Reference concentration (RfC) values used for health risk assessment are shown in Table 3, adapted from Kenessary et al. (2019). Maximum single concentrations of the pollutants are used for calculating HQ acute exposure (Hurt et al., 2001).

Table 3
Reference concentration

Parameter	Adult (59 years old)		Children (11 years old)	
	Male	Female	Male	Female
Body weight, BW (kg)	68	60	32.6	32
Inhalation rate (m^3/h)	0.63	0.47	0.58	0.54
Exposure duration, ED (year)	59		11	
Exposure time, ET (h/day)	24			
Exposure frequency, EF (day/year)	350			

Non-chemical factor values used in this study are summarised as displayed in Table 3. Adult Body weight (BW) is adapted based on the mean weight of Malaysia's South socio-demographic (Azmi et al., 2009). Meanwhile, children's BW is assumed based on the BW status of urban Malay primary school children (Yang et al., 2017). Inhalation rate (IR) parameters for children and adults are assumed from existing default values and recommendations for the European population's exposure assessment (Höglund et al., 2012). These default values are used because of the comprehensiveness of the respective age group and gender of the studied group. Also, the IR values for the respective studied groups are not stated in the guidelines by the Department of Environment (DoE) Malaysia (Hashim & Hashim, 2010). Values of Hazard Index (HI) less than 1 are equivalent to HQ, indicating that exposure is unlikely to cause negative consequences. This Equation 4 is used to determine HI values:

$$HI = \sum HQ_i \quad [4]$$

RESULTS AND DISCUSSION

Overall Emissions from 2016 to 2018

The data presented in Figure 2 indicates that the total emissions production during the period from 2016 to 2018 amounted to approximately 242 million mg/Nm^3 of SO_2, 126 million mg/Nm^3 of NO_2, and 91 million mg/Nm^3 of CO. These emission levels are substantial for a single CFPP and a relatively small developing country like Malaysia. It is noteworthy that the emissions exhibited a fluctuating trend over the studied period. Specifically, there was a decrease in emissions in 2017, but they subsequently increased again in 2018. This variation in emission levels suggests the presence of certain factors or events that influenced the emissions output during those specific years.

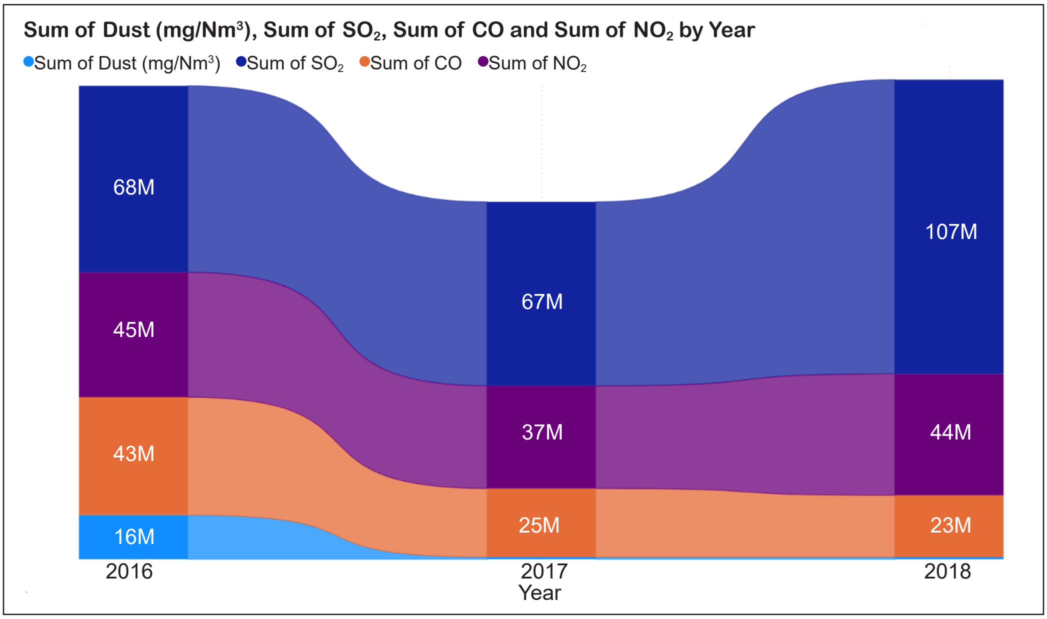


Figure 2. Evolution of emission levels in the period of 2016 to 2018

Effect of Other Emissions on SO_2

The findings from Figure 2 highlight that the period from 2016 to 2018 witnessed substantial emissions production from the CFPP, with SO_2 exhibiting the highest recorded emissions during this timeframe. A linear regression analysis was performed to gain a deeper understanding of the relationship between SO_2 emissions and other pollutants. The predictors used in the model were NO_2, CO, and dust. The regression analysis results revealed significant associations between these pollutants and SO_2 emissions. Specifically, NO_2 emerged as a significant positive predictor, with a coefficient (B) of 0.534, a p-value of 0.000, and an odds ratio (OR) of 1.707. It indicates that an increase in NO_2 emissions is linked to a corresponding increase in SO_2 emissions.

On the other hand, CO and dust were identified as significant negative predictors of SO_2 emissions. The regression analysis showed that CO had a B value of -0.035, a p-value of 0.000, and an OR of 0.694, implying that higher CO emissions were associated with lower SO_2 emissions. Similarly, dust exhibited a B value of -0.017, a p-value of 0.000, and an OR of 0.983, indicating that increased dust emissions were correlated with decreased SO_2 emissions.

As presented in Table 4, these findings underscore the interplay between different pollutant emissions and their impact on SO_2 emissions from the CFPP. The positive relationship between NO_2 and SO_2 emissions suggests a potential co-occurrence or shared sources of these pollutants within the power plant. Conversely, the negative associations between CO and dust emissions with SO_2 emissions might indicate competing mechanisms or the effectiveness of emission control measures targeting these pollutants.

Table 4
Effect of other emissions on SO_2

Parameter	B	Sig.	Exp(B)	95% Interval for Exp(B)	
				Lower	Upper
(Intercept)	4.935E-14	1.000	1.000	0.999	1.001
NO_2	0.534	0.000	1.707	1.705	1.709
CO	-0.035	0.000	0.965	0.964	0.967
Dust	-0.017	0.000	0.983	0.982	0.984
(Scale)	0.713[a]				

Comparison of Modelled Ground Level Concentration with Historical Data

This comparison aims to validate the simulation output's reliability and accuracy by benchmarking with the measured concentration. It is essential to validate the simulated output as atmospheric dispersion is a stochastic phenomenon. The simulation model is likely to have deviated from the measured concentration due to either a single factor or a combination of the model configuration, atmospheric chemistry and unpredictable human behaviour (Rao, 2005). Therefore, by analysing the simulated with the historical data, the source of errors can be pointed out, and corrective actions can be taken to improve the mathematical model.

The quarter-year interval historical data used for this study are an average of 24 hours of continuous data taken from February 20, 2018, to February 21, 2018, at 3 p.m. The data were taken at the AA4 sampling point in Kg. Chokoh Besar. The comparison between historical data and simulated data is summarised in Table 5, which shows the simulated concentrations of SO_2, NO_2, and CO are within the range of the historical data where the concentration of SO_2 is less than 30, while the concentration for both NO_2 and CO is less than 10. However, PM10 has a 63.67 square root mean error between the calculated and observed values.

One of the main factors contributing to this error is the meteorological data (Rao, 2005) because the meteorological data are obtained from Senai Station, where the distance between observation sites with the CFPP is about 30 km, and the reference height is 37.8 m. The second factor contributing to the high concentration reading is the location of the CFPP surrounded by other potential pollutant sources such as another power plant and port activities (Pelabuhan Tanjung Pelepas). Nevertheless, the simulated data are valid to be studied as possible adverse impacts on residents due to the pollutants emitted by the respective CFPP.

Table 5
Comparison between simulated concentrations and historical data concentration

Gases	Simulated data (µg/m^3)	Historical data (µg/m^3)
Sulphur dioxide (SO_2)	8.71	<30
Nitrogen dioxide (NO_2)	2.37	<10
Carbon monoxide (CO)	2.05	<10
Particulate matter (PM_{10})	0.33	64

Threat Zones for Worst-case Scenario by Using ALOHA Modelling

A graphical representation of the results is generated using ALOHA for SO_2, NO_2 and CO emissions. The modelled cases are then represented in Google Earth software to obtain an overview of the affected zone. Figure 3 shows that the concentration of SO_2 dispersion does not exceed Acute Exposure Guideline Levels-3 (AEGL) and AEGL-2, where the threshold is 78.6 mg/m^3 and 1.965 mg/m^3, respectively. However, the concentration of SO_2 emission does exceed AEGL-1, where the concentration threshold is 0.524 mg/m^3 for 60 min. A toxic zone whose concentration exceeds AEGL-1 reaches almost 3.5 linear km in the same wind direction and source point. SO_2 AEGL-1 value is based on the No Observed Effect Level (NOEL) for bronchoconstriction in exercising asthmatics. It means that the affected population may have a disabling effect from SO_2 exposure and only experience discomfort, irritation and certain asymptomatic (National Center for Biotechnology Information (NCBI), 2010).

In addition, the yellow line outside the threat zones in the Google Earth image is a wind direction confidence line. Wind direction confidence lines represent the range of uncertainty in the wind direction as wind rarely blows constantly from any one direction. In this simulated case, the wind direction confidence line is big due to the high potential of wind direction changes affected by low wind speed (EPA, 1999). The simulated case is also set at noon, where the stability class is B, which is moderately unstable.

Except for SO_2 toxic threat zones, other gas pollutants such as NO_2 and CO simulated outcomes show that the pollutant concentration does not exceed levels of concern (i.e., AEGL). SO_2 gas pollutant emission rate is the highest compared to other gases. Gaussian

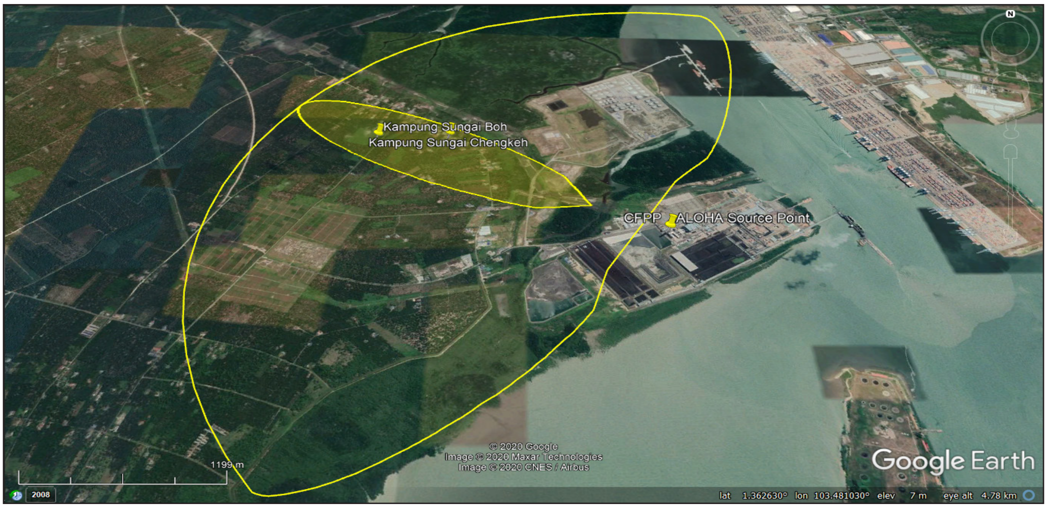


Figure 3. Toxic threat zone for the worst-case scenario of SO_2 emission

Plume Equation shows that the pollutant emission rate is directly proportional to the mean concentration of the diffusing substance at a point. Therefore, the higher the pollutant emission, the higher the ground level concentration and potentially exceed the levels of concern (LOC).

Furthermore, one of the factors for low gas concentration simulation outcomes is the stack height. In this study, the stack height is 200 m. According to Stack Height Vermont (2020), tall or adequate stack height is required to minimise the ground-level concentration of air pollutants. Hence, to obtain the ground-level concentration values for other gases, ALOHA's LOC is set to user-defined as below:

(1) LOC-1 (yellow zone) = 0.001 mg/m^3
(2) LOC-2 (orange zone) = 0.01 mg/m^3
(3) LOC-3 (red zone) = 0.1 mg/m^3

Figure 3 presents the results of the simulated NO_2 emissions. However, it is important to note a limitation of the ALOHA model, which does not make predictions for distances beyond 10 km from the release point (EPA, 1999). Therefore, the threat zone depicted in Figure 3 is truncated at the 10-km limit. Upon examination of Figure 4, it is evident that a zone exceeding LOC-3 extends up to approximately 5.3 km in the same wind direction and from the same source point. It indicates a higher level of concern within this zone. Moreover, it is worth mentioning that a zone surpassing both LOC-2 and LOC-1 extends beyond the 10-km mark. The simulation results also show that both threat points (Kampung Sungai Chengkeh and Kampung Sungai Boh) are in the LOC-3 threat zone.

Moving on to the simulation results for CO emission, as illustrated in Figure 5, it can be observed that the dispersion of CO emissions is slightly larger compared to NO_2. It is evident in the threat zone, which extends beyond the LOC-3 threshold by approximately

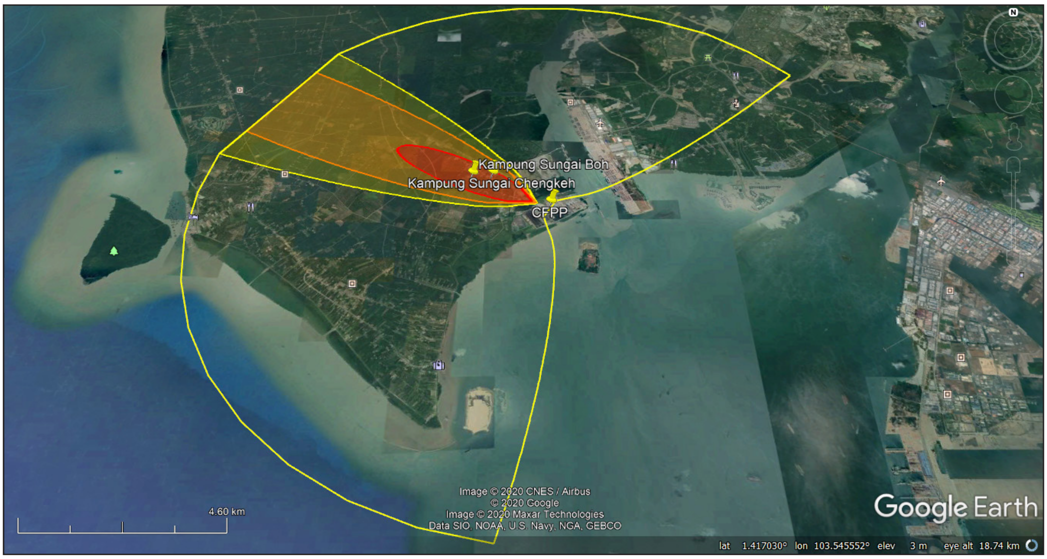


Figure 4. Toxic zone for worst-case scenario of NO_2 emission

Figure 5. Threat zone for worst-case scenario of CO emission

1.8 km in the same wind direction and source point as NO_2. Similar to the NO_2 dispersion modelling, the threat zones for LOC-2 and LOC-1 extend beyond the 10-km mark from the source point.

Threat Zones for Best-case Scenario by Using ALOHA Modelling

In the best-case scenario, assessing the ground-level concentration of pollutants is essential. The ALOHA model's Level of Concern (LOC) parameter is set to user-defined values to determine the ground-level concentration values. In this study, the following values were used for the LOC:

(1) LOC-1 (yellow zone) = 1E-12 mg/m^3
(2) LOC-2 (orange zone) = 1E-10 mg/m^3
(3) LOC-3 (red zone) = 1E-8 mg/m^3

Figure 6 depicts the threat zones simulated for the best-case scenario of SO_2 emissions. The results illustrate that Kampung Sungai Chengkeh falls within the threat zone LOC-1, indicating a relatively lower level of concern. On the other hand, Kampung Sungai Boh is observed to be within the threat zone LOC-2, indicating a slightly higher level of concern. Furthermore, it is worth noting that Kampung Sungai Boh is located closer to the downwind direction, which may affect the dispersion and concentration of SO_2.

The best-case scenario for NO_2 emissions is illustrated in Figure 7, allowing the examination of the threat zones resulting from this emission. Upon closer inspection of Figure 7, it becomes apparent that Kampung Sungai Chengkeh does not fall within any identified threat zones. It suggests the concern for NO_2 emissions in Kampung Sungai Chengkeh is relatively low. In contrast, Kampung Sungai Boh is within a threat zone that exceeds LOC-1, indicating a deeper concern for this area.

Figure 8 depicts the threat zones simulated for the best-case scenario of CO emissions. A similar result with the SO_2 emission threat zones was obtained. Once again, Kampung Sungai Chengkeh is located within the threat zone designated as LOC-1. It implies a relatively lower concern for CO emissions in Kampung Sungai Chengkeh. Conversely, Kampung Sungai Boh is observed to be within the threat zone corresponding to LOC-2, indicating a moderately higher level of concern for this area in terms of CO emissions.

Figure 6. Toxic threat zone for the best-case scenario of SO_2 emission

Figure 7. Toxic threat zone for the best-case scenario of NO_2 emission

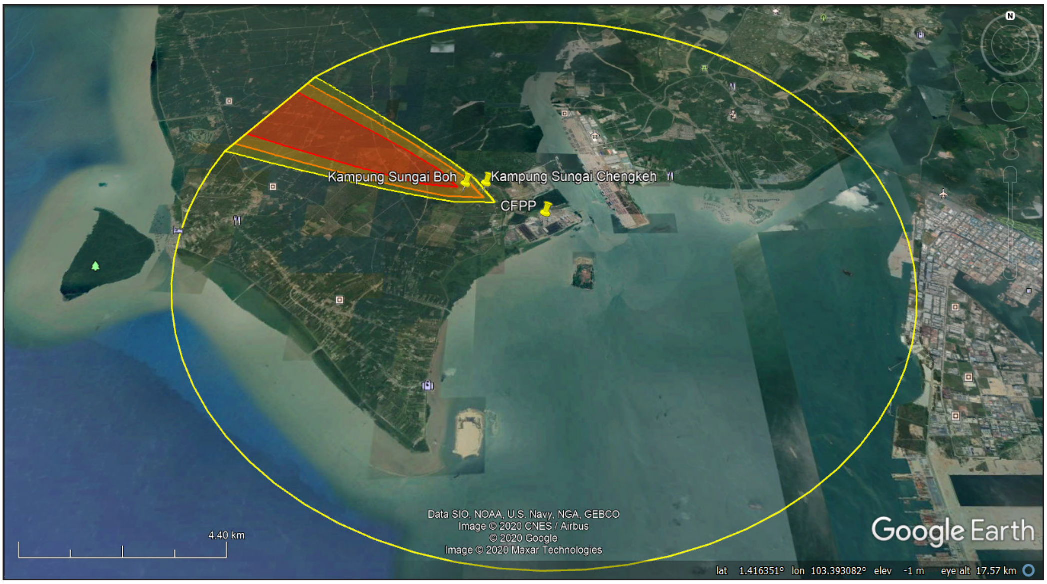
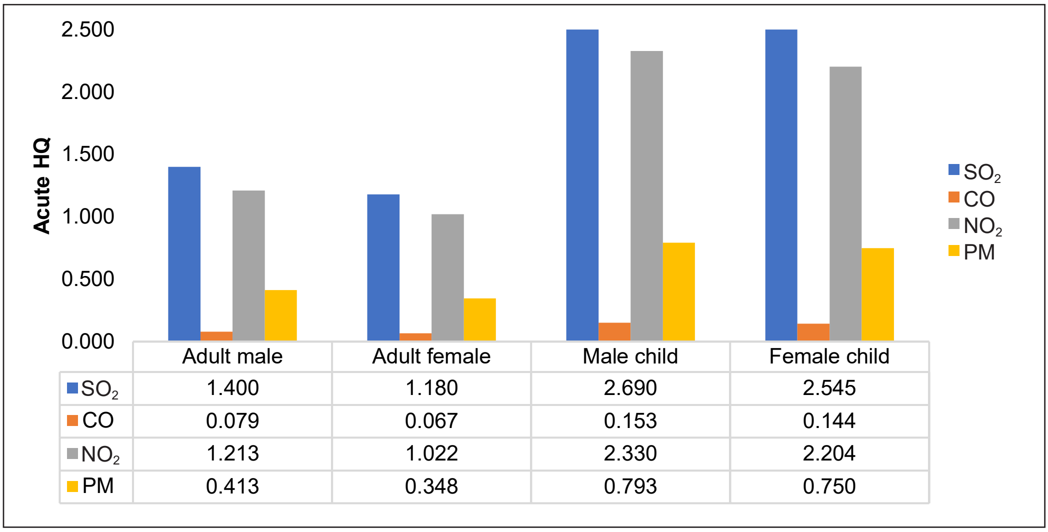


Figure 8. Toxic threat zone for the best-case scenario of CO emission

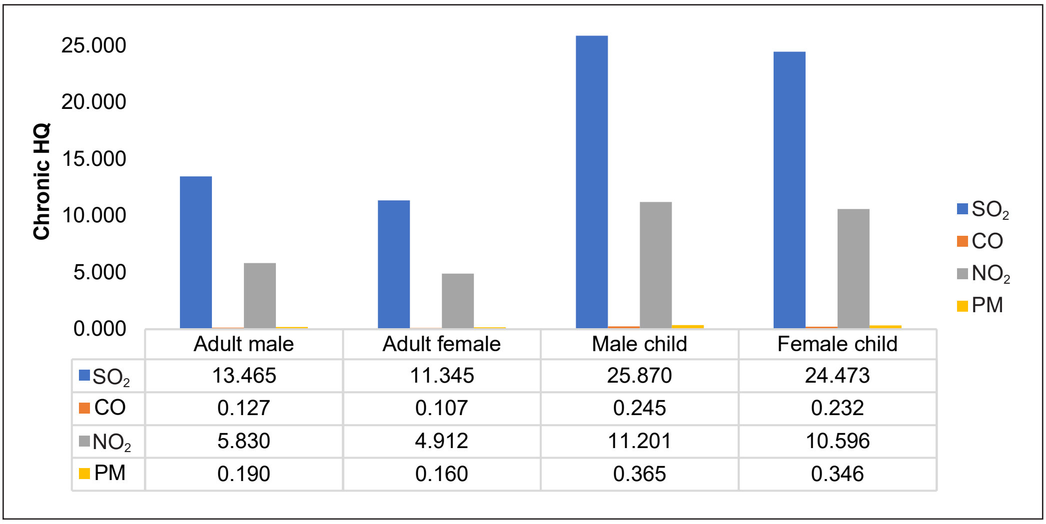
Health Risk Assessment

Hazard Quotient (HQ) for Acute and Chronic Health Effects of Worst-case Scenario. Figure 9 displays the estimated HQ values for acute health effects at Kampung Sungai Boh, while Figure 10 presents the HQ values for chronic health effects. Similarly, Figure 11 illustrates the estimated HQ values for acute health effects at Kampung Sungai Chengkeh, and Figure 12 showcases the HQ values for chronic health effects. It is important to note that when HQ values are less than 1, the likelihood of adverse health effects is considered low. Conversely, increased HQ indicates a higher probability of developing potential health risks. Furthermore, it is crucial to highlight that if HQ values exceed 10, the risk of chronic health effects is considered high (Chalvatzaki et al., 2019). Analysing the results for Kampung Sungai Boh (Figures 9 and 10), HQ values for adults and children exposed to SO$_2$ and NO$_2$ were observed to be above 1, suggesting a higher probability of potential health risks associated with these pollutants. On the other hand, HQ values for CO and



	Adult male	Adult female	Male child	Female child
🟦 SO$_2$	1.400	1.180	2.690	2.545
🟧 CO	0.079	0.067	0.153	0.144
⬜ NO$_2$	1.213	1.022	2.330	2.204
🟨 PM	0.413	0.348	0.793	0.750

Figure 9. Worst-case scenario of acute HQ for different studied groups in Kampung Sungai Boh



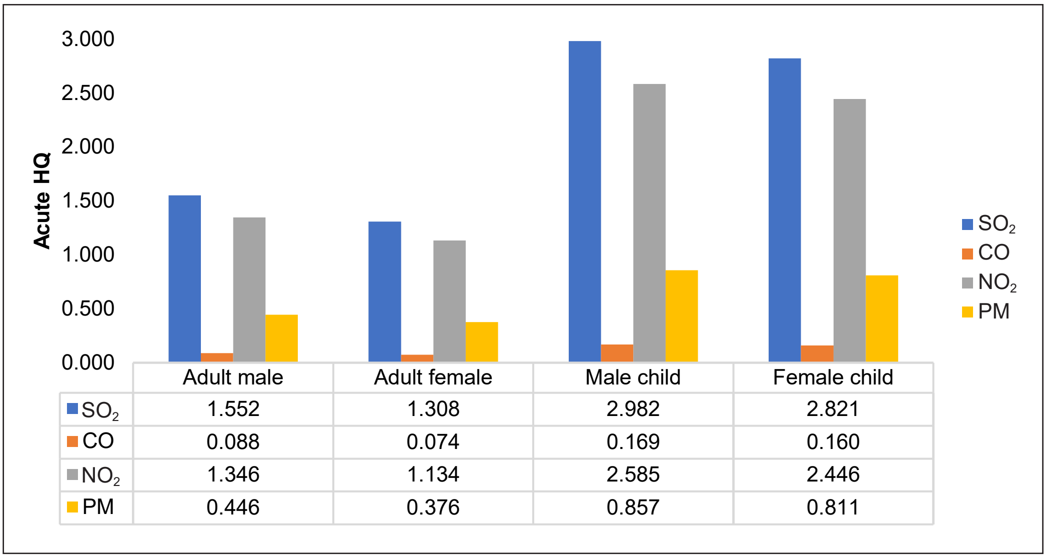
	Adult male	Adult female	Male child	Female child
🟦 SO$_2$	13.465	11.345	25.870	24.473
🟧 CO	0.127	0.107	0.245	0.232
⬜ NO$_2$	5.830	4.912	11.201	10.596
🟨 PM	0.190	0.160	0.365	0.346

Figure 10. Worst-case scenario of chronic HQ for different studied groups in Kampung Sungai Boh

PM10 exposure in adults and children are below 1, indicating a relatively lower likelihood of adverse health effects from exposure to these gases.

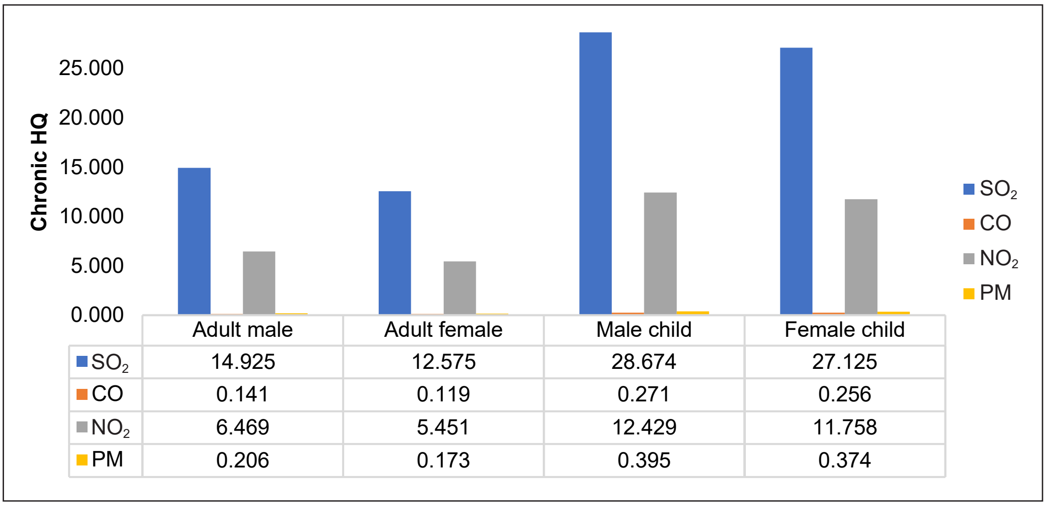
Similar patterns emerge in the results for Kampung Sungai Chengkeh (Figures 11 and 12), where HQ values for NO_2 and SO_2 exposure exceed 1 for adults and children, while HQ values for CO and PM10 exposure remain below 1 for both acute and chronic health effects. Notably, HQ values for all age groups exposed to SO_2 in both villages and NO_2 exposure for children in both villages exceed 10, indicating a high chronic health risk.

Regarding the comparison across age groups, male children are at a higher risk than female children, similar to adults, where males are at a higher risk than females. These



	Adult male	Adult female	Male child	Female child
SO_2	1.552	1.308	2.982	2.821
CO	0.088	0.074	0.169	0.160
NO_2	1.346	1.134	2.585	2.446
PM	0.446	0.376	0.857	0.811

Figure 11. Worst-case scenario of acute HQ for different receptor groups in Kampung Sungai Chengkeh



	Adult male	Adult female	Male child	Female child
SO_2	14.925	12.575	28.674	27.125
CO	0.141	0.119	0.271	0.256
NO_2	6.469	5.451	12.429	11.758
PM	0.206	0.173	0.395	0.374

Figure 12. Worst-case scenario of chronic HQ for different receptor groups in Kampung Sungai Chengkeh

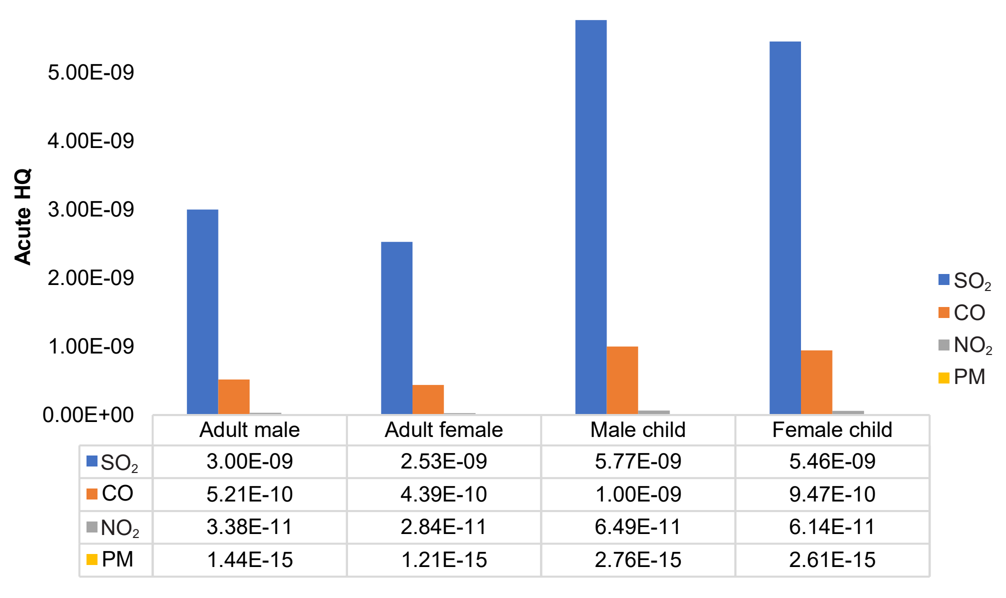
results can be attributed to the higher inhalation rate in males compared to females, resulting in a higher susceptibility to health risks from air pollution exposure. The findings illustrated in the four diagrams highlight that both short-term and long-term exposure to SO_2 pose the highest threat for both adults and children. It can be attributed to the high ground-level concentration of SO_2 and the low Reference Concentration (RfC) values associated with SO_2. Consequently, the HQ values for SO_2 are significantly higher compared to the other gases. Conversely, the RfC values of CO for both acute and chronic exposures are relatively higher compared to the other three gases. As a result, the HQ values due to CO exposure are the lowest among the gases studied. These results suggest that neither adults nor children face a potential health risk when exposed solely to CO and PM10.

Compared to a study conducted in an urban-industrial area in South Africa, where the pollutants originated from a CFPP, metallurgical industries, and a manganese smelter, the acute HQ findings from our study show notable differences. Morakinyo et al. (2017) reported acute HQ values for SO_2 exposure of 0.1 for children and 0.07 for adults. Additionally, for acute HQ values of PM10 exposure, they reported 0.11 for children and 0.03 for adults. These results indicate that the acute HQ values from our study are considerably lower when compared to the study conducted in South Africa.

However, contrasting findings are observed for chronic HQ exposures, as the chronic HQ values from this study are substantially higher than those reported in the South African study. For instance, this study found a chronic HQ 449 for SO_2 exposure in children and 682 for adults. Furthermore, for chronic HQ values of PM10 exposure, this study reported 362 for children and 281 for adults. These significant differences can be attributed to various factors, such as the differing conditions of pollutant emission sources and the utilisation of different RfC values in the South African study. It is crucial to acknowledge that the South African study encompassed multiple pollutant sources, which may have contributed to the variations in the findings. Furthermore, using different RfC values, representing the safe exposure limits for chronic effects could also account for the differences in the chronic HQ values between the two studies.

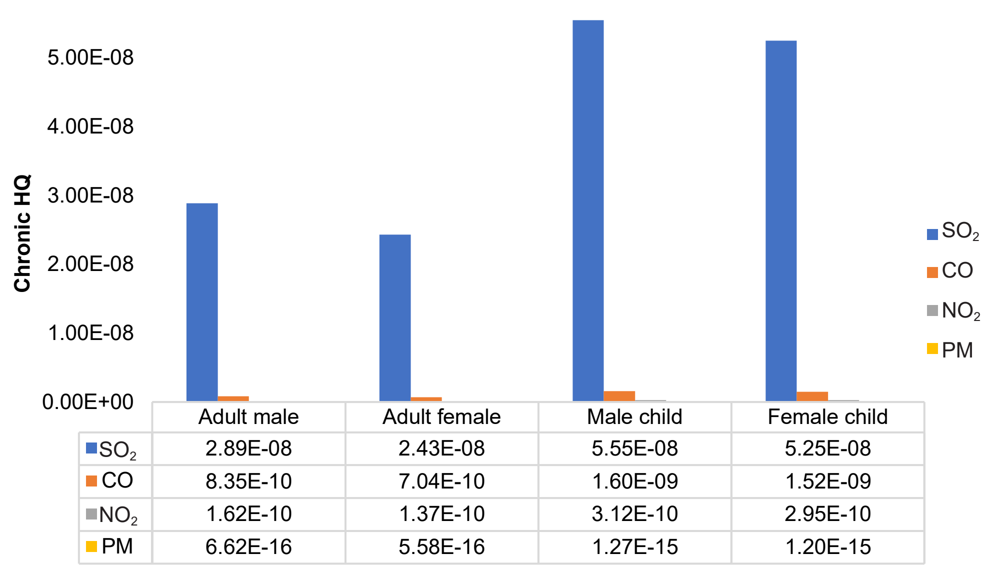
Hazard Quotient (HQ) for Acute and Chronic Health Effects of Best-case Scenario. In the analysis of the best-case scenario, the assessment of acute and chronic health effects involved using specific values tabulated in Figures 13, 14, 15 and 16, which provide essential data for calculating the HQ for the mentioned effects. Upon careful examination of Figures 13, 14, 15 and 16, it becomes apparent that all the HQ values obtained are relatively low, suggesting that the potential health risks associated with the best-case scenario can be considered negligible. Interestingly, although the inhaled Average Daily Doses (ADDs) of CO are higher than those of ADDs of SO_2, the acute and chronic HQs for SO_2 are significantly higher for both villages. This discrepancy arises from the fact that the

RfC values for SO_2 are 90% lower than the RfC values for CO. It is worth noting that the HQ values are inversely proportional to the RfC values. Therefore, the lower RfC values for SO_2 result in higher HQ values, indicating a potentially greater health risk associated with exposure to SO_2 in comparison to CO, despite the higher inhaled ADDs of CO in the best-case scenario.



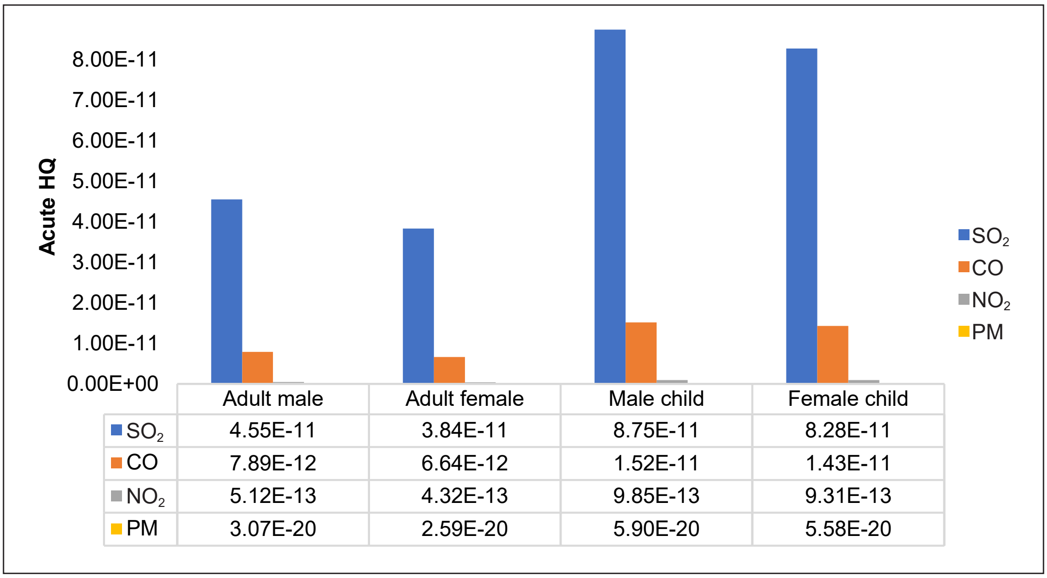
	Adult male	Adult female	Male child	Female child
🟦 SO_2	3.00E-09	2.53E-09	5.77E-09	5.46E-09
🟧 CO	5.21E-10	4.39E-10	1.00E-09	9.47E-10
⬜ NO_2	3.38E-11	2.84E-11	6.49E-11	6.14E-11
🟨 PM	1.44E-15	1.21E-15	2.76E-15	2.61E-15

Figure 13. Best-case scenario of acute HQ for different studied groups in Kampung Sungai Boh



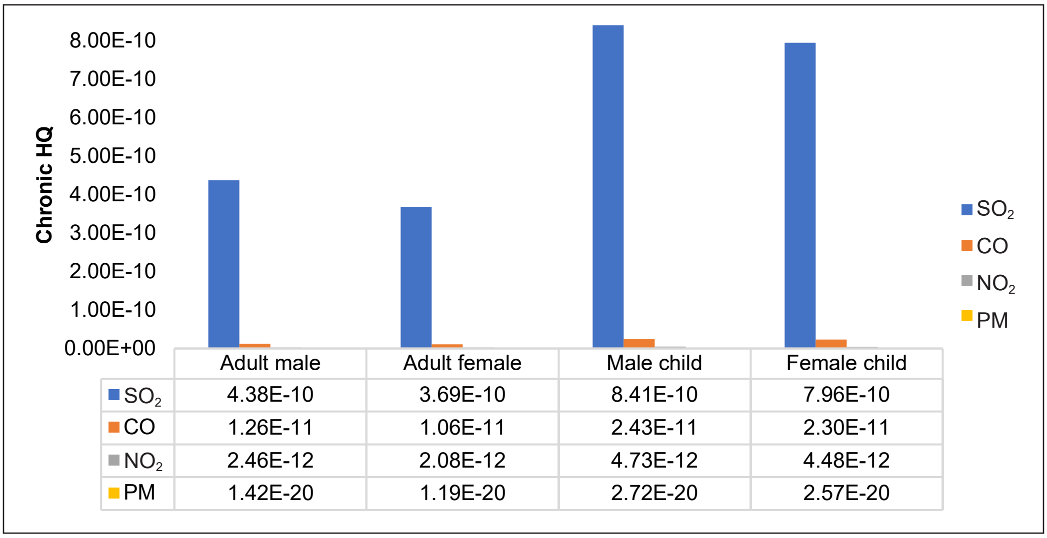
	Adult male	Adult female	Male child	Female child
🟦 SO_2	2.89E-08	2.43E-08	5.55E-08	5.25E-08
🟧 CO	8.35E-10	7.04E-10	1.60E-09	1.52E-09
⬜ NO_2	1.62E-10	1.37E-10	3.12E-10	2.95E-10
🟨 PM	6.62E-16	5.58E-16	1.27E-15	1.20E-15

Figure 14. Best-case scenario of chronic HQ for different studied groups in Kampung Sungai Boh



	Adult male	Adult female	Male child	Female child
■ SO_2	4.55E-11	3.84E-11	8.75E-11	8.28E-11
■ CO	7.89E-12	6.64E-12	1.52E-11	1.43E-11
■ NO_2	5.12E-13	4.32E-13	9.85E-13	9.31E-13
■ PM	3.07E-20	2.59E-20	5.90E-20	5.58E-20

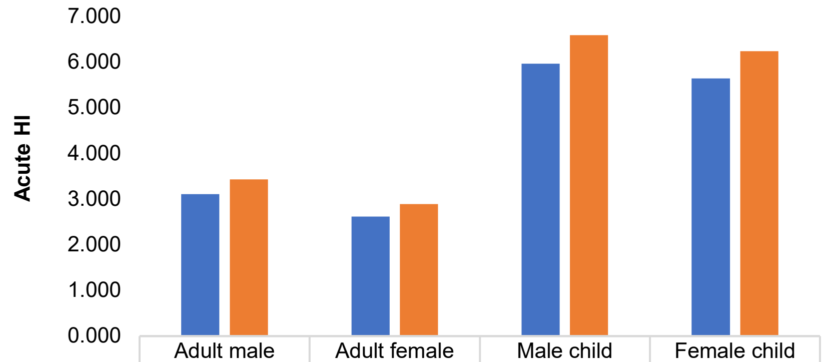
Figure 15. Best-case scenario of acute HQ for different studied groups in Kampung Sungai Chengkeh



	Adult male	Adult female	Male child	Female child
■ SO_2	4.38E-10	3.69E-10	8.41E-10	7.96E-10
■ CO	1.26E-11	1.06E-11	2.43E-11	2.30E-11
■ NO_2	2.46E-12	2.08E-12	4.73E-12	4.48E-12
■ PM	1.42E-20	1.19E-20	2.72E-20	2.57E-20

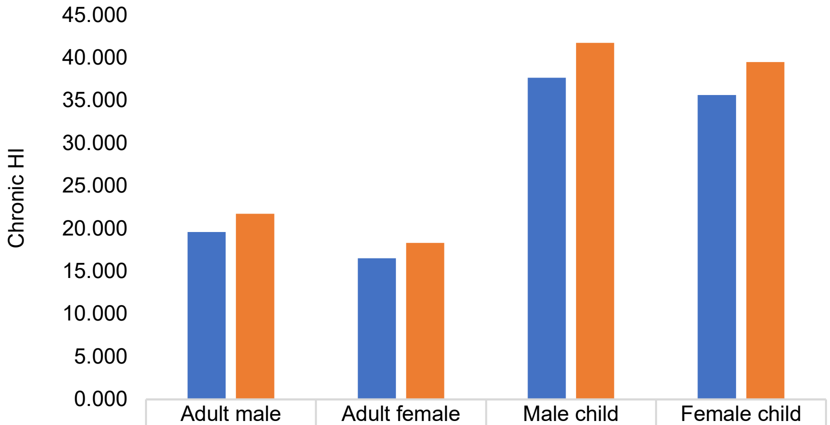
Figure 16. Best-case scenario of chronic HQ for different studied groups in Kampung Sungai Chengkeh

Hazard Index (HI) for Acute and Chronic Health Effects. Hazard Indexes (HI) were calculated using the previously determined HQ values to estimate the potential health risks associated with air pollutants. These HI represent the deposited dose resulting from the studied groups' exposure to the air pollutants. Figure 17 compares the acute exposure HI for different groups in Kampung Sungai Boh and the population residing in Kampung Sungai Chengkeh. On the other hand, Figure 18 displays the estimated HI for chronic exposure for all studied groups in both villages.



	Adult male	Adult female	Male child	Female child
🟦 Kampung Sungai Boh	3.105	2.616	5.966	5.644
🟧 Kampung Sungai Chengkeh	3.432	2.891	6.593	6.237

Figure 17. Comparison of acute exposure HI in Kampung Sungai Boh with Kampung Sungai Chengkeh



	Adult male	Adult female	Male child	Female child
🟦 Kampung Sungai Boh	19.613	16.525	37.681	35.646
🟧 Kampung Sungai Chengkeh	21.741	18.318	41.769	39.512

Figure 18. Comparison of chronic exposure HI in Kampung Sungai Boh with Kampung Sungai Chengkeh

According to the HQ recorded, it can be observed that SO_2, NO_2, PM10 and CO accounted for approximately 45%, 39%, 13%, and 3%, respectively, of the HI values for adult males, adult females, male children, and female children in both threat areas. Regarding chronic exposure HI, the HQ values for SO_2 accounted for more than 50% of the total, followed by NO_2 (30%), CO (0.65%), and PM10 (1%) for all studied groups. It was found that the values estimated for Kampung Sungai Chengkeh were 9.5% higher than those calculated for Kampung Sungai Boh when comparing the acute HI values. Similarly, for chronic health effects, the HI at Kampung Sungai Chengkeh were 9.8% higher than those at Kampung Sungai Boh for all studied groups. This observation aligns with the consistency of ground-level concentration data, as indicated in Figure 18, where Kampung Sungai Chengkeh exhibited approximately 10% higher estimated concentration values compared to Kampung Sungai Boh.

Based on the recorded findings, it is concerning that the estimated HI values for all studied groups are significantly above one, indicating a likelihood of adverse health effects. The SO_2, NO_2, and CO exposures are particularly concerning as they target the cardiovascular and respiratory systems, suggesting a high risk of cardiovascular and respiratory diseases for all individuals residing in Kampung Sungai Boh and Kampung Sungai Chengkeh.

However, it should be noted that the HI values for the best-case scenario are not included in this document due to their significantly low levels. The range of acute HI for both villages varies from 4.54E-11 (for an adult female residing in Kampung Sungai Chengkeh) to 6.84E-09 (for a male child residing in Kampung Sungai Boh). Similarly, for chronic HI values, adult females in Kampung Sungai Chengkeh have the lowest value of 3.81E-10, while male children in Kampung Sungai Boh have the highest value of 5.74E-08. These findings are influenced by the ADD values discussed in Figure 18, where male children residing in Kampung Sungai Boh have the highest values, while women in Kampung Sungai Chengkeh have the lowest.

CONCLUSION AND RECOMMENDATIONS

Reducing people's exposure to air pollution outdoors would significantly reduce mortality rates (Robert & Kevin, 2022). The uncontrolled release of SO_2 from SO_x has the same deadly effects on plants and animals as acid rain and causes various illnesses in humans, such as irregular heartbeat, skin cancer, asthma, cough, headache, and throat and nose irritations. Another vital pollutant from coal power plants that generate electricity is NO_x, which leads to fatal hypoxia in the respiratory system (Munawer, 2018). Most countries' greenhouse gas emissions come from power plants.

There is an immediate need for government action to reduce these emissions. Miller and Sullivan (2007) suggest that utilities, society, and the environment would benefit significantly from transitioning from energy generation based on fossil fuels to renewable fuels like hydropower. For example, the government may implement emissions tax to fund the construction of renewable energy power plants or the reforestation of Malaysian rain forests. The findings of this study have provided a solid foundation for building a programme to reduce emissions in Malaysia and conduct a cost-benefit analysis of switching to renewable energy sources for power generation. Furthermore, the impacts of pollution and particle matter can be reduced through individual interventions such as using face masks and air purifiers, regular physical activity, and a nutritious diet (Combes & Franchineau, 2019).

Regulations for health and the environment (protocols) should be defined globally to address these issues and encourage the widespread use of coal for power generation. Developing sound health and environmental safety protocols and providing adequate health and safety education will go a long way toward mitigating the effects on both the private and public sectors (Munawer, 2018). In addition, improved inhalation models are required to comprehend the impact of particle size and chemistry of various minerals on lung deposition and health impacts. Learning as much as possible about the health risks and exposure to PM from mining operations is essential to create estimating equations and a model with varying heights from the source. The outcomes can improve working conditions and environmental health (Patra et al., 2016).

This research demonstrates how prolonged exposure to air pollution causes health problems across all socioeconomic strata. This research backs up prior findings and suggests that the extent of the health effects may be more than previously thought. The findings suggest that reducing people's chronic exposure to fine particle pollution is necessary. Given that we only have data from a single CFPP and the authors used the participants' primary ZIP codes to determine their exposure levels, our estimation still has room for error. Despite the authors' best efforts to eliminate any potentially biased sensors, the degree to which ambient pollution monitors reflect the exposures of the subjects is imperfect. This research lacked information that would have allowed them to evaluate changes in exposure based on factors such as the possibility that some participants may have relocated and the subjects' activity and location, such as the amount of time they spent in traffic and indoors. Though they play a role in measurement and misclassification errors, they are unlikely to have introduced a bias that would account for the study's results.

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