MODELLING POLLUTION EMISSIONS FROM COAL-FIRED POWER PLANTS TO ASSESS THEIR ENVIRONMENTAL IMPACT

By

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Chairman : Mohd Zahirasri bin Mohd Tohir, PhD
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Coal-fired power plants (CFPPs) are significant sources of air pollution, emitting harmful pollutants that pose health risks to nearby communities. In Malaysia, limited research has been conducted on the specific health impacts of CFPP emissions on local populations. This study evaluates the health risks associated with air pollution emissions from a CFPP in southern Malaysia, focusing on the residential areas of Kampung Sungai Boh and Kampung Sungai Chengkeh. The primary objective is to assess acute and chronic health risks for various demographic groups, including adult males, adult females, male children, and female children. Pollutant dispersion modeling is performed using ALOHA software to simulate sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO) dispersion, while the Gaussian Plume Dispersion Model is applied for particulate matter (PM_{10}). The model's reliability is validated through benchmarking against historical data collected near the CFPP, providing a robust basis for health risk assessment (HRA) expressed in terms of hazard quotient (HQ) and hazard index (HI) for worst-case and best-case scenarios.

The results indicate that, in the worst-case scenario, HQs for SO_2 and NO_2 exceed 1 for all groups in both villages, suggesting a significant likelihood of non-carcinogenic health effects. In the best-case scenario, all HQs fall below 1, indicating a reduced health risk. Among the studied groups, male children are identified as the most vulnerable, followed by female children, adult males, and adult females. The research further confirms the model's reliability, as simulated SO_2, NO_2, and CO concentrations align with historical data. A review of the literature reveals a gap in research on CFPP-related health impacts in Malaysia, emphasizing the importance of this study. Overall, findings highlight the need for continuous monitoring and mitigation of CFPP emissions to protect public health, especially as coal remains a significant energy source in the region.

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

SDG: GOAL 3: Good Health and Well-Being, GOAL 13: Climate Action

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PEMODELAN PELEPASAN PENCEMARAN UDARA DARI LOJI-LOJI JANAKUASA ARANG BATU UNTUK MENILAI IMPAK ALAM SEKITAR

Oleh

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Loji jana kuasa arang batu (CFPP) adalah sumber pencemaran udara yang signifikan, mengeluarkan bahan pencemar berbahaya yang menimbulkan risiko kesihatan kepada komuniti berdekatan. Di Malaysia, penyelidikan mengenai kesan kesihatan khusus daripada pelepasan CFPP terhadap populasi tempatan masih terhad. Kajian ini menilai risiko kesihatan yang berkaitan dengan pelepasan pencemaran udara daripada CFPP di selatan Malaysia, dengan memberi tumpuan kepada kawasan kediaman Kampung Sungai Boh dan Kampung Sungai Chengkeh. Objektif utama adalah untuk menilai risiko kesihatan akut dan kronik bagi kumpulan demografi yang berbeza, termasuk lelaki dewasa, perempuan dewasa, kanak-kanak lelaki, dan kanak-kanak perempuan. Pemodelan penyebaran bahan pencemar dilakukan menggunakan perisian ALOHA untuk mensimulasikan penyebaran sulfur dioksida (SO_2), nitrogen dioksida (NO_2), dan karbon monoksida (CO), manakala Model Penyebaran Plume Gaussian digunakan untuk zarah terampai (PM_{10}). Kebolehpercayaan model ini disahkan melalui perbandingan dengan data sejarah yang dikumpul berhampiran CFPP, menyediakan asas yang kukuh untuk penilaian risiko kesihatan (HRA) yang dinyatakan dalam bentuk hazard quotient (HQ) dan hazard index (HI) bagi senario kes terburuk dan terbaik. Hasil kajian menunjukkan bahawa dalam senario kes terburuk, nilai HQ untuk SO_2 dan NO_2 melebihi 1 bagi semua kumpulan di kedua-dua kampung, menunjukkan kebarangkalian tinggi berlakunya kesan kesihatan bukan karsinogenik. Dalam senario kes terbaik, semua nilai HQ berada di bawah 1, menunjukkan risiko kesihatan yang lebih rendah. Antara kumpulan yang dikaji, kanak-kanak lelaki didapati paling terdedah, diikuti oleh kanak-kanak perempuan, lelaki dewasa, dan perempuan dewasa. Penyelidikan ini juga mengesahkan kebolehpercayaan model, kerana kepekatan simulasi SO_2, NO_2, dan CO selaras dengan data sejarah. Kajian literatur menunjukkan kekurangan penyelidikan tentang kesan kesihatan berkaitan CFPP di Malaysia, menekankan kepentingan kajian ini. Secara keseluruhan, penemuan ini menekankan keperluan untuk pemantauan berterusan dan langkah mitigasi pelepasan CFPP bagi melindungi kesihatan awam, terutamanya kerana arang batu kekal sebagai sumber tenaga penting di rantau ini.

Kata Kunci: Pelepasan CFPP, Pencemaran Udara, Penilaian Risiko Kesihatan, Kadar Bahaya, Indeks Bahaya

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ADD	Average daily dose
AEGL	Acute Exposure Guidelines Levels
ALOHA	Areal Locations of Hazardous Atmospheres (software)
AP-HRA	Air Pollution Health Risk Assessment
BW	Body weight
CAMEO	Computer-Aided Management of Emergency Operations
CFPP	Coal-fired power plant
CO	Carbon monoxide
CO_2	Carbon Dioxide
DoE	Department of Environment
ED	Exposure duration
EF	Exposure frequency
EPA	Environmental Protection Agency
ETA	Event Tree Analysis
ET	Exposure time
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
HI	Hazard Index
HQ	Hazard Quotient
HRA	Health Risk Assessment
IARC	International Agency for Research on Cancer
IR	Inhalation rate
IUR	Inhalation Unit Risk
LOAEL	Lowest-Observed-Adverse-Effect Level
MAAQG	Malaysian Ambient Air Quality Guideline

NO_2	Nitrogen dioxide
NOX	Nitrogen Oxide
NOAEL	No-Observed-Adverse-Effect Level
PM	Particulate Matter
PM_{10}	Particulate Matter (with a diameter of 10 micrometers or less)
RfC	Reference Concentration
RfD	Reference Dose
RR	Relative Risk
SO_2	Sulfur Dioxide

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Modern societies are highly dependent on a reliable supply of various energy sources, as energy is essential for activities like transportation, manufacturing, and heating. Raw materials such as oil, gas, and coal, that are extracted and transformed into usable products that support these processes as nation's economy rely on the insurance of a consistent supply of these materials for the infrastructure, economy stability, and the overall well-being. This aspect is referred to in the literature as energy security [1][2][3]. Energy security (ES) refers to the ability of a country or region to have a stable, affordable, and uninterrupted supply of energy. In today's world, energy is crucial for economic development and industrial activity. In other words, ensuring energy security means having access to diverse energy sources (like oil, gas, coal, renewable energy, etc.) without being overly dependent on any single supplier or region [4].

This concept is important as energy resources are often concentrated in specific countries or regions, which can influence global economy. Energy security can also affect national and international policies as governments must balance the need for reliable energy with concerns about the environmental impact, cost, and dependence on foreign supplies. In Southeast Asia, energy security is a growing concern due to the region's rapid economic development and population growth. Countries like Indonesia, Malaysia, and Vietnam are striving to meet increasing energy demands while reducing reliance on fossil fuels and imported energy. While it is worth noting that the region is rich in resources like coal, oil, and natural gas, but many nations are also exploring renewable energy options, such as solar, wind, and hydropower, to ensure long-term sustainability [5]. Additionally, regional cooperation through initiatives like the ASEAN Power Grid and Trans-ASEAN Gas Pipeline aims to improve energy connectivity and diversify energy sources, enhancing the overall energy security in the region [6]. However, the transition to cleaner energy faces challenges such as financing, infrastructure development, and balancing energy affordability, and most importantly meeting with environmental goals.

For Malaysia, the use of coal plays a significant role the country's energy landscape as a primary source to generate electricity, and it has been considered as one of the main ways of energy generation since 1990. Coal's dominance in the energy mix is evident, with an average annual growth rate of 3.12% from 1990 to 2020, although projections suggest a future decline as Malaysia shifts toward renewable energy sources. Under the Alternative Policy Scenario (APS), coal-based energy supply is expected to decrease by 1.082% annually until 2050 [5]. Despite these plans, coal production remains significant, with reserves estimated at 1.938 million tonnes in 2018, concentrated mainly in Sarawak and Sabah. However, the government has announced a gradual phase-out of coal-fired power plants, aiming for renewable energy to constitute 31% of the energy capacity by 2025 and 40% by 2040 [7]. As Malaysia transitions to a more sustainable energy to meet the 2030 UN's agenda [8], the environmental impact of coal usage is evident, with of coal-fired power plants (CFPPs) being a major contributor to CO2 emissions, aggravating air pollution and contributing to climate change. In fact, the significant environmental impacts of coal-fired power plants (CFPPs) are observed in several Malaysian states, particularly

Perak, Johor, and Negeri Sembilan. These states face challenges related to high water consumption, with Perak recording the highest water footprint due to its larger installed coal power capacity. While Perak and Negeri Sembilan experience moderate water stress, Johor has a lower water stress index [9].

As already mentioned, in Sarawak and Sabah, large coal reserves contribute to the country's coal supply, but the burning of coal in these regions increased CO2 emissions, and lead to environmental degradation and air pollution. While these two states are not the only contributors as the Tanjung Langsat coal-fired power plant (CFPP) in the state of Johor south Malaysia, found to be emitting a range of pollutants including nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter (PM10), mercury (Hg), cadmium (Cd), and dioxins. These emissions contribute to air pollution, with potential harm to both the environment and public health, particularly through air quality degradation [10]. Additionally, carbon monoxide, nitrogen oxides, and sulfur dioxide, pollutants have been linked to severe health issues, including respiratory diseases and premature deaths.

To assess the environmental and health impacts of these pollutants, dispersion modelling has become an essential tool. Dispersion models simulate how pollutants, once released into the atmosphere, are transported, diluted, and deposited in surrounding areas. By considering factors such as wind speed, atmospheric stability, and topography, these models predict pollutant concentrations at various distances from the source. For example, pollutants like NOx, SOx, PM10, and mercury from coal-fired power plants can travel significant distances, affecting regions far beyond the immediate vicinity of the plant [11].

To further understand dispersion modelling, it is important to refer to the Gaussian Plume Dispersion model, one of the foundational approaches used to predict the distribution of air pollutants emitted from point sources, such as coal-fired power plants. The Gaussian Plume Dispersion model assumes that pollutants disperse in the atmosphere following a normal distribution pattern, or a "Gaussian" shape, both horizontally and vertically. This model provides an analytical solution to the transport equation and has been widely used in atmospheric dispersion studies due to its simplicity and practicality. Some of the key features of the Gaussian Plume model include, steady-state approach, concentration distribution, atmospheric stability classes, plume rise and terrain effects [12, 13, 14].

The Gaussian Plume model has been a cornerstone of regulatory air quality assessments for decades, particularly in AERMOD, which integrates the Gaussian approach for near-field dispersion. This model is effective for short-term predictions of pollutant concentrations at various distances from emission sources and help to determine compliance with air quality standards. In the context of coal-fired power plants, pollutants such as SO_2, NOx, and particulate matter disperse in complex ways, influenced by local weather patterns and topography. The employment of Gaussian Plume modelling, would allow researchers and regulatory bodies to estimate the concentrations of these pollutants in the surrounding environment and predict their potential health and environmental impacts [13, 14]. As Malaysia continues to rely on coal for its energy needs while simultaneously striving to reduce environmental impacts encourage the investigation of the Coal-Fired Power Plants impact, and the application of dispersion models will remain integral in evaluating compliance with air quality standards and protecting public health.

1.2 Problem Statement

Coal-fired power plants (CFPPs) play an important role in Malaysia's energy security by providing a significant portion of electricity in the country. This reliance on coal comes with a cost that reflects on the environmental and public health safety. CFPPs are a major source of air pollution, emitting pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter (PM10). These emissions contribute not only to air quality degradation but also to large environmental and humans' health issues.

However, in the southwestern region of Johor, communities located near CFPPs, such as Kampung Sungai Boh and Kampung Sungai Chengkeh, are exposed to potentially harmful levels of these pollutants. While the general environmental and health impacts of CFPPs are well documented globally, there is a lack of localised research assessing the specific risks posed to these populations. To address this gap, it is important to model the dispersion of these pollutants and evaluate the associated environmental and health risks for various demographic groups in the affected areas. Thus, this study aims to provide a comprehensive assessment of the pollution emitted from CFPPs and its implications for public health and environmental sustainability in the Malaysian state of Johor.

1.3 Objectives

The main objective of this study is to evaluate the environmental and public health risks posed by emissions from coal-fired power plants (CFPPs) in the southwestern region of Johor, Malaysia. Specifically, the study aims to:

1. To determine pollution levels by accurately tracking and display dispersion of air pollutants emitted by CFPPs, utilising Gaussian Dispersion Modelling through the ALOHA software, alongside manual calculations.

2. Conduct a health risk assessment for various demographic groups, including adults (both male and female) and children (both male and female), focusing on short-term and long-term exposure to air pollutants from CFPP emissions.

3. Evaluate the environmental impact of CFPP emissions, focusing on air quality degradation and its implications for both public health and environmental sustainability in the affected communities of Kampung Sungai Boh and Kampung Sungai Chengkeh.

4. Provide evidence-based recommendations for mitigating the environmental and health impacts of CFPP emissions, aiming to inform policy-making and improve air quality standards in Malaysia.

1.4 Assumptions and Hypothesis

Assumptions

Several assumptions have been made for the purpose of this study, and listed as follow:

a. The pollutants emitted from the coal-fired power plants (CFPPs) are assumed to remain chemically stable, meaning no secondary air pollutants are formed through chemical reactions in the atmosphere.

b. It is assumed that the residents of Kampung Sungai Boh and Kampung Sungai Chengkeh are continuously exposed to the emitted pollutants throughout the year.

c. All individuals within the identified demographic groups (adults, children) are assumed to have the same level of exposure to the pollutants without variation in daily activities or time spent outdoors.

Hypotheses

a. The Gaussian Dispersion Model (used with ALOHA software) is suitable for accurately predicting the ground-level concentration of pollutants from CFPP emissions.

b. The acute and chronic hazard quotient (HQ) assessments will remain within acceptable health risk levels for both adults and children, except in extreme emission scenarios where higher health risks might be observed.

c. Children, especially male children, are hypothesised to face a higher health risk compared to adults due to their higher inhalation rates and physiological vulnerability to air pollution.

1.5 Significance of study

The findings of this study would be considered as a significant contribution to health risk assessments for communities impacted by CFPP emissions, while also enhancing public understanding and awareness of the associated environmental and health risks. Moreover, it will provide insights for rapid, effective emergency response strategies regarding the toxic gas emissions.

1.6 Scope and Limitation of Study

Scope of the Study

This study focuses on assessing the environmental and health impacts of air pollutants emitted by coal-fired power plants (CFPPs) in the southwestern region of Johor, specifically in the communities of Kampung Sungai Boh and Kampung Sungai Chengkeh. The pollutants of interest include sulfur dioxide (SO_2), nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter (PM10). The study aims to model pollutant dispersion using ALOHA software, complemented by manual calculations based on the Gaussian Plume Dispersion Model.

The study will focus on the following key aspects:

a. Predicting ground-level concentrations of key pollutants from CFPPs and analysing the spatial distribution of these pollutants in nearby residential areas.

b. Evaluating acute and chronic health risks for various demographic groups (adults and children) living within a 10 km radius of the CFPP.

c. Investigating the broader environmental impacts, including the potential for air quality degradation and its consequences on public health and the ecosystem in the studied area.

Limitations of the Study

a. This study is limited to the southwestern region of Johor and specifically involve the communities near Kampung Sungai Boh and Kampung Sungai Chengkeh. The findings may not be generalisable to other regions in Malaysia or other countries.

b. The health risk assessment will focus on non-carcinogenic health effects (e.g., respiratory issues, lung damage) associated with SO_2, NOx, CO, and PM10 exposure. Cancer risk and other long-term chronic diseases are out of the scope of this study.

c. The dispersion models assume steady-state meteorological conditions and do not account for possible chemical interactions between pollutants that could result in secondary pollutants.

d. Availability of reliable Data due to COVID19 pandemic

1.7 Thesis Layout

Chapter 1: Introduction

Provides a concise overview of the study, including the problem statement, objectives, hypotheses, and scope. Sets the foundation by highlighting the importance of assessing health risks associated with CFPP emissions, particularly in communities near Kampung Sungai Boh and Kampung Sungai Chengkeh.

Chapter 2: Literature Review

Examines existing research on CFPP emissions, Gaussian Plume Dispersion modeling, and health risk assessments. Focuses on the environmental and health impacts of pollutants such as SO_2, NO_2, CO, and PM, and reviews methods used to model pollutant dispersion and assess associated health risks.

Chapter 3: Methodology

Outlines the detailed methodology, including historical data analysis, topography assessment, and data inputs for dispersion modeling. Describes the Gaussian Plume model and ALOHA simulations used to estimate pollutant dispersion and the subsequent health risk assessment across various demographic groups.

Chapter 4: Results and Discussion

Presents and analyzes findings from the data, simulations, and health risk assessment. This includes comparisons between worst-case and best-case scenarios, with specific focus on pollutants' impact on different age and gender groups in both Kampung Sungai Boh and Kampung Sungai Chengkeh.

Chapter 5: Conclusion and Recommendation

Summarizes the key findings and health implications, with a focus on the most vulnerable groups. Offers recommendations for future research and potential interventions to mitigate the adverse health effects of CFPP emissions on nearby communities.

Figure 1.1 : Flow Chart of the Thesis

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Coal-fired power plants (CFPPs) play a significant role in electricity generation, contributing approximately 61% of global power production. However, the environmental and human health impacts of CFPPs are well-documented and concerning. These power plants are significant sources of pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM), which contribute to air quality degradation, respiratory diseases, and climate change. Accurately predicting the atmospheric behaviour of these pollutants through air emission modelling is essential to assess their spread and concentration in different regions. Gaussian Plume modelling has been widely used to simulate the dispersion of pollutants from CFPPs, providing a better understanding on how these emissions affect surrounding environments. This modelling must be paired with a detailed health risk assessment to fully understand the potential impacts on human health. Such assessments consider the exposure pathways and quantify the risks associated with pollutant inhalation, ultimately helping policymakers develop strategies to mitigate the adverse effects of CFPP emissions. The goal of this literature review is to discuss the coal dependency, the impact of Coal-Fired Power Plants on environment and health, and critically evaluate the existing research on air emission modelling, with a focus on Gaussian Plume models, and the associated health risk assessments of pollutants emitted by CFPPs.

2.2 Coal Fired Power Plant in Malaysia

Coal-fired power plants (CFPPs) are widely used in electricity generation due to their high efficiency and cost-effectiveness. These plants convert chemical energy from coal into electrical energy through a thermodynamic process. CFPPs operate on a closed-circuit steam-water cycle, primarily using the Rankine cycle, which consists of four main components: the boiler, turbine, condenser, and feedwater pump. The cycle begins with water from the condensation process being pumped into a low-pressure heater by a condensate pump. The water is then heated, and oxygen is removed in the deaerator before entering the economizer, where it is further heated by the flue gases. From the economizer, the water flows into the boiler, where it is converted into steam. The steam generated in the boiler passes through a superheater, where it is converted into high-temperature, high-pressure steam, which drives the turbine. The rotation of the turbine shaft generates electricity as it drives the connected generator. After passing through the turbine, the steam is condensed back into water in the condenser and recirculated in the system, along with make-up water, to complete the cycle. This closed-loop system is essential for maintaining efficiency and minimizing energy loss [15, 16]. The thermodynamic process used in CFPPs follows the Rankine cycle, which involves the reversible conversion of heat into work. In this process, heat is supplied externally in a closed system, where water is used as the working fluid. The heat converts the water into steam, which undergoes adiabatic expansion in the turbine, generating mechanical energy. The steam is then condensed back into water in the condenser and pressurized in the pump to complete the cycle. The Rankine cycle is highly efficient for converting thermal energy into mechanical and electrical energy, making it a critical process in CFPP operations [17]. Recent studies emphasize the ongoing improvements in CFPP technology to increase efficiency and reduce emissions. These developments focus on optimizing the boiler and turbine systems, integrating advanced materials for higher temperature and pressure operations, and incorporating carbon capture and storage (CCS) technologies to mitigate environmental impacts. However, despite these advancements, CFPPs continue to contribute significantly to global CO_2 emissions, highlighting the need for continued efforts to transition to cleaner energy sources [18, 17].

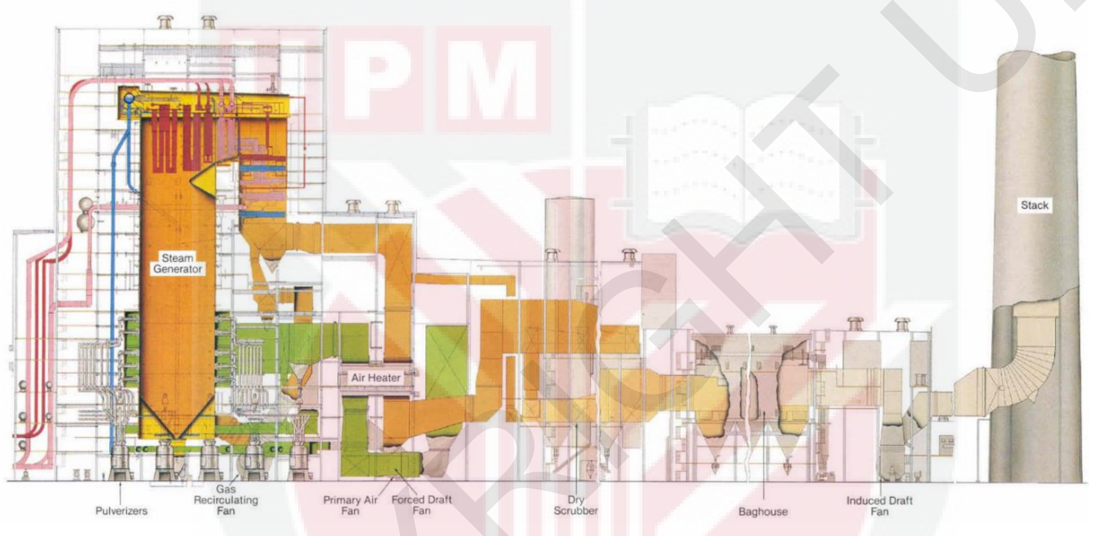

Figure 2.1 : Coal Power Plant Layout [19]

Before the 1980s, Malaysia's energy sector was predominantly reliant on oil. However, the global oil crisis of the 1970s significantly shifted this trajectory, prompting the development of key national energy policies aimed at reducing Malaysia's heavy dependence on oil and promoting long-term economic growth. Notable policies introduced in response included the National Energy Policy of 1979, the National Depletion Policy of 1980, and the Fuel Diversification Strategy in 1981, which was further updated in 1999 [20]. The original Four Fuel Diversification Strategy (1981) was designed to balance the use of natural gas, coal, oil, and hydroelectricity, providing a more resilient and diversified energy portfolio. In 1999, renewable energy was introduced as the fifth element in the energy mix, marking a shift toward sustainability. This diversification strategy also played a pivotal role in facilitating the construction of new coal-fired power plants (CFPPs) to stabilize electricity prices after the oil price shocks [21]. The first major CFPP in Malaysia, the Kapar Power Plant (KPP), also known as the Sultan Salahuddin Abdul Aziz Shah Power Station, began operations in 1987 and remains the largest power facility in the Klang Valley. KPP is unique for its fuel flexibility, being capable of using oil, coal, and natural gas for electricity generation. A Japan International Cooperation Agency (JICA) study in 1993 identified KPP as one of the main sources of nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter emissions in the Klang Valley region (Mokhtar, 2016). Records show that KPP's coal consumption reached an annual peak of 806,400 tons, making it a significant contributor to air pollution among power plants in Malaysia. Currently, Malaysia operates several CFPPs, which emit millions of tons of pollutants each year. Key CFPPs in Peninsular Malaysia include the Manjung, Tanjung Bin, and Jimah plants, with a combined capacity of 7,600 MW. In contrast, Sarawak has a smaller coal-fired capacity of 320 MW due to its total installed power generation capacity of only 1,315 MW, compared to Peninsular Malaysia's 21,817 MW [22]. Sarawak's energy mix also includes hydroelectric power, diesel engines, gas turbines, and combined-cycle plants.

TNB Fuel Services (TNBFS) Sdn Bhd oversees coal supply to TNB Generation and Independent Power Producers (IPP) through Power Purchase Agreements (PPA) with TNB. In 2010, coal consumption at KPP surged to around 4 million tons per year, contributing to a cumulative coal throughput of nearly 16 million tons annually across four major CFPPs in Peninsular Malaysia. While Malaysia has domestic coal reserves in Kapit, Mukah (Sarawak), and Maliau (Sabah), logistical challenges and high extraction costs mean that Malaysia remains heavily reliant on imported coal, primarily from South Africa, Australia, China, and Indonesia. These imports are more economically viable due to the infrastructure limitations and remote locations of domestic coal deposits [20].

Table 2.1 : Coal-Fired Power Plant (CFPP) in Malaysia [21]

Power plant	Location	Operator	Capacity (MW)	Operation year
Sultan Salahuddin Abdul Aziz Shah Pow	Kapar, Selangor	Kapar Energy Ventures Sdn Bhd	600 (Phase 1)	1987
			1000 (Phase 2)	2001
Sejingkat Power Corporation Plant	Kuching, Sarawak	Sejingkat Power Corporation Sdn Bhd, a subsidiary of Sarawak Energy Berhad	210	1993
Manjung Power Station	Manjung, Perak	Tenaga Nasional Berhad (TNB) Janamanjung Sdn Bhd	2100	2003
			1000	2016
PPLS Power Generation Plant	Kuching, Sarawak	PPLS Power Generation, a subsidiary of Sarawak Energy Berhad	110	2002
Tanjung Bin Power Station	Pontian, Johor	Tanjong Bin Power Sdn Bhd, a subsidiary of Malakoff	2100	2007
			1000	2016
Jimah Power Station	Lukut, Negeri Sembilan	Jimah Energy Ventures Sdn Bhd	1400	2008

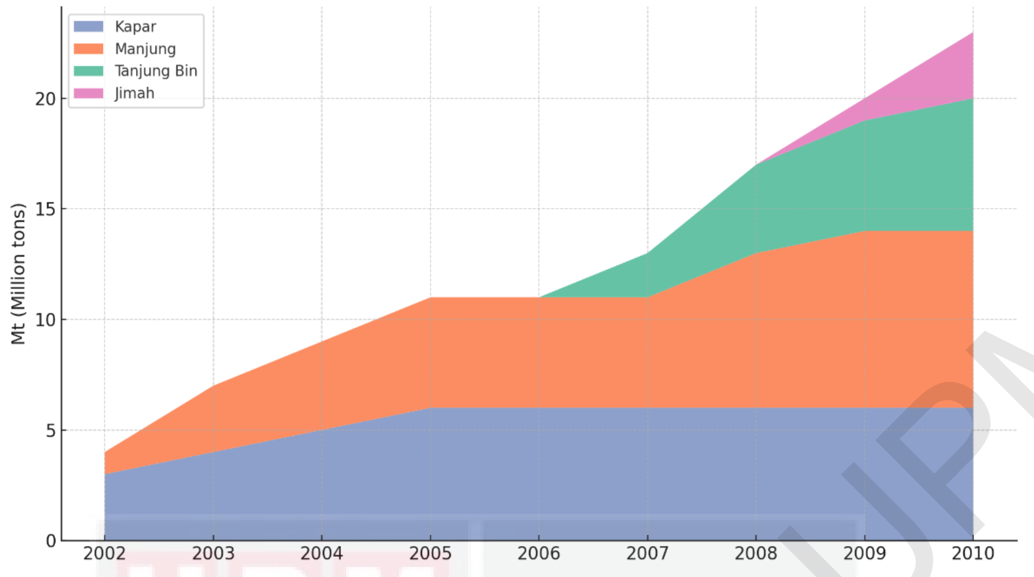

Figure 2.2 : Coal Demand (Million Tonne Per Year) in Peninsular Malaysia [23]

Coal-fired power plants (CFPPs) are widely criticized for their environmental and health impacts. In Malaysia, between 2008 and 2010, a controversial plan to develop a CFPP in Sabah (eastern state of Malaysia) highlighted these concerns. The project, first proposed in 2006 to address frequent blackouts and brownouts, was initially planned for Silam, Lahad Datu, in 2008, but was later relocated several times, including a shift to the Palm Oil Industrial Cluster (POIC) Sandakan in 2009 and then to Felda Sahabat in 2010 [24]. The proposed CFPP faced strong opposition from local communities and non-governmental organizations (NGOs), who raised concerns about air and water pollution and its potential impact on marine ecosystems. They also highlighted health risks, including the potential for birth defects, gene mutations, and an increased incidence of chronic diseases such as cancer and heart disease [25]. The growing demand for electricity, especially for industrial and residential use, has led to increased reliance on alternative energy sources, particularly coal. This shift is partly due to the depletion of petroleum reserves and the global fuel oil crisis. Coal-fired steam power plants generate large amounts of solid waste, including flue gas, slag, fly ash, and other by-products of coal combustion [26]. Fly ash, a byproduct of coal's inorganic material melting during combustion, contains various harmful elements such as arsenic, mercury, and cadmium [27]. The improper disposal of fly ash, which is often accumulated in landfills or industrial sites, poses significant environmental risks. The variability of fly ash composition depends on the type of coal used, though silicon dioxide (SiO_2) and calcium oxide (CaO) are consistently present.

Despite these environmental risks, coal demand in Peninsular Malaysia has continued to rise. Malaysia's electricity generation currently relies on a mix of 33% coal, 58% natural gas, and 9% hydropower. However, with natural gas prices expected to increase, Malaysia is projected to become even more dependent on coal, with forecasts suggesting that by 2019, the energy mix will consist of 64% coal, 32% natural gas, and 4% hydropower. The relatively stable price of coal compared to natural gas makes it an attractive option for controlling electricity generation costs. The expansion of CFPPs, including Manjung and Tanjung Bin, is expected to increase national capacity by 2,000 MW by 2016, leading to an annual coal consumption increase of approximately 25 million tonnes. While this expansion addresses energy demand, it also raises concerns about increased air pollutant emissions, highlighting the energy sector's challenge of balancing growing energy needs with environmental sustainability.

Coal's dominance in electricity generation, particularly in developing countries, is expected to persist due to its abundant reserves. Many regions, including parts of Southeast Asia, will likely continue to rely on coal in the near future [28]. This global reliance on coal has prompted numerous studies on CFPP emissions, with research conducted in countries such as Japan [29, 30], China [31, 32, 33], Poland [34], Korea [35], Spain, the Netherlands, and Taiwan [36]. These studies reflect the growing awareness of coal's environmental and health impacts and the need for comprehensive strategies to mitigate them.

2.3 Energy Security and Coal Dependency

Sustainability has become a central concept in addressing the environmental, economic, and social challenges of the 21st century. It refers to the practice of meeting the needs of the present without compromising the ability of future generations to meet their own needs. Sustainability covers three main pillars: environmental protection, economic viability, and social equity [37] . As the global population continues to grow and natural resources become increasingly strained, the importance of sustainable practices has grown. These practices aim to balance resource consumption with preservation, ensuring that ecosystems can maintain their functions and support human life in the long term. Environmental sustainability focuses on protecting ecosystems and reducing human impacts, particularly through the reduction of carbon emissions, waste, and the overexploitation of natural resources [38].

Key strategies include transitioning from fossil fuels to renewable energy sources and improving energy efficiency. Economic sustainability seeks to support growth and development in ways that do not deplete resources or cause long-term environmental harm. It emphasises innovation in green technologies, sustainable supply chains, and circular economies, where resources are reused and recycled rather than discarded [39]. However, Energy security has become an increasingly important issue as many nations area dealing with growing energy demands, the need to mitigate environmental impacts, and protect human lives. Energy security refers to the availability of reliable, affordable, and sustainable energy sources, essential for economic stability, national security, and the functioning of modern societies [40]. Traditionally, it focused on ensuring uninterrupted access to fossil fuels such as oil, coal, and natural gas. As the risks associated with fossil fuel dependency—including price volatility, geopolitical tensions, and environmental degradation—have become more pronounced, the focus has shifted toward diversifying energy sources and incorporating renewable energy into national strategies [41]. In the context of sustainability, energy security is increasingly linked to the transition from carbon-intensive fossil fuels to renewable energy sources like wind, solar, and hydropower. Renewable energy contributes to reducing greenhouse gas emissions while providing countries with more decentralized and resilient energy systems.

This transition is seen as vital not only for mitigating climate change but also for enhancing energy security by reducing reliance on unstable fossil fuel markets [42] The shift to renewable energy also aligns with the goals of the Paris Agreement, which underscores the need for sustainable, low-carbon development to limit global temperature rise [43]. Another crucial aspect of energy security is improving energy efficiency, mainly by enhancing the efficiency of energy use in industrial, transportation, and residential sectors, countries can reduce overall energy demand, extend the life of existing energy resources, and lower emissions. Advances in energy storage technologies and smart grid systems are also key to managing the intermittent nature of renewable energy, ensuring a stable and reliable energy supply [44]. Despite the growing emphasis on renewable energy and sustainability, the world remains heavily dependent on coal as a primary energy source. Coal continues to play a significant role in global energy production, particularly in electricity generation and industrial processes such as steel and cement manufacturing [18].

For instance, in 2020, coal accounted for nearly 27% of the world's primary energy consumption and approximately 36% of global electricity generation [45]. This reliance is particularly prominent in countries with rapidly growing economies, such as China and India, where coal provides a significant portion of energy due to its relative affordability and abundance [46]. By looking to south east Asia, Coal dependency remains a significant issue in Malaysia despite global trends toward renewable energy adoption. In Malaysia, coal continues to play a crucial role in the energy mix, accounting for approximately 45% of the country's electricity generation [47]. The country's reliance on imported coal, particularly from Indonesia and Australia, highlight its dependency on this fossil fuel to meet growing energy demands driven by industrialization and economic development [28].

While the Malaysian government has set renewable energy targets, coal remains an attractive option due to its affordability and reliability. This situation mirrors larger trends across Southeast Asia as it does not exclusively represent Malaysia, where countries like Indonesia, Vietnam, and the Philippines are also heavily dependent on coal for energy production, with coal contributing significantly to electricity generation across the region [18]. In fact, coal-fired power plants (CFPPs) present significant environmental and policy challenges, particularly in coal-reliant nations like Malaysia. One of the most critical environmental issues associated with CFPPs is their substantial contribution to greenhouse gas emissions. Coal is among the most carbon-intensive energy sources, and CFPPs produce large amounts of CO_2, along with harmful pollutants, which contribute to air pollution and respiratory diseases [10].

From a policy standpoint, governments face complex challenges in addressing the environmental impact of CFPPs while ensuring energy security and economic development. In Malaysia, where coal remains economically important for affordable and reliable energy, transitioning away from coal requires significant investments in renewable energy infrastructure, which poses financial and logistical barriers [48]. Policymakers must balance these trade-offs, weighing the short-term economic benefits of coal against the long-term environmental risks. Measures such as carbon pricing, stricter emissions regulations, and incentives for clean energy adoption are crucial, but they often encounter resistance from industries and communities dependent on coal [28]. Moreover, aligning national energy policies with international climate commitments, such as the Paris Agreement, adds further complexity as governments attempt to reduce emissions while supporting economic growth [18].

2.4 Environmental Impacts of Coal-Fired Power Plants

Coal-fired power plants (CFPPs) are among the largest contributors to air pollution Figure 2.3, emitting significant amounts of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM). These pollutants are responsible for degrading air quality, contributing to the formation of smog and acid rain, and causing adverse health effects, including respiratory and cardiovascular diseases [49]. Particulate matter, especially PM2.5, is of particular concern due to its ability to penetrate deep into the lungs, leading to long-term health issues such as lung cancer and chronic obstructive pulmonary disease (COPD) [50]. Additionally, CFPPs are major contributors to climate change through the emission of large amounts of carbon dioxide (CO_2), which intensifies global warming. Studies show that coal combustion for energy is responsible for a substantial portion of global CO_2 emissions, complicating efforts to meet international climate targets, such as those outlined in the Paris Agreement [18].

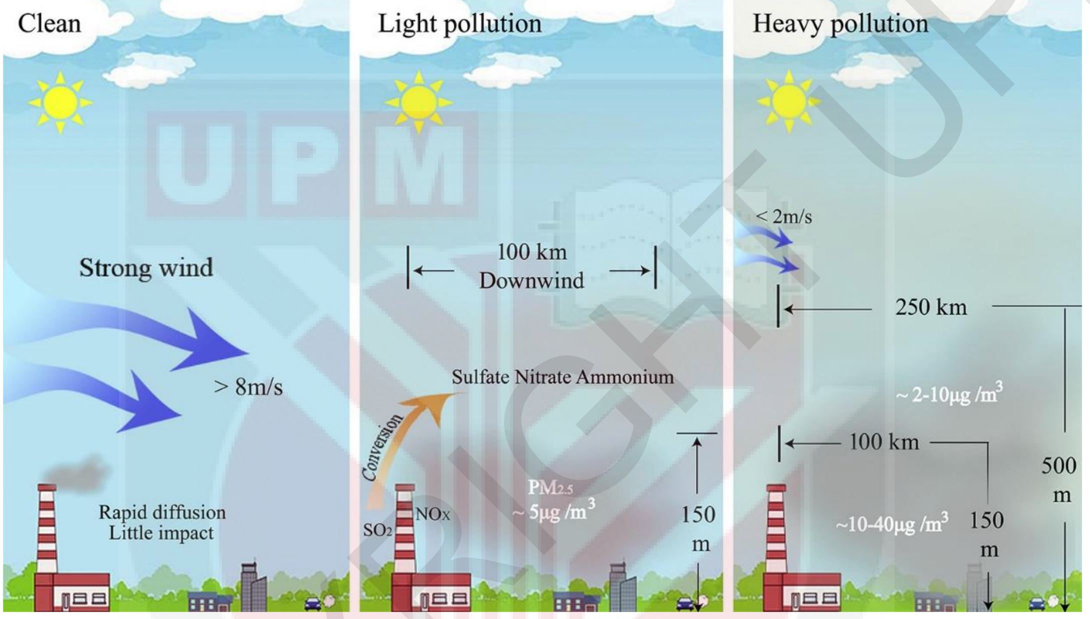

Figure 2.3 : The Dispersion and Concentration of Air Pollutants from Coal-Fired Power Plants [50]

Environmental degradation extends beyond air pollution, with coal mining and the operation of CFPPs having detrimental effects on local ecosystems and biodiversity. The destruction of habitats through mining and the release of pollutants into the atmosphere and water bodies disrupt ecosystems, leading to loss of biodiversity [51]. Furthermore, CFPPs are known for their high-water consumption, requiring large volumes of water for cooling and steam production. Coal-fired power plants are also major contributors to climate change due to the large amounts of carbon dioxide (CO_2) they emit. According to the International Energy Agency [18], coal combustion accounts for a significant share of global CO_2 emissions, with CFPPs being responsible for around 30% of total emissions from energy production. This reliance on coal for energy complicates international efforts to reduce greenhouse gas emissions and achieve climate targets, such as those outlined in the Paris Agreement, which aims to limit global warming to 1.5°C above pre-industrial levels [52]. An analysis of the potential environmental impact associated with modifying Malaysia's fuel mix, as presented in Table 2.2 by Jafar et al [25], suggests a projected increase in CO_2, SO_2, and NO_x emissions by 2020. This rise is attributed to the anticipated growth in coal burning for electricity generation. Additionally, Shekarchian et al [53], stated that high coal usage accounted for 56% of total emissions (CO, CO_2, SO_2, and NOx) from electricity generation in Malaysia in 2008.

Table 2.2 : Change in Fuel Use as Aimed in Fuel Diversification Strategy [54]

Fuel	**Percentage (%) of fuel use**	
	Year 2000	Year 2020
Gas	74.9	40
Coal	9.7	29
Hydro	10.4	30
Petroleum	5	1

In addition to SO_2, NOx, CO_2, and CO emissions, CFPP produces toxic and hazardous heavy metals, dioxins, hydrogen fluoride (HF) and hydrogen chloride (HCl)[55, 56]. In recognition of the environmental concerns associated with CFPPs, Malaysia categorizes their development as a 'Prescribed Activity' under the Environmental Quality (Prescribed Activities) (Environmental Impact Assessment) Order 1987. This regulation mandates a Detailed Environmental Impact Assessment (DEIA) study prior to any CFPP development. Additionally, emissions from operational CFPPs must comply with the stringent limitations established in the Environmental Quality (Clean

Air) Regulations. Emission limits for CFPP in Malaysia were initially based on the Environmental Quality (Clean Air) Regulations 1978 for fuel-burning equipment, which only specifies 400 mg/Nm^3 for particulate matter (PM). Kapar Power Plant (the first CFPP in Malaysia) installed only an electrostatic precipitator (ESP) as an air pollution control system to meet the PM limit. In 2005, the Department of Environment (DOE) Malaysia implemented a revised Environmental Quality (Clean Air) Regulation, superseding the 1978 version. This update (hereafter referred to as the 2014 Regulations) mandated stricter emission limits for CFPPs in Malaysia, as detailed in Table 2.3. Notably, the (Clean Air) Regulations 2014 introduced limitations for a broader range of pollutants compared to the previous version, including Hg, dioxins/furans, NO_2, HF, SO_2, HCl, and CO.

Table 2.3 : Emission Limits for Coal-Fired Power Plant (CFPP) as Stipulated in the Environmental Quality (Clean Air) Regulations 2014

Fuel type	Pollutant	Capacity	Limit value
Solid and liquid fuels	Sum of SO_2 and SO_3 expressed as SO_2	> 10 MWe	500 mg/Nm^3
	Sum of NO and NO_2 expressed as NO_2	> 10 MWe	500 mg/Nm^3
	Hydrogen chloride (HCl)	> 10 - < 100 MWe	200 mg/Nm^3
	Hydrogen chloride (HCl)	≥ 100 MWe	100 mg/Nm^3
	Hydrogen fluoride (HF)	> 10 - < 100 MWe	30 mg/Nm^3
	Hydrogen fluoride (HF)	≥ 100 MWe	15 mg/Nm^3
	Carbon monoxide (CO)	> 10 MWe	200 mg/Nm^3
	Total particulate matter (PM)	> 10 MWe	50 mg/Nm^3
	Mercury (Hg)	> 10 MWe	0.03 mg/Nm^3
	Dioxin/furan (PCDD/PCDF)	> 10 MWe	0.1 ng TEQ/Nm^3

Note: Emission limit at standard conditions for temperature and pressure for dry gas (volume at 273K, 101.3 kPa), O2 reference content at 6%.

When Malaysia's new emission limits are compared to emission limits from other countries (Table 2.4), the new emission limits are less stringent. However, the new SO_2 and NO_2 limits of 500 mg/Nm^3 are still far too high compared to other countries.

Other countries, such as the European Union (EU), China, the United States and Japan, impose stringent limits due to their coal dependence, which can reach 78% in China [57], resulting in the existence of numerous CFPPs in their respective countries. On the other hand, Malaysia has a diverse energy mix that includes natural gas, coal, and hydro.

Table 2.4 : Emission Limits and Emissions from Best Performing Coal-Fired Power Plants from Other Countries

Pollutant	European Union (EU)	United States	China	Japan
Sulphur dioxide (SO_2) mg/Nm^3	[a]Existing plants 130 (annual average) 205 (daily average) New plant 75 (annual average) 110 (daily average)	[a]50 – 60 (new units) 22 (new plants)	[a]Existing plants 50 (hourly average) New plant 35 (hourly average)	[a]30 – 35 (annual average)
Nitrogen oxides (NOx) mg/Nm^3	[a]150	45 – 70[a*]	[a]Existing plants 100 (hourly average) New plant 50 (hourly average)	[a]60 – 70 (annual average) 40 (new plants)
Particulate matter (PM) mg/Nm^3	[a]16 (large existing plants) 10 (new plants)	N. A	5[a*]	4 – 5[a*]
Mercury (Hg) mg/Nm^3	[a]0.004 (existing plants) 0.002 (new plants)	[a]0.0015 (existing plants) 0.0005 (new plants)	[b]0.03	N. A

Note:
[a]Myllyvirta et al. [57]
[b]Ancora et al. [58]
*Emissions data from best performing coal-fired power plants
N.A – not available

Several studies [59, 60, 61] have stated that CFPP emitted many air pollutants and greenhouse gases including SO_2, NO_X, PM_{10}, $PM_{2.5}$, and CO. CFPP also release other pollutants, including heavy metal (lead, cadmium, mercury, and nickel), dioxins and radioactive wastes such as uranium and thorium. The dispersion of air pollutants can span vast distances, potentially impacting air quality in regions hundreds of kilometres away from the CFPP across the area, depending on their physical and chemical properties. Some pollutants will also have a long lifetime, which could stay for days and weeks in the ambient. All these gases give bad impacts not only to the Mother Nature but also to human health.

2.4.1 Carbon Monoxide (CO)

When coal is not burnt completely inside the CFPP, carbon monoxide (CO) will form. Fortunately, CO emissions from CFPP are generally low especially when the CFPP is equipped with good combustion control [62]. CO potentially forms during system start-up and upsets. The same book also explained that CO does not have detrimental effects to environment as only minor involvement in photochemical reactions which will form ozone. However, CO poses a significant health risk due to its detrimental physiological and pathological effects at high concentrations. In severe cases, CO exposure can be fatal. The U.S. Environmental Protection Agency (USEPA) [57] highlights that CO inhalation allows it to enter the bloodstream, subsequently hindering oxygen delivery to vital organs and tissues. This poses a severe health risk, particularly for individuals suffering from cardiovascular diseases like angina pectoris. Furthermore, CO exposure can manifest in various adverse effects, including reduced manual dexterity, diminished work capacity, hindered learning, visual impairment and cognitive abilities.

2.4.2 Sulfur Dioxide (SO2)

CFPP too emits a large amount of sulfur dioxide (SO_2). From 2008 to 2014, statistics emissions inventory for IPPs in Peninsular Malaysia had shown that the amount of

SO_2 emissions have increased about 70%, and are expected to continually increase as shown in Table 2.5. Awang, et al.[63] deduced that other than emissions of unburnt hydrocarbons from mother vehicles, electric power generation is equally serious as the main source of SO_2 emissions in Prai, Pasir Gudang and Johor Bahru. Inhaling SO_2 has an acute effect on human body as SO_2 will dissolve into sulphite and bisulphite in the aqueous surfaces of the respiratory system as mentioned in Alberta Environment Report Paper [64]. Sulphite affects the metabolic process and body's immune system.

Table 2.5 : Emission inventory for Coal Power Plants in Peninsular Malaysia from 2008 to 2014 [65]

Year	Coal power plants (metrics ton per year					
	SO_2	NO_x	PM_{10}	$PM_{2.5}$	CO	CO_2
2008	52 163	19 720	1 272	573	9 542	6 113 273
2009	58 233	22 015	1 420	639	10 652	6 824 615
2010	76 952	29 092	1 877	845	14 077	9 018 423
2011	84 936	32 110	2 072	932	15 537	9 954 041
2012	90 109	34 066	2 198	989	16 483	10 560 342
2013	87 364	33 028	2 131	959	15 981	10 238 676
2014	90 160	34 085	2 199	990	16 493	10 566 253

2.4.3 Nitrogen Oxide (NOX)

Other than CO_2 and SO_2, CFPP also releases nitrogen oxide (NO_x) including nitrogen dioxide (NO_2). A typical CFPP with emission controls, emits 3.300 tons of NO_X per year. Emission inventory analysis also shows increment of NO_X emissions from 19.720 metric tons per year in 2008 to 34.085 metric tons per year in 2014 [59]. Inhaling nitrogen dioxide (NO2) can harm human health, causing both immediate and long-lasting problems. Short-term exposure to high concentrations of NO_2 can induce severe pulmonary complications in individuals with otherwise healthy respiratory systems. Individuals with pre-existing chronic lung disease and the elderly population are particularly subjected to the detrimental consequences of NO_2 exposure, experiencing short-term responses like altered lung function and airway hyperresponsiveness. Furthermore, NO_2 exposure can also impair sensory function, potentially reducing an individual's olfactory capacity.

2.4.4 Particulate Matters

Particulate matters (PM) are also associated with CFPP emissions. The definition of PM is suspension of solid and liquid particles dispersed within a gaseous medium (typically air). Coal combustion releases particulate matter 10 (PM_{10}) which the diameter is larger than 2.5μm but smaller than 10μm. The maximum amount of air pollution that can be present in ambient air is known as the Threshold Limit Value (NAV). 150 g/m^3 is the NAV PM_{10} value. PM_{10} (particulate matter with a diameter of 10 micrometres or less) encompasses a diverse range of airborne particles, including metals, salts, acids, dust, smoke, and soot. Indirect formation of particles is also possible when gases from industries and motor vehicles react chemically in the environment. PM scatters and absorbs light which can cause visibility impairment and lead to haze. The PM_{10} exposure impacts are cardiopulmonary-related mortality, decreased paediatric lung function development, reduction in life expectancy, lung cancer, asthma, pneumonia, and bronchitis [66, 67].

2.5 Health Impacts of Coal-Fired Power Plants

Coal-fired power plants (CFPPs) are a major source of air pollutants that pose significant risks to public health. The pollutants released during coal combustion, including sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM2.5), and heavy metals like mercury, arsenic, and lead, are known to cause severe health impacts, particularly in vulnerable populations such as children, the elderly, and those with pre-existing health conditions. These pollutants contribute to respiratory and cardiovascular diseases and have been linked to an increase in mortality and morbidity in regions near CFPPs [56]. Particulate matter, especially fine particles smaller than 2.5 microns (PM2.5), is of primary concern due to its ability to penetrate deep into the lungs and enter the bloodstream. Long-term exposure to PM2.5 has been associated with a wide range of health issues, including chronic obstructive pulmonary disease, asthma, lung cancer, and cardiovascular diseases such as heart attacks and strokes [68]. Recent studies confirm that elevated exposure to PM2.5 from CFPP emissions is correlated with increased hospital admissions for respiratory and cardiovascular diseases. A 2020 study in China demonstrated that communities living near CFPPs had a significantly higher incidence of lung cancer and heart disease compared to those living further away [68]. Similarly, a study conducted in the United States showed that long-term exposure to PM2.5 from coal power plants was linked to increased mortality from respiratory conditions [69].

The adverse effects of SO_2 and NO_x emissions are also well documented. When inhaled, these gases can irritate the respiratory system, causing inflammation and exacerbating conditions like asthma and bronchitis. SO_2 and NO_x can also contribute to the formation of secondary particulate matter and ground-level ozone, which further degrades air quality and worsens health outcomes. Ground-level ozone, a key component of smog, is particularly dangerous for individuals with asthma, as it can trigger asthma attacks and reduce lung function [67]. Vulnerable populations, including children, the elderly, and individuals with pre-existing health conditions, are disproportionately affected by the pollutants emitted from CFPPs. Children are especially susceptible because their respiratory systems are still developing, and they breathe in more air per unit of body weight than adults. This increases their exposure to airborne pollutants and makes them more vulnerable to respiratory infections and asthma [70]. A recent study in India revealed that children living near coal power plants had significantly higher rates of respiratory illnesses, such as asthma and bronchitis, compared to those living in areas with cleaner air [70]. Additionally, older adults are more likely to suffer from heart and lung diseases, making them particularly sensitive to the harmful effects of air pollution from CFPPs.

However, Malaysia is not immune to the global trends linking CFPP emissions to adverse health outcomes. Several studies have demonstrated that air pollution from CFPPs is a significant public health concern. For instance, a 2021 study conducted in the Klang Valley region, where several CFPPs operate, found that the number of hospital admissions for respiratory and cardiovascular diseases increased significantly during periods of high pollution from these plants [71]. The study demonstrated a strong correlation between air pollution levels and the prevalence of respiratory conditions such as asthma and COPD, particularly among older adults and children. Another study conducted in 2020, highlights the main contributors to air pollution, including industrialisation and fossil fuel combustion, and examines how these pollutants affect cardiovascular and respiratory health. Key findings align with the previous study and include the strong correlation between air pollution and increased rates of hospital admissions for cardiovascular diseases, asthma, and respiratory infections. The review also discusses the economic burden of health issues caused by air pollution and emphasizes the need for stricter air quality monitoring and public health interventions [72]. These local studies align with global research, reinforcing the idea that proximity to coal-fired power plants increases exposure to harmful pollutants and, consequently, elevates the risk of severe health conditions. The health impacts of CFPP emissions are not only localised but are also a nationwide concern, particularly as Malaysia continues to rely on coal for electricity generation.

2.6 Air Pollution Emission Standard in Malaysia

Malaysia has advanced toward becoming an industrialized country as the year 2020 approaches. According to that determination, Malaysia's air quality is a major concern. Air pollution stems from a diverse array of natural sources and anthropogenic such as power plants, factories, commercial activities like emissions from vehicles, windblown dust particles, dry cleaners, and uncontrolled wildfires [73, 5]. Among environmental threats, air pollution is now considered the biggest driver of premature deaths, with an estimated global impact of seven million fatalities annually. In addition, air pollution exposure significantly contributes to the development and exacerbation of long-term health conditions, including heart disease, cancer, lung disease and asthma [74]. Fossil fuel combustion in various sectors for instance transportations, households, and industry, as well as uncontrolled wildfire and dust, are the primary sources of air pollution in Malaysia [47].

According to WHO [74], air pollution in Malaysia represents a critical public health concern, accounting for one out of every nine deaths. Since air pollution is one of the main elements affecting people's quality of life, this is a matter of great concern that needs to be addressed immediately by all relevant agencies globally. Among air pollution causes in Malaysia include industrial operations (stationary sources), cross-border pollution from neighbouring countries, and increased mobility (mobile sources). These factors are making air pollution a significant environmental problem in the country. Exposure to air pollution in the atmosphere can trigger acute or chronic health problems in humans and other living things, while also degrading the natural and built environment. Respiratory problems, such as irritation and difficulty breathing, alongside headaches, fatigue, dizziness, and skin issues, are all potential consequences of poor air quality [75].

For the past few decades, the main challenge for environmental issues has been air pollution caused by anthropogenic activities and natural disasters. The interplay between anthropogenic activities and population expansion shapes the overall composition of the atmosphere and the atmosphere-damaged earth. International efforts to address climate change in Southeast Asia (SEA) face a significant hurdle due to the repeated occurrence of natural disasters such as floods and tsunamis. Transboundary haze has plagued SEA as a major environmental concern since 1983. Air pollution caused by fires that spread across borders negatively impacts the environment because of greenhouse gas (GHG) emissions, ecosystems, and biodiversity, which have contributed to climate change in recent decades [76].

In April 1983, haze first appeared in Malaysia. As the source of the haze remained unknown, several possibilities were considered, including open burning agriculture in neighbouring countries, smoke particles from massive forest fires, floating ash from volcanic eruptions and local agricultural burning. From June to October 1991, haze pollution disrupted daily life in August 1990. Since 1992, this phenomenon has occurred every year in August to October. Prior to 1997, the cause of Southeast Asia's recurring haze remained elusive. That year, however, fires originating from forests and farms in South Sumatra, Kalimantan, and other Indonesian islands were confirmed as the culprit, prompting efforts towards regional solutions. This suggests that from August to November of that year when the surrounding environment becomes hazy due to pollution [77].

While SEA experienced several severe smoke haze episodes since 1983, most notably in April 1983, August 1990, June 1991, October 1991, and August 1994, the most catastrophic event occurred in 1997, shrouding the entire region in thick smoke for nearly half a year [77]. Malaysia's experience with severe transboundary haze episodes in Southeast Asia, particularly those of 1983, 1984, 1991, 1994, and 1997, served as a catalyst for improved air quality management. This resulted in heightened environmental awareness and the establishment of key measures like the Malaysian Air Quality Guidelines, Air Pollution Index, and National Haze Action Plan. Air quality monitoring, a crucial element of this strategy, allows for proactive measures to be taken during periods of increased pollution [58].

Air pollution is a significant environmental health risk for humans, particularly children. Exposure to it is associated with the development of chronic obstructive pulmonary disease in children under five and lung cancer in adults. Pneumonia, a form of acute lower respiratory tract infection, is a significant global health threat, responsible for more than 2 million deaths in young children annually [51]. Air pollution has adverse effect on the environment and humans caused by the intensity of solids, liquids, or gases in the air. A multitude of pollutants exist, originating naturally (dust, wildfires, volcanoes) or through human actions. These contaminants encompass both visible and invisible forms, with some possessing noticeable Odors while others remain undetectable. Air pollution comes in many forms, some lasting just minutes, others lingering for years. These pollutants can affect a small area, an entire country, a whole region, or even the entire planet. They can be directly released from human activities or natural processes. [78]. In contrast, secondary pollutants result from reactions between sunlight, atmospheric components, and primary pollutants. Human-caused air pollutants include the following:

- Sulfur oxides (SOx), specifically sulfur dioxide (SO_2): Sulfur is present in varying degrees in fossil fuels, coal, and oil, and are released into the air when fuels are burned, like in power plants or factories, unless they are captured beforehand. Without proper treatment or capture, SOx emissions pollute the air. These emissions are known to harm human health and the environment, and they can also contribute to the formation of harmful fine particles.

- NO_2 (nitrogen dioxide), NO_X (nitrogen oxides), and NO (nitric oxide): NO_X is produced by High-intensity burning, primarily in transportation and power generation, or by the oxidation of NO_2 in the atmosphere. NO_2 is a toxic gas that can cause particulate matter and ozone formation.

- Particulate matter (PM) is a mixture of organic and inorganic solids and liquids that can be a primary or secondary pollutant. PM has been linked to severe health consequences. Size plays a vital role in determining these effects: - "Coarse particles" have a diameter of 2.5 to 10 micrometres (m), while "fine particles" have a diameter of less than 2.5 μm. The health effects of PM_{10} are less severe than those of fine particles; however, there is a long history of data on PM_{10}, and many cities still lack the equipment to monitor outdoor $PM_{2.5}$ concentrations. Black carbon, a type of fine PM, is produced by the incomplete combustion of fossil fuels and bioenergy, and it is a short-lived climate pollutant.

- Carbon monoxide (CO) is a colourless, odourless, toxic gas produced by the incomplete combustion of gasoline, natural gas, coal, or wood.

- Volatile organic compounds (VOCs) are released into the environment as they evaporate or sublimate from chemicals, solvents, or fuels (as well as natural sources); they are linked to various adverse health effects. For example, methane (CH4), the main component of natural gas (also an SLCP), is frequently considered separately from other VOCs due to its distinct properties.

- Ammonia (NH3) is produced as a byproduct of agricultural and waste management activities; once in the atmosphere, ammonia reacts with nitrogen and sulfur oxides to form secondary particles.
- In the presence of sunlight, NO_X and VOCs combine to form ground-level ozone (O_3). Ozone is a pollutant and an SLCP at high concentrations.

Other pollutants include heavy metals such as lead, which is emitted by industry, power generation, waste incineration, and in some countries transportation fuels, as well as mercury, which is primarily emitted by coal combustion. Several pollutant-caused diseases and effects can be found in the environment, over 384 harmful gases have been identified [79]. However, six of these gases, known as "common air pollutants" or “criteria air pollutants,” are the most dangerous: CO, NO, ground level O, SO, particulate matter (PM), and lead. Various authorities and institutes worldwide have published several clean air quality standards. The concentrations of common air pollutants in WHO standards and in Malaysia are shown in Table 2.6 and Table 2.7.

Table 2.6 : WHO Air Quality Guidelines (Adapted from WHO, [74])

Pollutant	Concentration ppm mg/m^3		Exposure Measured as
CO	10.0	10	8 hour mean
NO_2	0.1	0.20	1 hour mean
O_3	0.06	0.12	8 hour mean
SO_2	0.06	0.17	24 hour mean

The Malaysian Department of Environment (DoE) has established the Malaysian Ambient Air Quality Guidelines (MAAQG) to ensure the air quality in Malaysia. The MAAQGC is shown in Table 2.7.

Table 2.7 : Malaysian Ambient Air Quality Guideline (Adapted from [66])

Pollutant	**Averaging time (hour)**	**Malaysian guideline (mg/m^3)**
SO_2	1	0.35
NO_2	1	0.320
CO	1	35
PM_{10}	24	0.15 (API=100)

2.7 Air Pollution Modelling

Air pollution modeling is a systematic approach that utilizes mathematical and computational techniques to simulate the physical and chemical processes affecting air pollutants as they disperse, react, and transform in the atmosphere. This modeling is essential for understanding how pollutants behave under varying conditions, such as different emission rates and meteorological factors. According to recent studies, air quality models can effectively characterize both primary pollutants—those emitted directly into the atmosphere—and secondary pollutants formed through complex atmospheric reactions [80]. The primary types of air quality models include dispersion models, which estimate pollutant concentrations at specific locations surrounding emission sources; photochemical models, which simulate the impacts of multiple sources over larger spatial areas; and receptor models, which analyze observed data to identify source contributions to air quality problems. For example, the Community Multiscale Air Quality (CMAQ) model is widely used for regulatory assessments, allowing for the evaluation of pollutant impacts across different scales and informing policy decisions aimed at achieving National Ambient Air Quality Standards (NAAQS) [81].

Recent advancements have also incorporated machine learning techniques to improve predictive accuracy in forecasting air quality indices (AQI) and pollutant concentrations, demonstrating significant potential for enhancing model reliability [82] . These models play a significant role in regulatory compliance by helping agencies ensure that new projects meet NAAQS and by allowing for the assessment of existing regulations' effectiveness. By simulating future pollutant concentrations from multiple sources, air pollution modeling assists in estimating the potential impacts of new regulatory programs on public health and environmental quality. Thus, continuous refinement of these models is crucial for effective air quality management and public health protection.

2.7.1 Model Selection

In this study, the Gaussian Plume Dispersion Model is chosen after considering several factors. The Gaussian plume model uses a realistic representation of dispersion, where it describes an analytical solution to the diffusion equation for idealized circumstances [83]. Point out that Gaussian dispersion model is the most widely used dispersion model, well understood, easy application, and produces reliable results [84, 85, 86, 87, 88, 83]. This is due to the extremely fast response because only a single formula is used instead of solving multiple different equations [85]. The formula is shown in equation (1) . In the context of this study which is CFPP's pollutant emissions, the Gaussian Plume Modelling is most used to model the pollutants emissions [79, 89, 90, 91, 92]. The Gaussian Plume Dispersion formula is:

$$\mathbf{C(x,y,z)} = \frac{\mathbf{Q}}{\mathbf{2\pi\sigma_y\sigma_z u}}(\mathbf{e}^{-\frac{\mathbf{y^2}}{\mathbf{2\sigma_y^2}}})(\mathbf{e}^{\frac{\mathbf{-(z-H)^2}}{\mathbf{2\sigma_z^2}}} + \mathbf{e}^{\frac{\mathbf{-(z+H)^2}}{\mathbf{2\sigma_z^2}}}) \qquad \textit{(1)}$$

Where:

C(x, y, z)	=	mean concentration of diffusing substance at a point (x,y,z) (kg/m^3)
X	=	downwind distance (m)
Y	=	crosswind distance (m)
Z	=	vertical distance above ground (m)
Q	=	contaminant emission rate (kg/s)
σ_y	=	lateral dispersion coefficient function (m)
σ_z	=	vertical dispersion coefficient function (m)
U	=	mean wind velocity in downwind direction (m/s)
H	=	Effective height (m)

The Gaussian plume formula is derived by assuming steady state conditions [93, 88] which is independent of time. According to Koracin [94], steady state conditions are the assumption of unchanged meteorological conditions over time from source to receptor. Emissions and meteorological conditions can change from time to time; hence the model calculations are designed to calculate for the respective time condition but independent of other time. Hence, the steady state models would stimulate hourly-average concentration, based on the parameters used. Gaussian models are also based on the assumption of continuous emission which is applicable in this study. Next assumption for the Gaussian Plume Model is mass conservation which means that during the transport of pollutants from source to receiving environment, the mass that emitted from the source is assumed to remain constant in the ambient. Lastly, the assumption is made based on the crosswind and vertical concentration distributions. It is assumed that the horizontal (perpendicular to the path of transport (downwind) concentration profiles are well presented by the Gaussian Model and similarly to the concentration profiles in vertical direction (perpendicular to the downwind direction). The coordinate system of Gaussian distribution is shown in Figure 2.4.

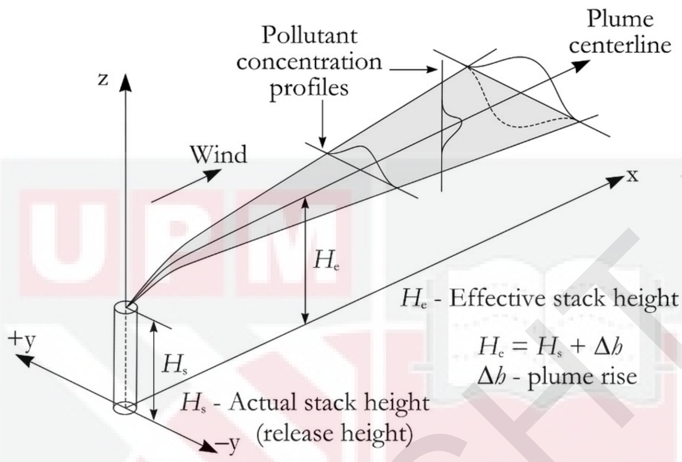

Figure 2.4 : Gaussian Plume Distribution Coordinate System [13]

where;

x = air pollutant concentration in mass per volume (kg/m^3)

x = downwind distance (m)

y = crosswind distance (m)

z = vertical distance above ground or to the downwind direction (m)

Hs=Actual stack height

He= Effective height of the centreline of the pollutant plume.

Abdel-Rahman [95] describes that the Gaussian model integrates meteorological, terrain, physical and chemical characteristics of the effluent and source design to simulate the formation and transport of pollutant plumes. He also emphasized that meteorological data such as wind direction, wind speed and vertical temperature structure of the local atmosphere highly affect the Gaussian model. Vertical temperature structure of local atmosphere consists of four layers: (i) troposphere (near to the earth surface); (ii) stratosphere (ozone layer); (iii) mesosphere (colder and lower density layer with roughly 0.1% of the atmosphere and (iv) thermosphere (top layer with thin hot air).

This vertical temperature structure also indicates that temperature decreases with height because the sun's energy is constantly absorbed by the ground which makes the troposphere gain heat from the ground rather than from the sun directly. Next, as height increases, air pressure also decreases and as air rises into areas of lower pressure, hot air from lower level will expand and release their energy to move apart from each other. Hot air also will continually rise upward as it is less dense compared to cold air and eventually will lose its energy. Therefore, if the rate of temperature decreases with height higher than the adiabatic lapse rate (atmosphere is in unstable equilibrium) it will enhance vertical motions.

This scenario will lead to moderate pollution concentration or weakness at ground level as the pollutants are dispersed. In contrast, if the rate of temperature decreases with height lower than adiabatic lapse rate (stable atmosphere) or inversion layer (warm temperatures above surface due to temperature increase with height) will lead to damped or reduced vertical motions. This will cause high pollution concentration at ground level and increase the risk of health impact on the local population.

In addition, Gaussian plume models are ideal for this study because the terrain of southern-west of Johor and the dispersions are not complex as illustrated in Figure 2.5.

These models also are very convenient to use due to their common features. Ministry for the Environment, New Zealand [105] describes that these models do not require significant computer resources as they can be run on any desktop PC. Next, they are widely used and well-developed knowledge, hence the findings can easily be compared between different studies. Therefore, Gaussian plume is selected to predict the pollutants emissions from the CFPP.

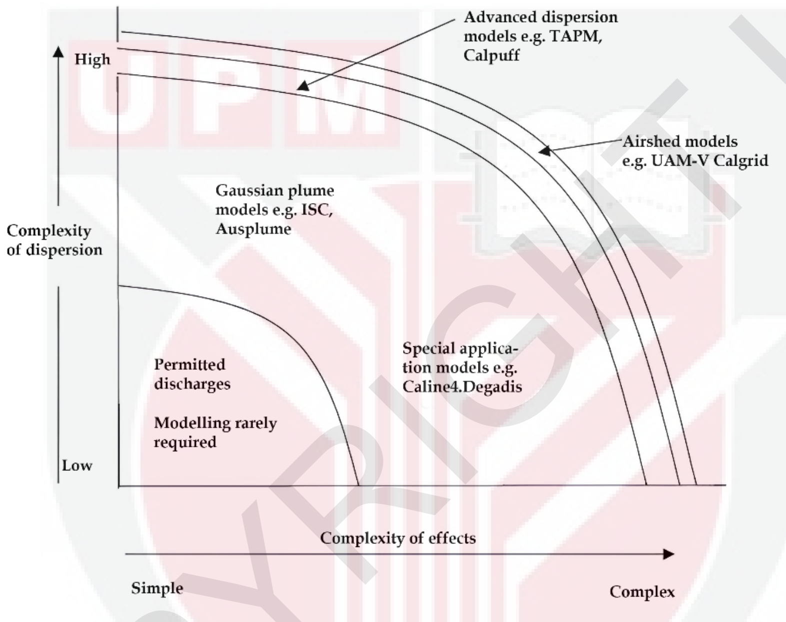

Figure 2.5 : Type of Model Typically Applied according to the Complexity of the Dispersions [105]

2.7.2 Atmospheric Dispersion Modelling System

Atmospheric Dispersion Modelling System is a simulation software to represent the air dispersion models. Simulation modelling is important as it estimates or predicts the real scenarios problems safely and efficiently. It also provides an important analysis or prediction that is easily verified and understood. The software also helps researchers save time and get more accurate data analysis compared to manual modelling techniques. There are a few software options to be used in this study such as American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD), CALINE3, Offshore and coastal dispersion model (OCD), Atmospheric Dispersion Modelling System (ADMS 3), Industrial Source Complex (ISC3), Shoreline Dispersion Model (SDM), AERO-Pollution model (AEROLPOL), Air Quality Dispersion Modelling (DISPMOD) [110] and Areal Locations of Hazardous Atmospheres (ALOHA).

All these systems are using Gaussian dispersion modelling for stable atmospheric conditions. AERMOD is the most widely used tool for simulating air dispersion. Based on the literature review conducted for this study, several researchers have selected AERMOD as their preferred simulation system. This model accounts for the atmospheric boundary layer turbulence structure, handles multiple ground-level and elevated sources, and is suitable for both rural and urban terrains.

Meanwhile, CALINE3 is used to determine pollution concentrations downwind of highways, and OCD is designed to model the impact of offshore emissions, primarily hydrocarbon releases. ADMS is an advanced dispersion model used to calculate pollutant concentrations from continuous or discrete point sources, while ISC3 is suitable for modeling pollutants in industrial complexes. AEROPOL, developed in Estonia, is designed to simulate plume depletion due to wet or dry deposition, as well as the effects of buildings. Lastly, DISPMOD is specifically designed to simulate plume fumigation, which occurs when a pollution plume intersects a growing thermal internal boundary layer (TIBL).

2.7.3 Dispersion Modelling System Selection

Despite all these features, ALOHA has been chosen as the tools to conduct the study due to several reasons. ALOHA is a hazard model software developed as Computer-Aided Management of Emergency Operations (CAMEO) to analyze and simulate accidental and heavy gas releases. This simulation model was jointly developed by organizations including the United States Environmental Protection Agency (USEPA), Chemical Emergency Preparedness and Prevention Office (CEPPO) and National Oceanic and Atmospheric Administration Office of Response and Restoration (NOAA) [111]. ALOHA has been widely used in evaluating toxic chemical releases, short term and long-term dispersion analysis and comparison studies for different types of modelling, chemicals, and scenarios [111–114]. several research found that ALOHA has provided several advantages like easy-to-use for powerful decision-making strategy and pollution statistics for a chosen region which will help potential worst-case scenarios. The model dispersion is a free application and recommended by the USEPA as a tool for the assessment of toxic cloud threat zones.

This model stands out for its ability to simulate the spread of over 900 chemicals quickly and easily. This makes it a powerful tool for predicting and responding to emergencies involving air pollution. It is also an easy and convenient tool to use to estimate the pollutants release within 1 hour duration and up to 10 km downwind from the source [113]. Due to its fast response, this model can do high number of runs, hence it is suitable for statistical analyses compared to other software applications. ALOHA can predict rates of pollutants released from direct source, or broken gas pipes, evaporating puddles, and leaking tanks. There are two main ways to model how pollutants spread: 'direct source' for sudden or ongoing releases from a single point, like a factory smokestack, and 'puddle' for situations where a liquid evaporates or boils, forming a localized source of air pollution. The model can also account for different source shapes. A 'tank' option is used for horizontal or vertical cylinders and spheres on the ground with a single opening, while a 'pipe' option is used for pressurized pipes releasing gas at ground level.

ALOHA results can be presented in terms of threat zones or pollutants concentration profile based on the downwind and crosswind coordinates as shown in Figure 2.6. The threat zones also can be exported to be displayed on Google Earth or MARPLOT Software as shown in Figure 2.7. Display on Google Earth or MARPLOT Software helped to view clearly on the affected zones so that health risk assessment can be conducted. By establishing threat zones based on Levels of Concern (LOC), communities can better understand the potential risks posed by air pollution from sources like toxic plumes, fires, and explosions.

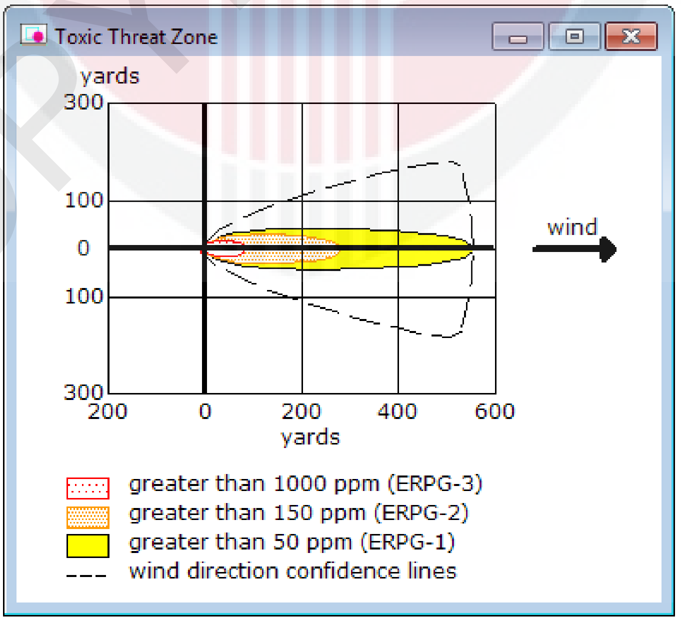

Figure 2.6 : Toxic Threat Zone Simulated by ALOHA

LOC helped to assess the threat posed to the general public by the chemical releases. LOCs for toxic inhalation hazards are specific to the chemicals and extracted from CAMEO Chemicals. ALOHA is integrated with data file limits for AEGLs (Acute Exposure Guidelines Levels), ERPGs (Emergency Response Planning Guidelines), PACs (Protective Action Criteria) and IDLH (Immediate Danger to Life and Health). ALOHA also includes data on chemical flammability, physical properties such as molecular weight and toxicological data, therefore, less input data required to run the modelling [115]. As the input data needed for the ALOHA are minimum, the parameters needed for the models are: time and location, meteorological data such as wind speed, wind direction, air temperature, relative humidity, cloud cover, mixing layer height (inversion), atmosphere stability category, information about the release (air pollutant, release duration, amount of pollutants release and source height (stack).

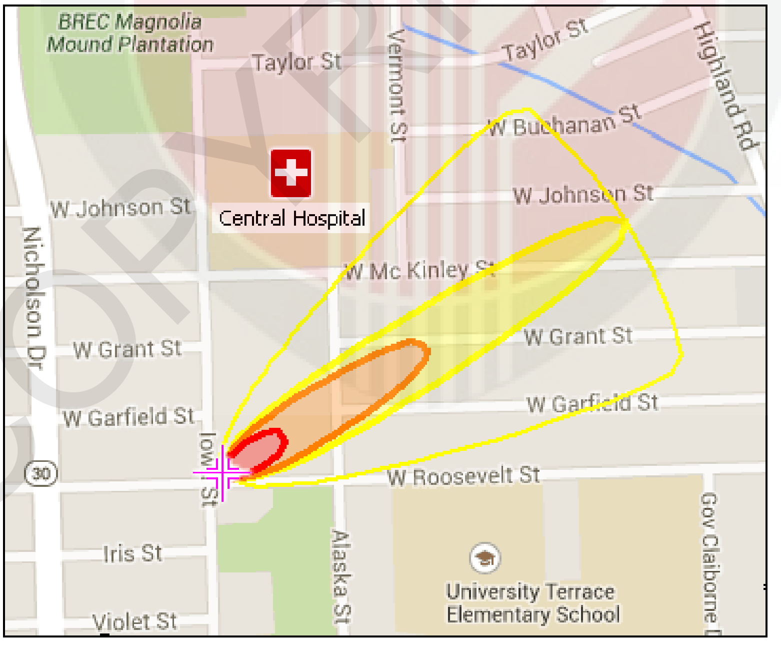

Figure 2.7 : Toxic Threat Zones Plotted on MARPLOT Software

2.7.4 Environmental Risk Assessment

Environmental degradation has long been a pressing issue in the industrial world, and concern for environmental health is increasingly paramount today. As industries expand and human activities intensify, effective risk assessment methodologies, particularly Environmental Risk Assessment (ERA), have become essential. ERA is a systematic process that identifies, analyses, and evaluates risks that threaten the environment due to organizational activities, aiding in decision-making regarding site selection for construction and other developments. This technique employs various methods such as the Leopold Matrix, Hazard, and Operability Study (HAZOP), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and Failure Mode and Effects Analysis (FMEA), which collectively provide organizations with comprehensive insights into potential risks, enabling them to implement effective management strategies [102, 103]. Moreover, ERA fosters compliance with regulations while enhancing organizational sensitivity to environmental issues, thereby promoting a culture of sustainability that aligns with societal goals of protecting natural resources for future generations. Recent studies highlight the importance of integrating probabilistic hazard assessments and developing historical environmental databases to improve risk estimation and vulnerability assessments within ERA frameworks [104, 105]. As environmental concerns continue to escalate, the role of ERA will undoubtedly become even more critical in guiding responsible decision-making across various sectors [106].

2.7.5 Health Risk Assessment

The World Health Organization Regional Office for Europe's [107] defined health risk assessment is the scientific evaluation to human health from exposure to specific hazards by carefully evaluating the potential for negative health effects which in this context study is pollutant emissions from CFPP. Air pollution Health risk assessment (AP-HRA) is often go hand in hand with modeling how pollutants spread through the air by reason of air emissions from CFPP have high possibility to give health impact even to healthy people. AP-HRA will not only provide insights on setting priorities for assessments due to the harmful effects potential, but also provide subsequent risk management activities [108].The health impact includes difficulties with respiration, including irritation or tightness in the airways. The severity of health problems caused by air pollution depends on several factors. These include a person's overall health, the type and amount of pollutant they breathe in, and how long they are exposed. Health impacts due to CFPP are concerning as based on detailed analysis conducted by Koplitz et al. [109], it is estimated around 19, 880 excess deaths per year in Southeast Asia at present and will be increasing to 69, 660 by 2030. Considering the continuous amount of air pollutants emitted from the CFPP into the ambient air in southwestern region of Johor, it is necessary to take a preliminary health risk assessment for residents living near to the CFPP.

2.7.6 Air Pollution Health Risk Assessment (AP-HRA)

AP-HRA has four main key parameters which are population distribution, amount of air pollution presence, pollutants exposure and lastly is the degree of effects or harmful to human health. The health risk is expressed as Relative Risk (RR) which is a concentration-response function [107]. According to RR, health risk assessment outcome is proportional to the pollutants concentrations in µg per m^3 or parts per billion (ppb). There are several methods in approaching health risk assessment such as [107] :

(i) Health impact assessment tools

(ii) Estimation of cancer risk

(iii) Estimation of non-cancer effects potential

Several tools for air pollution health impact assessment have been developed to automate the process of an AP-HRA. One of the commonly used tools for AP-HRA is AirIQ+ as demonstrated in [110, 111]. AirIQ+ is a free software developed by World Health Organization (WHO). It requires several inputs such as total population of interest, baseline incidence of selected disease in the interest population, a cut-off concentration value, and relative risk (RR) [112]. However, there are only few studies that have been conducted in Malaysia regarding the relative risk and baseline incidence. Henceforth, the sources and reliable data are limited to be used in this study. Second method is an estimation of cancer risk which developed by United States Environmental Agency (US-EPA). The estimation of cancer risk expression as shown in equation (2):

$$Cancer\ risk = LADD \times CSF \qquad \textbf{\textit{(2)}}$$

Where:

LADD = Lifetime average daily dose (mg/kg-day)

CSF = Cancer slope factor $(mg/kg\text{-}day)^{-1}$

This cancer slope factor is also known as Inhalation Unit Risk (IUR) when the units are at risk per μ/m^3. Environment Protection Agency (EPA) [113] developed this slope as a linear extrapolation from exposures observed in the animal or occupational study. However, International Agency for Research on Cancer (IARC) has classified SO_2 as Group 3 carcinogen due to insufficient evidence to indicate a carcinogenic potential for humans [114]. Meanwhile, for other gases there is no specific study to determine the IUR value. Meanwhile, quantitative estimation of potential for non-cancer effects are commonly expressed as hazard quotients (HQ). HQ is widely used by regulatory authorities such as US-EPA as it is a very important concept in chemical risk assessment [115]. This is because, HQ is a comparison between potential exposures of a specific substance to the threshold value which no adverse effect will be observed [116]. HQ less than one ($HQ<1$) shows that pollutant exposure does not exceed the RfD value, thus $HQ< 1$ is considered safe. In contrast, if the $HQ>1$, suggests that the non-carcinogenic effect is likely to occur. The threshold values are indicated as Reference Concentration (RfC) or Toxicological Reference Dose (RfD). Based on US-EPA, RfD is defined as an estimate of daily oral or dermal exposure to the human population to pose no appreciable risk of adverse health effects. Similarly, RfC is for direct inhalation exposures. RfC and RfD are derived from no-observed-adverse-effect level (NOAEL) or lowest-observed-adverse-effect level (LOAEL) of the dose-response curve with corresponding uncertainty factors (UF) [117]. Hence, HQ with respected to RfC can be calculated as shown in equation (3) [113, 118, 119]:

$$HQ = \frac{Ca}{RfC} \quad \textbf{\textit{(3)}}$$

Where:

Ca	=	Total concentrations of air pollutants (mg/m^3)
RfC	=	Reference concentration (mg/m^3)

However, this equation does not consider non-chemical specific exposure such as inhalation rate (IR), body weight (BW), exposure frequency (EF), exposure duration (ED) and exposure time (ET). These factors are important as different age groups and different socio-demographics have different respective values. Therefore, equation (3) is altered to Equation (4), Equation (5) and Equation (6) as employed by Eleftheria et al. [120] and RfD is obtained by back-calculating the published RfC values based on standard adult inhalation rate ($20m^3$/day) and body weight (70kg) [121, 122, 123]. The standard adult inhalation rate and body weight are also recommended by the DoE [124]. The Average Daily Dose (ADD), RfD and HQ respected to RfD are calculated by using equations below and the input data are explained in Section 4.4.

$$ADD = \frac{Ca \times IR \times ET \times EF \times ED}{BW \times AT} \quad (4)$$

$$\mathbf{RfD = RfC \times \frac{20m^3/day}{70kg}} \quad (5)$$

$$HQ = \frac{ADD}{RfD} \quad (6)$$

Where:

Ca	=	Ground level concentration obtained from simulation modeling (mg/m^3)
ADD	=	Average daily dose (mg/kg day)
RfC	=	Reference concentration
RfD	=	Reference dose (mg/kg day)

ET = Exposure time (hour/day)

ED = Exposure duration (year)

EF = Exposure frequency (day/ year)

AT = Average time (day)

IR = Inhalation rate (m^3/h)

BW = Body weight (kg)

IRd = Daily inhalation rate (m^3/day)

2.8 Conclusion

From the reviewed literature, several conclusions can be drawn. Firstly, air emissions from coal-fired power plants (CFPP) pose significant health risks and must be addressed by local authorities. Secondly, Gaussian Plume Dispersion Models are widely used and proven reliable, as discussed in 2.7.3 .Thirdly, this study explores the advantages of ALOHA as an accurate alternative for atmospheric dispersion modeling, with its reliability carefully evaluated. Finally, the study incorporates health risk assessments by using the hazard quotient, particularly because carcinogenic gases were found to be negligible in this context.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

The purpose of this chapter is to explain in detail the research methods and the methodology implemented for this study. The chapter explains about historical data analysis and CFPP topography. This is followed by a discussion on data input for simulating an atmospheric dispersion model. The chapter continued with hazard quotient evaluation and concluded with an overall flow chart of the research methodology.

3.2 Flow Chart of the Research Methodology

The flowchart Figure 3.1 illustrates the sequential steps followed in the research methodology. The process begins with a historical data analysis to understand past trends and gather essential background information. Next, coal-fired power plant topography observation is conducted to assess the geographical and environmental characteristics relevant to the study area.

Following these preliminary steps, the atmospheric dispersion model is simulated to predict the spread and concentration of emissions from the power plant. The results of this simulation are then compared with historical data to validate the model's accuracy. Finally, a health risk assessment is performed based on the findings to evaluate potential impacts on public health. Each stage builds on the previous one, creating a structured approach to analyze environmental and health impacts systematically.

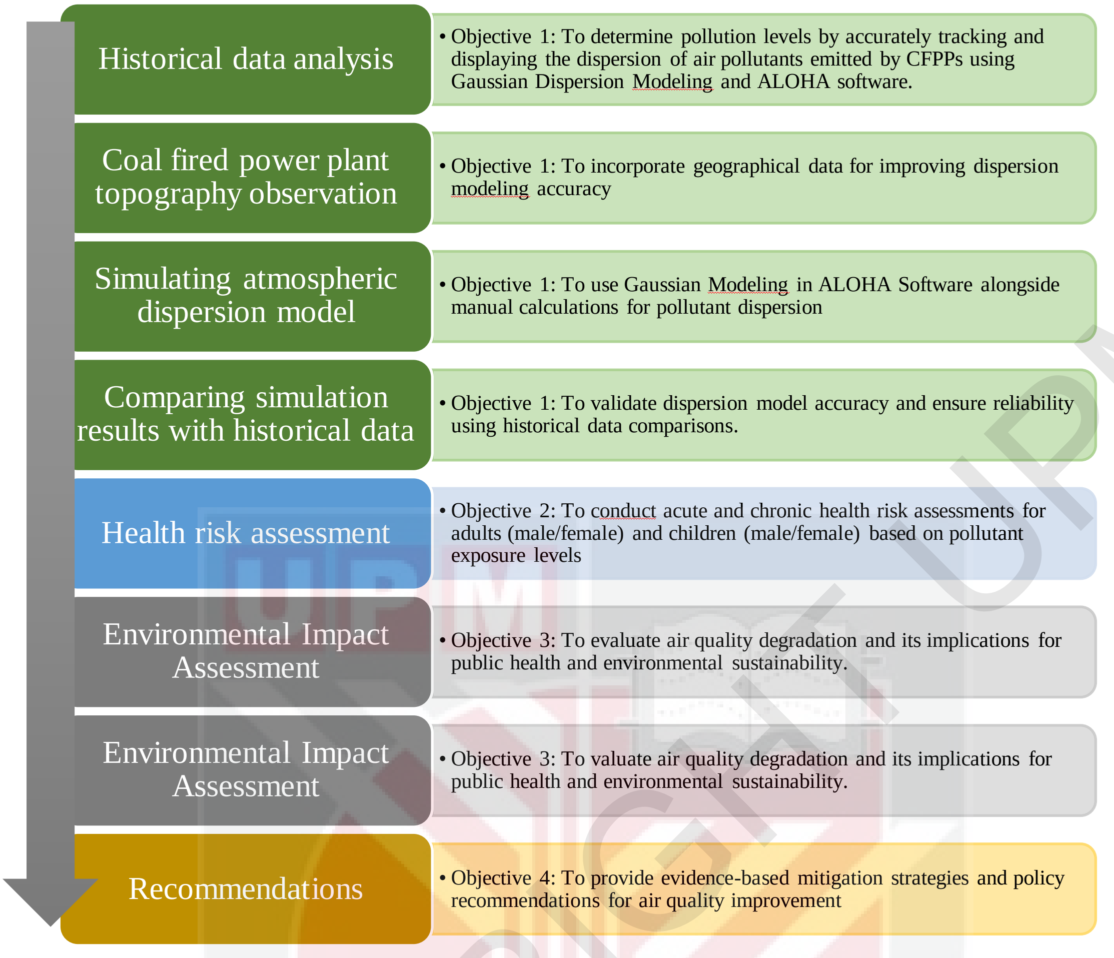

Figure 3.1 : Flow Chart of Research Methodology

3.3 Historical Data Analysis

The historical data collected can be divided into two groups: (i) quarter-year interval data collected at four sampling points from May 2016 to June 2019 and (ii) thirty-minute interval data collected at the main stack of the CFPP from January 1, 2016, to August 31, 2019. Data limitations were primarily due to the COVID-19 pandemic, which caused data collected between 2019 and 2021 to be unstable and unreliable for drawing conclusions. This instability arose from operational restrictions and adjustments implemented by power plants during this period. Thus, this study focuses on the analysis of the latter dataset, specifically from February to December 2018, using Microsoft Excel 2013, as it is completer and more reliable than other available data.

The analysis includes calculating essential indexes, such as the maximum, mean, and minimum values of pollutant emissions, which serve as parameters for pollutant emission modeling. The quarter-year interval data is used to benchmark and validate the simulation results, a critical step in estimating health impacts on citizens under different pollutant concentration scenarios. For sampling and analyzing particulate matter (PM). It is worth noting that standards followed the Australian/New Zealand Standards AS/NZS 3580.9.6:2003 and AS/NZS 3580.9.14:2013, developed by the Joint Standards Australia/New Zealand Committee EV-007. Meanwhile, SO_2 and NO_2 are analyzed using the ISC Method, and CO is sampled and analyzed following the USEPA Method 10 by the United States Environmental Protection Agency, as summarized in Table 3.1.

Table 3.1 : Sampling and Analyzing Methods

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

3.4 Coal-Fired Power Plant Topography and Target Population

The CFPP used as the subject for this study, located in the south-western region of Johor, Malaysia. In this research, Google Earth Pro 7.3 has been selected as the geobrowser to obtain all the geographic data related to the CFPP location. Before experimenting, several variables have been verified as listed below:

a) Residential areas located around the CFPP.

b) Location of the sampling point.

c) The topography around the CFPP.

Table 3.2 : Location Coordinates and Distance from the CFPP

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

Based on Google Earth Pro 7.3, there are several residential areas located less than 10 kilometers from the CFPP location. Google Earth Pro also helped to determine the coordinates of the CFPP. Kampung Sungai Boh and Kampung Sungai Chengkeh have been selected as the threat points for hazard quotient assessment due to three main reasons:

a) Nearest population area to the CFPP location

b) High-density population

c) Prevailing wind direction.

The respective area coordinates and the distance from the CFPP are listed as shown in Table 3.2 . The distance is measured by using ruler tools in Google Earth Pro 7.3 with the viewpoint at the north. Meanwhile, a topographic map of the south-western region of Malaysia is obtained from Worldwide Elevation Finder/ Topographic map/ Altitude map to view the terrain as shown in figure Figure 3.2.

Figure 3.2 : Topography Map of Southern-Western of Johor

3.5 Coal Fired Power Plant (CFPP) Location

The CFPP subject for this study is in south-western region of Johor. Topography of the area is mostly flat and not complex as appears on topography map [125], making the air emissions modelling easier to model. The location of the CFPP is beside the bay of Johor Strait and Pulai River. As shown in Figure 3.3 and Figure 3.4, there are several residential areas located around the CFPP.

Figure 3.3 : West Region of CFPP Layout

Figure 3.4 : East Region of CFPP Layout

All these residential areas are less than 10 kilometers distance from the CFPP. Based on the west region of CFPP as displayed in Figure 11, there are two nearest residential areas to the CFPP location which are Kampung Sungai Chengkeh and Kampong Sungai Boh with 2.10 and 2.63 kilometers respectively. Meanwhile, for other residential areas such as Kg. Chengkeh, Kg, Chokoh Besar, Kampung Sungai Kuali, Kampung Permas Kechil and Kampung Air Masin have 4.20, 4.19, 7.63, 8.33, 5.47 and 9.73 kilometers respectively.

There are also several residential areas located in the east region of the CFFP. Same as in the west region, all the residential areas are less than 10 kilometers distance from the CFPP. The nearest one is a primary school which is SK. Tg. Adang with 3.86 kilometers distance. Other villages are Kampung Tanjung Adang, Kampung Pekajang and Kampung Pok which are 3.91, 4.76 and 4.89 kilometers located form the CFPP respectively. Considering the potential health impact on the residents because of persistent exposure to emission, it is necessary to simulate the air pollution modelling and conduct the health risk assessment. Proximity to pollution sources significantly elevates health risks for nearby residents and workers [126].

3.6 Atmospheric Dispersion Model Simulation

In this study, ALOHA (Areal Locations of Hazardous Atmospheres) software, Version 5.4.7, was downloaded from the official USEPA website to simulate the dispersion model. ALOHA was selected as the modeling tool due to its incorporation of the Gaussian Plume model, which is widely recognized for accurately simulating atmospheric dispersion in various environmental conditions. This software allows for comprehensive and reliable assessment of air dispersion patterns, particularly in scenarios involving hazardous material releases. The specific data and parameter requirements necessary for effective air dispersion modeling are detailed and explained in section 3.6.1, including meteorological conditions, emission rates, and terrain characteristics, among others.

3.6.1 Site, Chemical, Meteorological Data and Source Strength Model

Approximate location and geographical data of the CFPP as explained in Section 3.4 are manually input in the ALOHA as the location of CFPP is outside of the United States. ALOHA Version 5.4.7 has an integral database that includes toxicological, chemical, physical, and properties for a wide range of chemicals [101]. Different types of chemicals that are not available in ALOHA data files can be added manually as the data files in the ALOHA are subsets of CAMEO Chemicals database (compilation of hazardous chemicals). The toxicological properties that are important to be included in the chemical data input: (i) AEGLs (Acute Exposure Guideline Levels) and (ii) IDLH (Immediate Danger to Life and Health).

The historical meteorological data for 2018 of the Southern-western of Johor are obtained from Jabatan Meteorologi Malaysia which include cloud cover, speed, relative humidity, air temperature, wind direction, and wind measurement height. Based on the meteorological data input, stability class has been set according to Pasquill Stability Categories. Meteorological data inputs are taken as an average based on different emission scenarios or the minimum values for the given stability class. The summary is shown as follows:

Table 3.3 : Meteorological Data Input

Data input	**Emissions based on threat points**		**Emission based on sampling point (AA4)**
	(Worst-case scenario)	**(Best-case scenario)**	
Wind direction (◦)	120	120	Meteorological data are taken based on the respective time of the pollutant emissions.
Stability class	B	E	
Wind speed (m/s)	2.0	4.45	
Relative humidity (%)	82.0	82.0	
Cloud covers (Oktas)	7.0	7.0	
Temperature	28.3	28.3	

However, the data are obtained from Senai Station and the reference height is 37.8m. Therefore, an accurate assessment of wind speed at the 200-meter stack height requires extrapolation from the measured data obtained at 37.8 meters by using Equation (7) power law wind speed profile [127]. Power law exponents (n) can be referred to The Meteorological Resource Center website [128] and assumed the CFPP terrain is rural.

$$u_1 = (\frac{z_1}{z_2})^n \times u_2 \quad (7)$$

Where:

u_1	=	Wind speed at height z_1
u_2	=	Wind speed at height z_2
z_1	=	Stack height (200m)
z_2	=	Reference height (37.8m)
n	=	Power law exponents.

Direct source strength is used for the simulation which includes continuous release type, number of pollutants entering the atmosphere per hour and source height (height of the main stack). Number of pollutants entering the atmosphere per hour are taken from the historical data analysis.

3.7 Gaussian Plume Manual Calculation

According to the ALOHA User's Manual, ALOHA is not designed to model particulate dispersion [129]. ALOHA is primarily a tool for modelling chemical gas releases and specializes in predicting the dispersion behavior of gaseous emissions in the atmosphere. While highly effective for scenarios involving gas emissions, ALOHA does not account the complexities associated with particulate matter (PM) dispersion [130, 131].

This limitation is significant when analyzing the behavior of particulate pollutants, as ALOHA does not incorporate critical dynamics unique to particles within turbulent flows. Unlike gases, particulate matter is influenced by additional forces such as gravitational settling and inertial effects, which impact the way particles move and spread. ALOHA lacks the ability to account for these factors, including particle inertia, which affects how particles resist changes in motion, and turbulent dispersion effects, which describe how turbulence in the atmosphere impacts particle distribution. These aspects are fundamental to accurately modelling particulate transport and behavior in the environment [132, 133]. To address this limitation and to model PM_{10} dispersion, calculations must be performed manually using Microsoft Excel 2013, to account for a better accuracy.

However, there are several factors have been considered when estimating the effective release height, H (H is used in Equation (11)). One of the factors is Vertical Settling (h_v) where the particulates experience the rapid descent toward the ground due to the gravity influence [134]. The second factor is Initial Buoyancy Flux (F_b) which the buoyancy-driven plume rise resulting from the temperature differential between the effluent and the surrounding atmosphere [86, 127, 135].

Based on these two factors, several equations have been compared to get the nearest estimated ground concentration values with the historical data. The equations used to calculate h_v, F_b, plume rise (Δh) and H are shown below:

$$h_v = \frac{3 \times 10^{-5} \times x \times {d_\rho}^2 \times \rho_\rho}{u} \quad \textbf{(8)}$$

$$F_b = \frac{W_0 {R_0}^2 g}{T_{P0}(T_{P0} - T_{a0})} \quad \textbf{(9)}$$

$$\Delta h = \frac{21.425 \times {F_b}^{0.75}}{u} \left(Fb < \frac{55m^4}{s^3}\right) or\ \Delta h = \frac{38.71 \times {F_b}^{0.6}}{u} \left(Fb > \frac{55m^4}{s^3}\right) \quad \textbf{(10)}$$

$$H = (h + \Delta h - h_v) \quad \textbf{(11)}$$

Where:

h_v	=	Vertical settling (m)
x	=	Downwind distance (m)
d_ρ	=	Particulate diameter (assumed to be 10µm)
ρ_ρ	=	Particulate density (assumed to be 1.65g/cm^3 [136]
W_0	=	Initial velocity of gas flow (m/s)
R_0	=	Stack diameter (m)
T_{P0}	=	Initial plume temperature (K)
T_{a0}	=	Ambient temperature at the stack (K)
g	=	Gravity (9.8m/s^2)
H	=	Effective release height (m)
Δh	=	Plume rise (m)

3.8 Health Risk Assessment

The Acute and Chronic Air Pollution Health Risk Assessment (AP-HRA) represents the most recent phase of this study, building upon the earlier assessment of population exposure to specific air pollutants through air quality modeling. This phase focuses on quantifying health risks associated with exposure to both acute and chronic levels of air pollution. Notably, non-carcinogenic gases are considered more immediately impactful on public health compared to carcinogenic gases, which may have longer latency periods for health effects. Therefore, the Hazard Quotient (HQ) is calculated to assess the risk level of these non-carcinogenic pollutants on exposed populations.

Recognizing that physiological factors, such as respiration rates, metabolic rates, and body weight, vary significantly among different demographic groups, the AP-HRA analysis was tailored for four distinct groups to account for these variations in risk assessment [137, 138]. These groups include:

a) adult males

b) male children

c) adult females

d) female children

This stratification ensures that the assessment more accurately reflects the health risks faced by each demographic. Children, for instance, often show higher respiration rates relative to body weight, which may increase their exposure risk. Similarly, gender-based physiological differences can affect susceptibility to certain pollutants. By differentiating between these groups, the AP-HRA provides a more precise understanding of health risks posed by air pollution, enabling targeted public health interventions.

3.8.1 Hazard Quotient (HQ) Data Input

The formulas used to calculate HQ are Equation (4), Equation (5) and Equation (6) as shown in Section 2.7.6. For non-cancer assessment, average time is equal to the ED which converted into days [137]. Reference concentration (RfC) values used for health risk assessment are shown in Table 3.4 [118] and obtained from Kenessary et al. [118]. Maximum single concentrations of the pollutants are used for calculating HQ acute exposure [139, 140], meanwhile, average daily values are for HQ chronic exposure.

Table 3.4 : Reference Concentration [118]

Gas	Reference concentration, RfC (mg/m^3)	
	Maximum single	Average daily
SO_2	0.5	0.05
CO	5	3
NO_2	0.2	0.04
PM_{10}	0.23	0.48

The non-chemical factor values used in this study are summarized in Table 3.5. The body weight (BW) for adults is based on the average weight from the socio-demographic data of South Malaysia [141], while children's BW is estimated based on data from urban Malay primary school children [142]. Inhalation rate (IR) parameters for both children and adults are adapted from established estimates for European populations [143], chosen for their detailed categorization by age and gender, which aligns closely with the demographic profile of the studied groups. Since specific IR values are not provided in the Department of Environment (DoE) Malaysia guidelines [124], these external values were utilized.

The exposure duration (ED) for both adults and children are set according to age group assumptions, under the presumption that they have continuously resided within the residential area as advised by the DoE [144]. The DoE also recommends an exposure frequency (EF) of 365 days per year. However, based on previous research, an annual absence of 14 days has been assumed for the studied groups [145], resulting in an adjusted EF of 350 days per year. Consistent with prior studies, a 24-hour exposure duration is assumed across all groups to account for potential acute effects from single-day exposures [120, 146, 144]. Therefore, for calculating acute effects, EF is excluded as demonstrated in these referenced studies.

Table 3.5 : Summary of Non-Chemical Factors Input

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			

3.8.2 Hazard Index

Another important concept in HQ is the hazard index (HI). HI is defined as a summation of multiple chemicals hazard quotient when receptors are exposed to these chemicals occur simultaneously [147, 148]. Similar to HQ, HI value below 1 indicates a low likelihood of adverse health effects arising from the exposure. Calculation of HI are carried out according to the following formula:

$$HI = \sum HQ_i \qquad \textbf{\textit{(12)}}$$

Where HQ_i is hazard quotients for the i^{th} air toxic and HI are calculated for both acute and chronic effects respective to Kampung Sungai Boh and Kampung Sungai Chengkeh.

3.9 Conclusion

As for the methodology presented in this chapter, we aim to assess the environmental and health risks associated with emissions from a coal-fired power plant (CFPP) in Johor, Malaysia. Using historical data, we will model the dispersion of gaseous and particulate pollutants, focusing on PM10, SO_2, CO, and NO_2. By applying both manual and software-based approaches to analyze emission patterns, the methodology will estimate potential health impacts on surrounding residential areas. The study's health risk assessment will focus on both acute and chronic exposure scenarios across different demographic groups, providing a basis for understanding exposure-related health risks and informing future air quality management efforts.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the key insights derived from the analysis of emission data. It begins with an examination of historical emission data for SO_2, NO_2, CO, and PM_{10}. This is followed by an analysis of the ALOHA modeling results and the Gaussian Plume Dispersion calculations for both worst-case and best-case scenarios. Next, the chapter discusses the results of the health risk assessment, which is divided into three main sections. The first section covers the Average Daily Dose (ADD) inhaled by the studied group, the second section addresses the Hazard Quotient (HQ), and the final section discusses the Hazard Index (HI). The HQ and HI are evaluated based on the acute and chronic health effects for both worst-case and best-case scenarios.

4.2 Historical Data Analysis

The emission data for sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter (PM_{10}) was collected from a coal-fired power plant over an eleven-month period, spanning from February 1st to December 31st, 2018, at 30-minute intervals. The dataset provides significant insights into the plant's emissions patterns, operational efficiency, and potential environmental and health impacts. Visual representations of the emissions data are provided in Figure 4.1 through Figure 4.4, showing fluctuations and peak emissions that highlight the plant's operational dynamics and their implications.

Figure 4.1 illustrates SO_2 emissions, which were notably the highest among the four pollutants measured, with the maximum hourly rate recorded at 3414.73 kg/h on April 4th, 2018, at 8:30 pm. This elevated emission is primarily attributed to the high sulfur content in the coal used at the plant [149, 150].

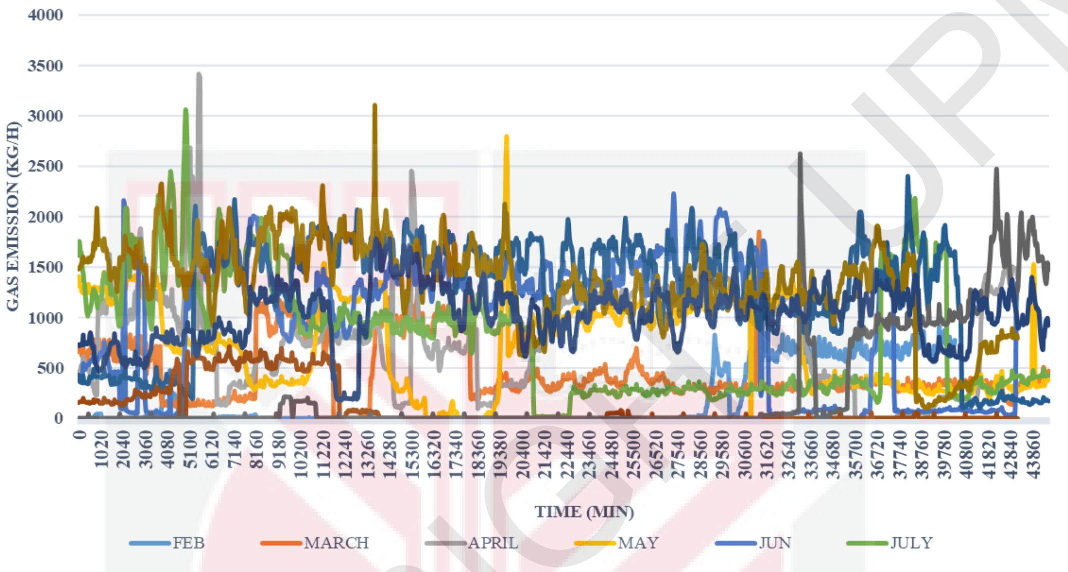

Figure 4.1 : Sulfur Dioxide (SO2) Gas Emission Rates at the Respective Time of the 2018 Data Collection

On average, SO_2 emissions were 725.12 kg/h, which is significantly higher than the other pollutants, highlighting the SO_2's dominance in the plant's emission profile. The high variability in SO_2 emissions suggests fluctuating sulfur content in the coal supply or inconsistencies in combustion efficiency, both of which could result in substantial spikes that pose long-term health risks, particularly respiratory issues due to prolonged exposure [151, 152].

Figure 4.2 displays NO_2 emissions, with the highest emission recorded at 1183.3 kg/h on June 26th, 2018, at 11:30 pm. The average emission for NO_2 over the monitoring period was 312.76 kg/h, which is approximately 56% lower than the average SO_2

emission. This reduction aligns with the plant's use of subbituminous coal, which has a nitrogen content approximately half that of sulfur by weight [153, 154]. The data shows relatively consistent NO_2 emissions, though with occasional spikes that may be attributed to changes in combustion conditions or variations in coal composition. While NO_2 emissions are lower than SO_2, they remain a significant health concern, contributing to respiratory issues and forming ground-level ozone, which aggravate air pollution and negatively impacts both human health and the environment.

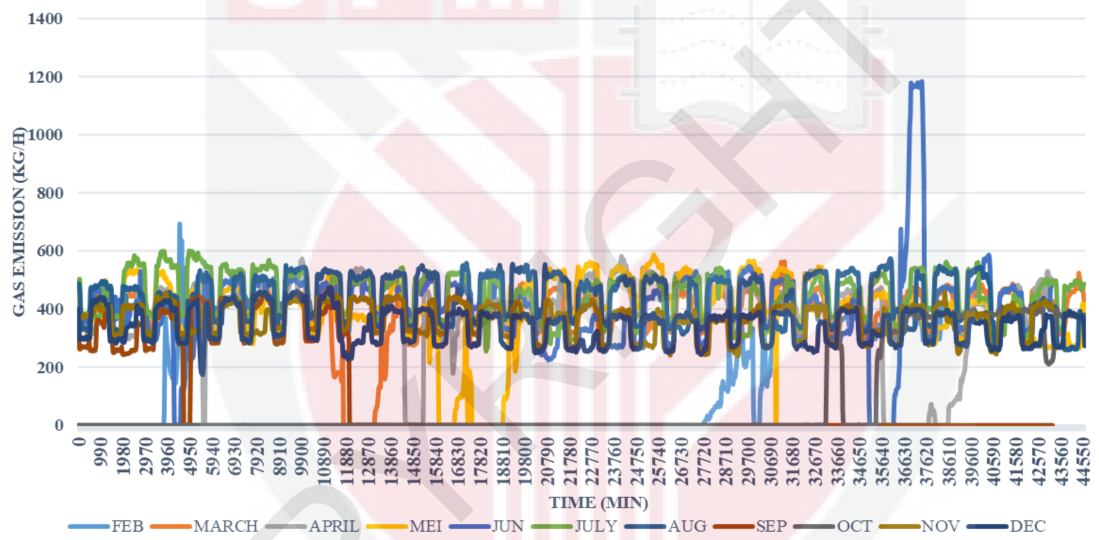

Figure 4.2 : Nitrogen Dioxide (NO_2) Emission Rates (kg/h) at the Respective Time of the 2018 Data Collection

The CO emission data, presented in Figure 4.3, shows a maximum rate of 2211.74 kg/h on November 16th, 2018, at 9:30 am. CO emissions averaged 114.61 kg/h over the eleven months, which is relatively lower than SO_2 and NO_2 but still considerable. The high CO emissions can be also attributed to incomplete combustion, which often occurs when there is a high coal flow rate with inadequate air supply. This inefficiency in combustion not only increases CO emissions but also represents an operational inefficiency, as incomplete combustion wastes fuel and reduces the plant's energy output [155]. CO, being a toxic gas, poses immediate health risks, especially in cases of short-term exposure to high concentrations, making the emission peaks concerning for nearby residents.

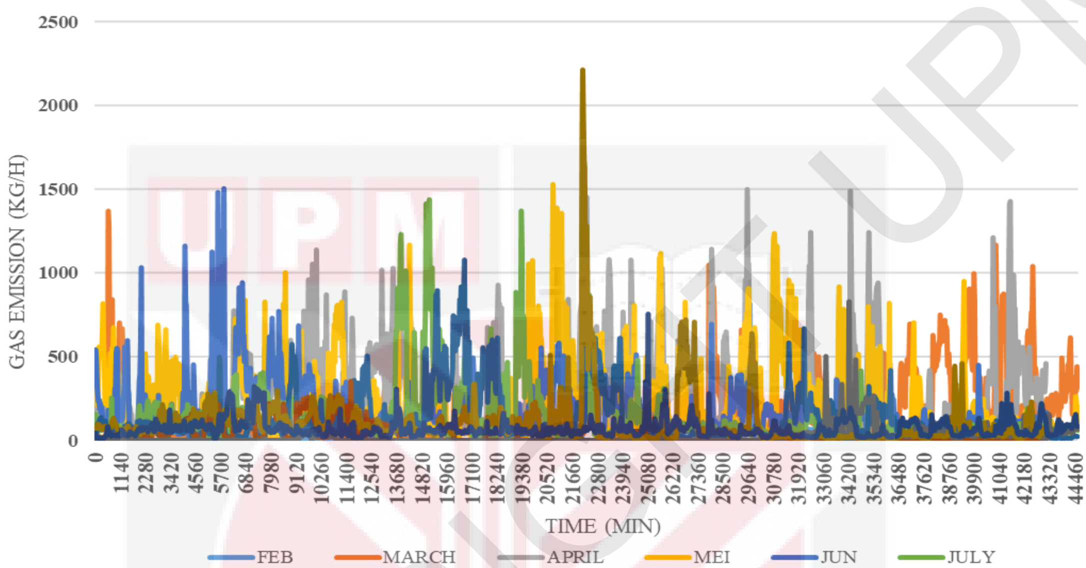

Figure 4.3 : Carbon Monoxide (CO) Emission Rates at Respective Time of the 2018 Data Collection

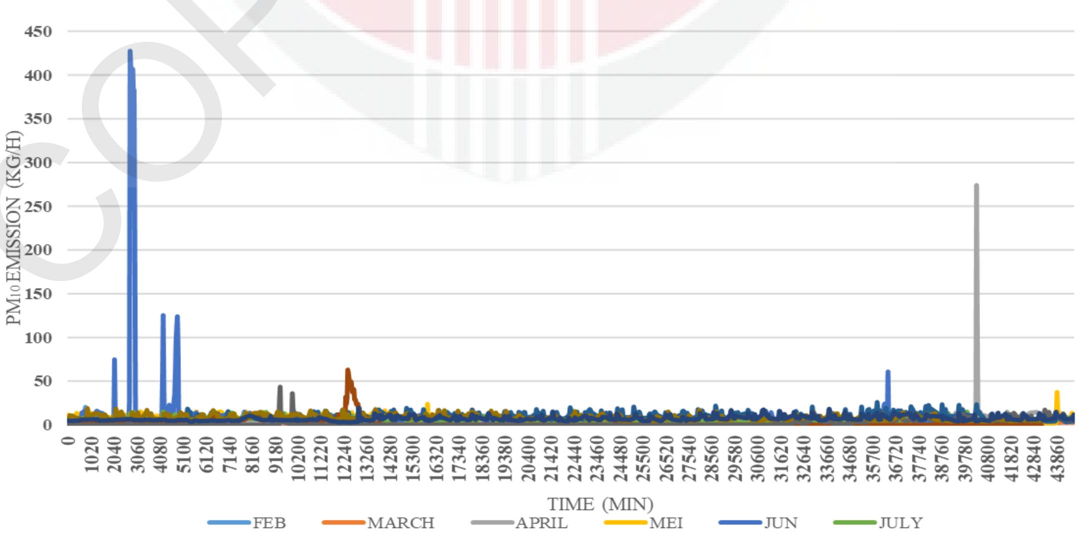

Figure 4.4 : Particulate Matter (PM_{10}) Emission Rates at Respective Time of the 2018 Data Collection

The PM_{10} emissions are highlighted in Figure 4.4, it can be seen that they were significantly lower than the other gases, with an average rate of 5.03 kg/h. The highest recorded PM_{10} emission was 427.44 kg/h on June 2nd, 2018, at 10 pm. The generally low PM_{10} emissions can be attributed to the use of fabric filters that capture fine particulate matter before it is routed to the emission stack [156, 157]. However, occasional spikes, like the one on June 2nd, indicate potential issues with filter performance.

These spikes may result from improper dust-cake formation on the fabric filter, which would cause dust particles to pass through or “bleed-through,” temporarily increasing the dust emission rate [158, 157]. While PM_{10} emissions are lower, their presence is still of concern, as particulate matter can penetrate deep into the respiratory tract, causing health issues upon prolonged exposure. A notable observation from Figure 4.1 through Figure 4.4 is the lowest recorded emissions for SO_2, NO_2, and CO on September 12th, with values of 0.022 kg/h, 0.0001 kg/h, and 0.039 kg/h, respectively, while PM_{10} reached its minimum on September 30th at $1.03e^{-06}$ kg/h. These reductions are likely due to a temporary or permanent operational shutdown at the plant, highlighting how operational status directly influences emission levels. This correlation suggests that maintenance schedules, shutdowns, or reductions in output could serve as critical control measures for managing emissions.

The data overall shows significant variability in gas release rates, particularly for SO_2 and CO, which indicates inconsistent combustion efficiency and emission control practices. Such fluctuations complicate efforts to maintain stable emission rates and may reflect variations in coal quality or operational practices, highlighting the need for improved combustion control and emission regulation strategies. Continuous high emission rates, especially of SO_2, present significant health risks due to chronic exposure. Long-term effects of such exposure can include accelerated lung aging, reduced lung function, and shortened lifespan [159]. Acute exposure to high concentrations of these pollutants, particularly during peak emission events, can also cause immediate respiratory issues, such as coughing, shortness of breath, and potential lung damage [160].

The health impacts of SO_2 exposure are particularly concerning, as outlined in the Material Safety Data Sheet (MSDS). SO_2 can irritate the eyes, throat, nose, and sinuses, and in severe cases, high concentrations can lead to pulmonary edema, fluid accumulation in the lungs, and even death [161]. These symptoms underscore the critical need for effective SO_2 control to protect the health of nearby communities. The spread of these pollutants is further influenced by weather conditions, including wind direction, turbulence, and atmospheric stability, which dynamically impact emission dispersion and increase the health risks for populations residing near the plant [162]. Studies indicate that residents within a 300-meter radius of industrial zones face a heightened risk of respiratory conditions, with data suggesting a 1.37-times increase in the risk of decreased lung function capability and a 1.62-times increase in overall risk of lung function decline compared to the general population [163, 164, 165, 166].

4.3 ALOHA and Manual Calculation of Gaussian Plume Simulation Results

ALOHA simulations were conducted to model the dispersion and concentration of four gaseous pollutants, specifically sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO). These simulations served as a benchmark against historical data under both best-case (minimum) and worst-case (maximum) scenarios, providing a comprehensive risk assessment framework. The simulations were configured with an averaging period of one hour to align with standard exposure limits and facilitate meaningful comparisons.

In addition to these pollutants, particulate matter (PM_{10}) was analyzed separately through manual calculations in Excel 2013, as it required a different modeling approach. The manual calculations were performed to estimate PM_{10} dispersion under various conditions, complementing the ALOHA outputs for a complete evaluation of air quality impacts.

The results of these analyses are detailed as follows:

4.3.1 Comparison of Modeling Ground Level Concentration with Historical Data

This comparative analysis aims to validate the reliability and accuracy of the simulation outputs by benchmarking them against actual measured concentration data. Given that atmospheric dispersion is a stochastic and complex phenomenon, it is essential to validate simulation results to ensure accuracy and reliability. Deviations between simulated and measured concentrations may arise due to factors such as model configuration, atmospheric chemistry, and unpredictable human activities [11]. By analytically comparing simulation data with historical data, we can identify potential sources of error and take corrective actions to refine the mathematical model.

For this study, the historical data spans a quarter-year interval, averaged over a continuous 24-hour period from 3 pm on February 20, 2018, to 3 pm on February 21, 2018. These measurements were collected at the AA4 sampling point in Kg. Chokoh Besar.

A comparison of historical and simulated data is presented in Table 4.1. The table reveals that simulated concentrations for SO_2, NO_2, and CO fall within the range of historical data, with SO_2 concentrations below 30 and both NO_2 and CO concentrations below 10. However, PM_{10} shows a notable deviation, with a root mean square error of 63.67 between calculated and observed data. As the formulas used were previously validated and used in several previous studies, the primary factor contributing to this discrepancy may be the meteorological data source [167]. The meteorological data used in the simulation were sourced from Senai Station, approximately 30 km from the observation site, with a reference height of 37.8 meters. Additionally, the location of the CFPP is near other potential pollution sources, including another power plant and the port activities at Pelabuhan Tanjung Pelepas, which may further influence concentration levels.

Despite these discrepancies, the simulated data remains valuable for assessing the potential adverse impact of CFPP emissions on residents. Future improvements to the model could incorporate localized meteorological data and additional pollutant sources to increase the accuracy of predictions.

Table 4.1 : Comparison between Simulated Concentrations and Historical Data Concentrations

Gases	Simulated data ($\mu g/m^3$)	Historical data ($\mu g/m^3$)	CFPP DoE Limits [174]
Sulfur dioxide (SO_2) (ALOHA)	8.71	<30	<500mg/m3
Nitrogen dioxide (NO_2) (ALOHA)	2.37	<10	<200mg/m3
Carbon monoxide (CO) (ALOHA)	2.05	<10	<500mg/m3
Particulate matter (PM_{10}) (Calculations)	0.33	64	<50mg/m3

4.3.2 Threat Zones for Worst-Case Scenario by Using ALOHA Modelling

After inputting the required data into ALOHA, graphical representations of the dispersion result for SO_2, NO_2, and CO emissions were generated. These modelled cases were then imported into Google Earth software, providing a spatial overview of the affected zone, as shown in Figure 4.5.

In fact, Figure 4.5 illustrates that the simulated SO_2 dispersion concentrations do not exceed the Acute Exposure Guideline Levels (AEGL-3 and AEGL-2), where the thresholds are set at 78.6 mg/m^3 and 1.965 mg/m^3, respectively. However, SO_2 concentrations do exceed AEGL-1, which has a threshold of 0.524 mg/m^3 for a 60-minute exposure. This AEGL-1 level represents the No Observed Effect Level (NOEL) for bronchoconstriction in exercising asthmatics, meaning that while the affected population may not experience severe or disabling effects, they may encounter discomfort, irritation, and mild asymptomatic responses [168] .

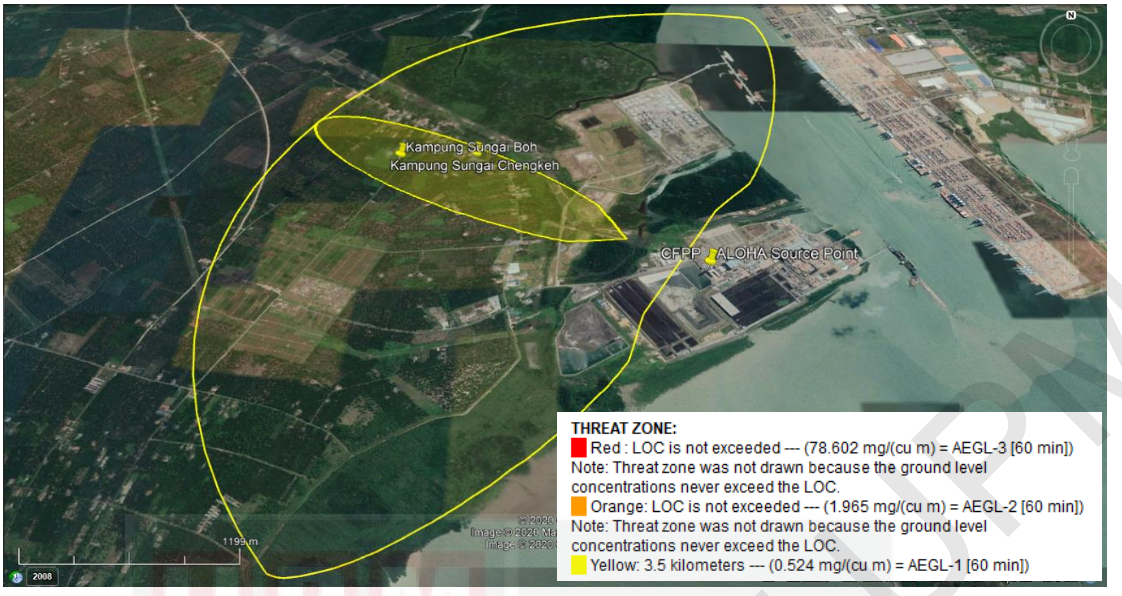

Figure 4.5 : Toxic Threat Zone for the Worst-Case Scenario (Maximum) of SO_2 Emission

The resulting toxic zone with SO_2 concentrations above AEGL-1 extends nearly 3.5 kilometres in a linear direction from the source, aligned with the prevailing wind direction. In the Google Earth visualization, a yellow line outside the threat zones indicates the wind direction confidence line, which represents the uncertainty in wind direction. Due to the natural variability of wind speed and direction, which rarely remain constant over time, this confidence line is particularly broad in the simulation. The uncertainty is further amplified by low wind speed conditions, which are known to increase fluctuations in wind direction [168, 169].

Additionally, the simulation was conducted under conditions typical of noon, with a stability class of B, indicating moderate atmospheric instability. This instability further influences dispersion patterns and should be considered when interpreting the results. It is essential to note that the simulated pollutant concentrations are only valid for the specific data inputs and methodologies outlined in Section 3.6.

Apart from the SO_2 toxic threat zones, the simulated outcomes for other gas pollutants, such as NO_2 and CO, show that their concentrations remain below the levels of concern (AEGL thresholds). This result aligns with expectations outlined in Section 2.7.3, where it was noted that SO_2 emissions are higher than those of other gases. According to the Gaussian Plume Equation, there is a directly proportional relationship between the pollutant emission rate and the time-averaged concentration of that pollutant at a given downwind location. Consequently, higher pollutant emissions correlate with increased ground-level concentrations, potentially surpassing the levels of concern (LOC).

Another key factor influencing the lower concentration of other gases in the simulation is the stack height, which in this study is set at 200 meters. As stated in the Stack Height Guidance by the Department of Environmental Conservation Vermont [170], a tall or adequately designed stack height helps reduce ground-level concentrations of air pollutants by dispersing emissions over a larger area. This dispersion reduces the likelihood of these gases reaching harmful concentrations at ground level.

To specifically assess ground-level concentrations for NO_2 and CO, customized Levels of Concern (LOC) were set in ALOHA's parameters. These user-defined LOC thresholds were used to provide a more precise analysis of ground-level impacts for these pollutants, considering the conditions of this study:

a) LOC-1 (yellow zone) = 0.001 mg/m^3

b) LOC-2 (orange zone) = 0.01 mg/m^3

c) LOC-3 (red zone) = 0.1 mg/m^3

Figure 4.6 displays the results of the simulated NO_2 emissions. It is essential to note that ALOHA has a limitation on its predictive range, restricting its calculations to a maximum distance of 10 kilometers from the release point. Consequently, the modeled threat zone is capped at this 10-kilometer boundary.

As shown in Figure 4.6, the area where NO_2 concentrations exceed the LOC-3 threshold extends up to 5.3 kilometers from the source in the same wind direction. In contrast, zones exceeding LOC-2 and LOC-1 thresholds extend beyond the 10-kilometer range, although ALOHA cannot provide concentration estimates beyond this limit.

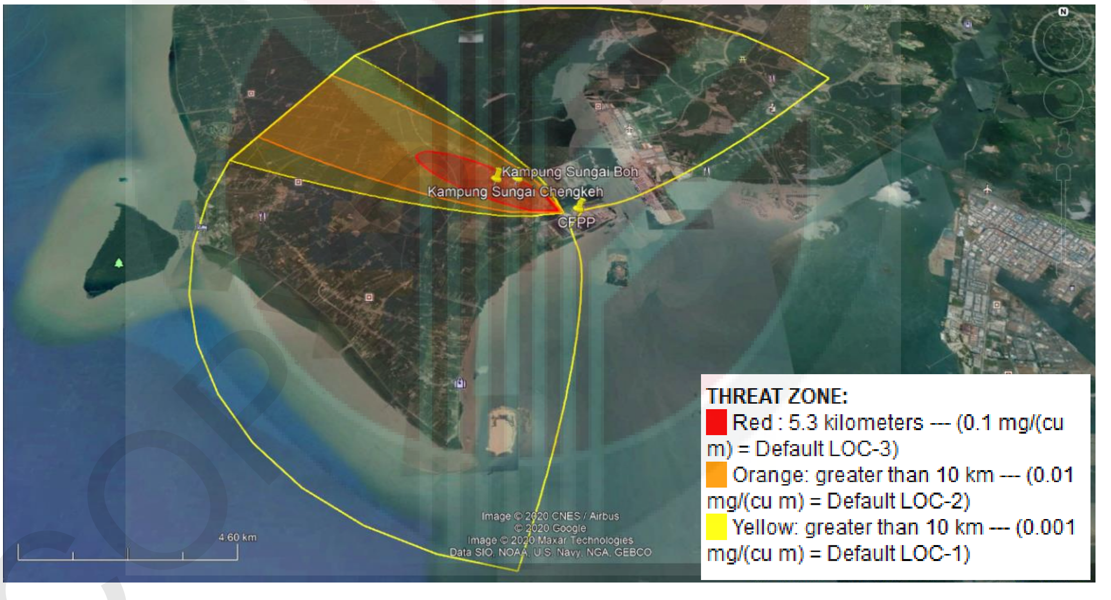

Figure 4.6 : Toxic Zone for Worst-Case Scenario (Maximum) of NO_2 Emission

The simulation results also indicate that both Kampung Sungai Chengkeh and Kampung Sungai Boh fall within the LOC-3 threat zone. This placement suggests that these locations may experience concentrations of NO_2 that could pose significant health risks based on the established LOC-3 criteria.

Looking at the outcome simulation for CO emission as display in Figure 4.7, the dispersion of CO emission is slightly bigger compared to NO_2. This can be observed as a threat zone that exceeds LOC-3 reaches 1.8 kilometers further compared to NO_2 in the same wind direction and source point. Similar to NO_2 dispersion modelling, threat zone for LOC-2 and LOC-1 are greater than 10 kilometers from the source point.

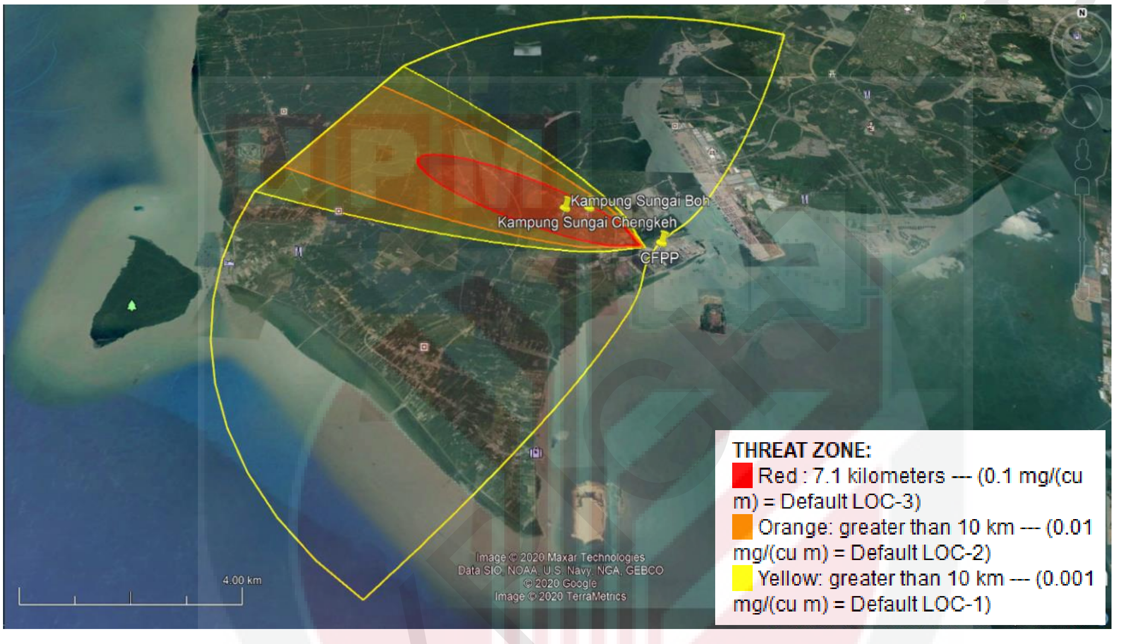

Figure 4.7 : Threat Zone for Worst-Case Scenario (Maximum) of CO Emission

4.3.3 Threat Zones for Best-Case Scenario by Using ALOHA Modelling

For best-case scenario (minimum), the ground level concentration is very low. Therefore, to obtain the ground level concentration values, ALOHA's LOC are set to user defined as below:

a) LOC-1 (yellow zone) = $1e^{-12}$ mg/m^3

b) LOC-2 (orange zone) = $1e^{-10}$ mg/m^3

c) LOC-3 (red zone) = $1e^{-8}$ mg/m^3

Figure 4.8 illustrates the threat zones simulated for the best-case scenario of SO_2 emissions. In this scenario, Kampung Sungai Chengkeh is located within the LOC-1 threat zone, indicating a lower level of concern. On the other hand, Kampung Sungai Boh is within the LOC-2 threat zone and is positioned closer to the downwind path, indicating a higher concentration level that may pose a more significant risk.

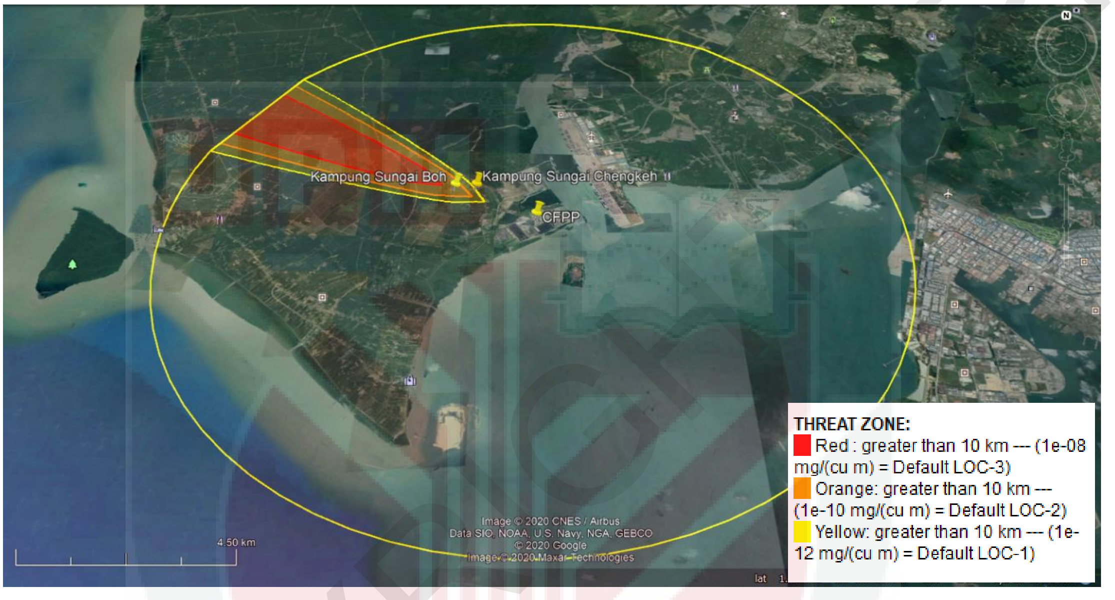

Figure 4.8 : Toxic Threat Zone for the Best-Case Scenario (Minimum) of SO_2 Emission

The best-case scenario for NO_2 emissions is displayed in Figure 4.9. This figure shows that Kampung Sungai Chengkeh lies outside any threat zones, suggesting minimal exposure risk. In contrast, Kampung Sungai Boh falls within the threat zone where concentrations exceed the LOC-1 threshold, indicating a low-level health concern for that area.

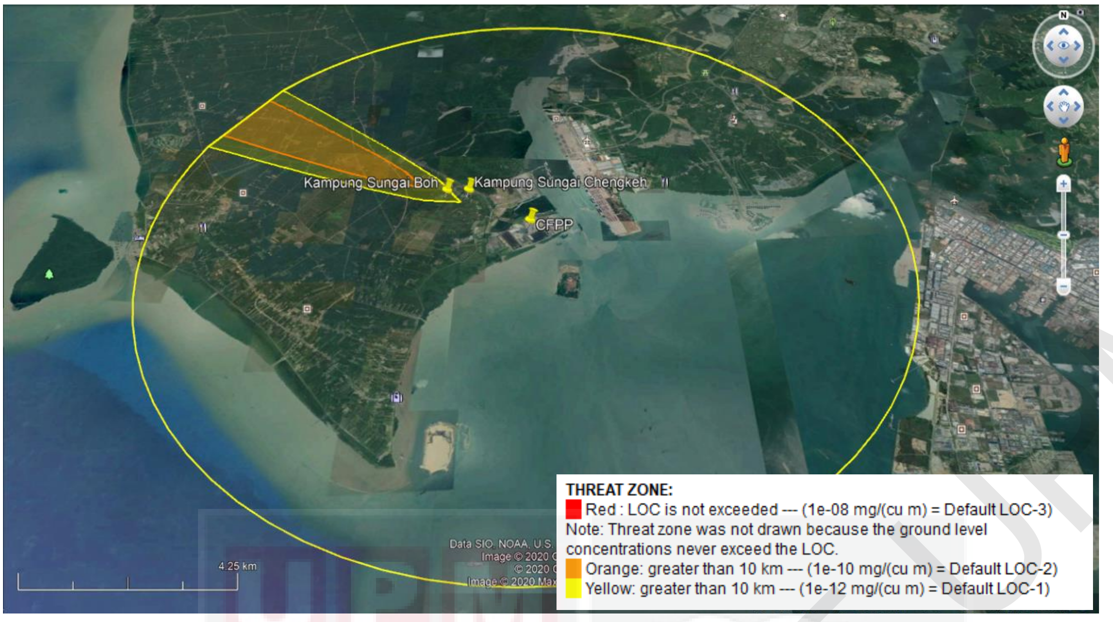

Figure 4.9 : Toxic Threat Zone for the Best-Case Scenario (Minimum) of NO_2 Emission

Similarly, Figure 4.10 presents the simulated threat zones for CO emissions under the best-case scenario. In this case, as with the SO_2 emission scenario, Kampung Sungai Chengkeh is within the LOC-1 threat zone, while Kampung Sungai Boh is situated in the LOC-2 threat zone. This positioning implies that Kampung Sungai Boh may experience higher CO concentrations than Kampung Sungai Chengkeh, warranting more attention to potential health impacts in this area.

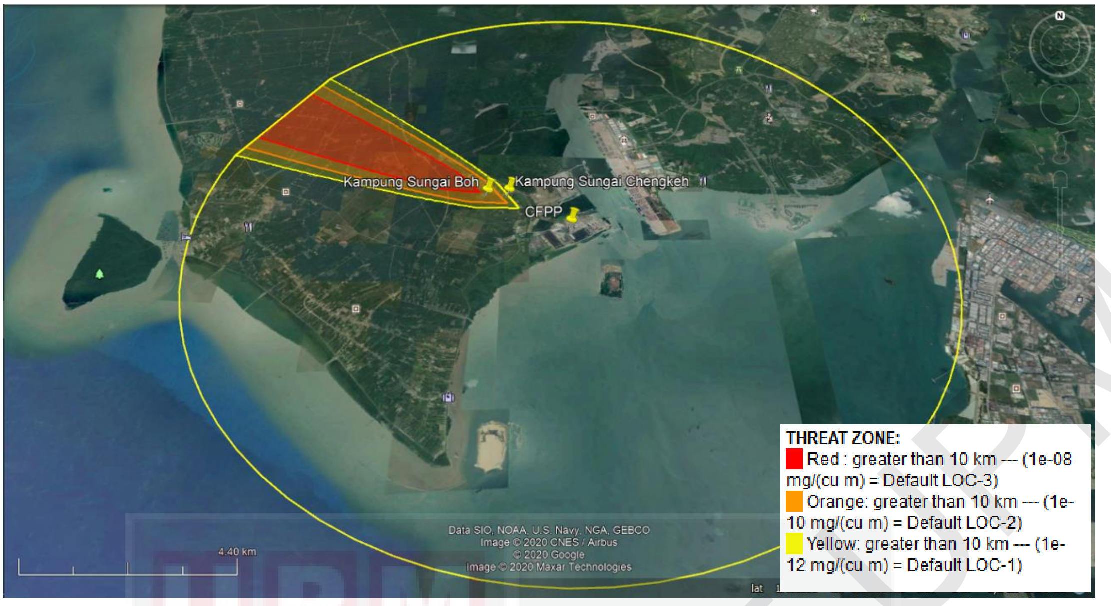

Figure 4.10 : Toxic Threat Zone for the Best-Case Scenario of CO Emission

4.3.4 Ground Level Concentrations of Threat Points for Worst-Case Scenario

Two treat points (Kampung Sungai Boh and Kampung Sungai Chengkeh) have been selected as discussed in Section 4.3.2. Ground level concentrations of the threat points are evaluated by specifying the coordinates of the source point as demonstrated in Figure 4.11**.** The input coordinates Y and X of the respective points are tabulated in Table 4.2**.** Other than that, the position of the treat points also can be expressed in term of downwind and crosswind which would be used for PM_{10} manual calculation.

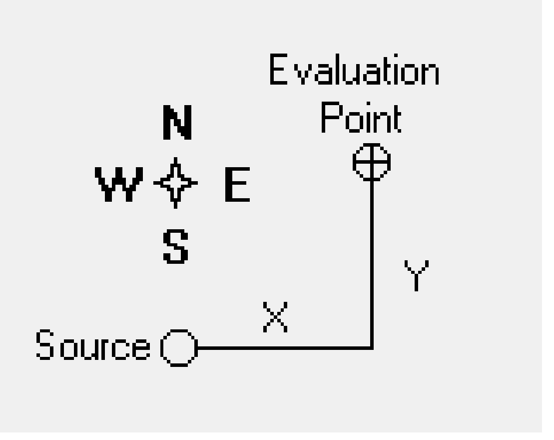

Figure 4.11 : Fixed Coordinates of Evaluation Point

Table 4.2 : Threat Points Coordinate

Threat point	Coordinate X	Coordinate Y	Downwind	Crosswind
Kampung Sungai Boh	2.33 West	1.23 West	2.633 km	0.099 km
Kampung Sungai Chengkeh	1.72 North	1.24 North	2.116 km	0.211 km

As shown in Table 4.3, ground-level concentrations of pollutants at Kampung Sungai Chengkeh are approximately 10% higher than those at Kampung Sungai Boh. The simulations indicate that SO_2 concentrations are the highest, followed by CO, NO_2, and PM_{10}. This result aligns with expectations, demonstrating that increased emission rates lead to higher ground-level concentrations, as discussed in the previous section. Another factor influencing concentration levels is the relative density of the gases. SO_2 has the highest relative density compared to NO_2 and CO, causing it to disperse more slowly and travel longer distances before natural dilution occurs. In contrast, NO_2 and CO, being more buoyant, mix quickly with the surrounding air, leading to a rapid decrease in their concentrations as they disperse [171, 172]. Consequently, SO_2 shows the highest concentration at the threat points among the gases analyzed.

Table 4.3 further reveals that SO_2 is the only pollutant exceeding the 1-hour Maximum Acceptable Ambient Concentration for Air Quality (MAACQ) at both threat points, with simulated levels approximately 60% above the DoE's guideline. For NO_2, concentrations exceed the 1-hour MAACQ only at Kampung Sungai Chengkeh. CO levels, however, remain well below its 1-hour MAACQ at both locations. Due to the absence of historical Air Pollution Index (API) data, PM_{10} concentrations could not be directly compared to the MAACQ. In the worst-case scenario (maximum), the ranking of ground-level concentrations for pollutants at both threat points is as follows: SO_2 > CO > NO_2 > PM_{10}.

Table 4.3 : Ground Level Concentrations at Threat Points for Worst-Case Scenario (Maximum)

Gas Pollutants	Ground Level Concentrations (mg/m^3) for worst-case scenario		
	Kampung Sungai Boh	**Kampung Sungai Chengkeh**	**CFPP DoE Limits** [174]
Sulphur Dioxide (SO_2)	0.895	0.992	<500mg/m3
Carbon monoxide (CO)	0.508	0.562	<200mg/m3
Nitrogen Dioxide (NO_2)	0.310	0.344	<500mg/m3
Particulate Matter (PM_{10})	0.121	0.131	<50mg/m3

Exposure to sulfur dioxide (SO_2) poses significant health risks, particularly to respiratory health and lung function. Individuals working extended hours without breaks may be especially vulnerable to these adverse effects when SO_2 levels are elevated [152]. Studies in industrialized areas, such as South Africa, have also investigated the health risks associated with SO_2 pollution [173]. Additionally, individuals with a larger body mass may experience increased respiratory strain due to factors like lung capacity; greater lung volumes lead to higher air intake, making

SO_2 exposure potentially more harmful for these individuals. It is important to recognize that body weight is influenced by various factors beyond diet, including nutrition, cultural influences, hormonal balance, and environmental conditions.

4.3.5 Ground Level Concentrations of Threat Points for Best-Case Scenario

As shown in Table 4.4, ground-level concentrations at Kampung Sungai Boh are significantly higher than those at Kampung Sungai Chengkeh across all four pollutants. In the best-case scenario, CO has the highest ground-level concentration, followed by SO_2 and NO_2, with PM_{10} showing the lowest concentration among the pollutants. This hierarchy reflects emission rates, where PM_{10} had the lowest emissions, followed by NO_2, SO_2, and CO. While passive samplers provide a convenient method for monitoring air quality, they come with certain limitations. Environmental factors such as temperature, sampling duration, wind speed, and existing pollutant concentrations can influence the accuracy of passive sampling results. Additionally, passive samplers often require extended sampling periods to collect sufficient material for analysis and may struggle to accurately measure fewer volatile compounds due to slow diffusion rates [175, 176].

Table 4.4 : Ground Level Concentrations at Threat Points for Best-Case Scenario

Gas Pollutants	Ground Level Concentrations (mg/m^3) for best-case scenario		
	Kampung Sungai Boh	Kampung Sungai Chengkeh	CFPP DoE Limits
Sulphur Dioxide (SO_2)	$1.92e^{-09}$	$2.91e^{-11}$	<500mg/m3
Carbon monoxide (CO)	$3.33e^{-09}$	$5.04e^{-11}$	<200mg/m3
Nitrogen Dioxide (NO_2)	$8.63e^{-12}$	$1.31e^{-13}$	<500mg/m3
Particulate Matter (PM_{10})	$4.23e^{-16}$	$9.03e^{-21}$	<50mg/m3

To address these limitations and gain a more comprehensive understanding of pollutant distribution, this study incorporated data from active air quality monitoring stations, which offer real-time and more precise measurements. This approach allowed for a detailed evaluation of pollutant levels and spatial distribution, providing a clearer picture of air quality in the studied locations.

4.3.6 Comparison between Ground Level Concentrations of Threat Points for Worst-Case Scenario and Best-Case Scenario

As observed in Table 4.3 and Table 4.4, a key difference (almost 100 difference) between the worst-case and best-case scenarios is the distribution of ground-level concentrations between Kampung Sungai Chengkeh and Kampung Sungai Boh. In the worst-case scenario, Kampung Sungai Chengkeh has higher pollutant concentrations than Kampung Sungai Boh. Conversely, in the best-case scenario, Kampung Sungai Boh records higher ground-level concentrations than Kampung Sungai Chengkeh.

This discrepancy between scenarios can be attributed primarily to differences in atmospheric stability classes. As discussed in Chapter 3, the worst-case scenario was modelled under stability class B, indicating a moderately unstable atmospheric condition. In contrast, the best-case scenario was modelled under stability class E, which represents a slightly stable atmosphere. According to Tim Larson [177], unstable wind conditions promote more pronounced vertical dispersion, while stable wind conditions favor horizontal spreading, as illustrated in Figure 4.12.

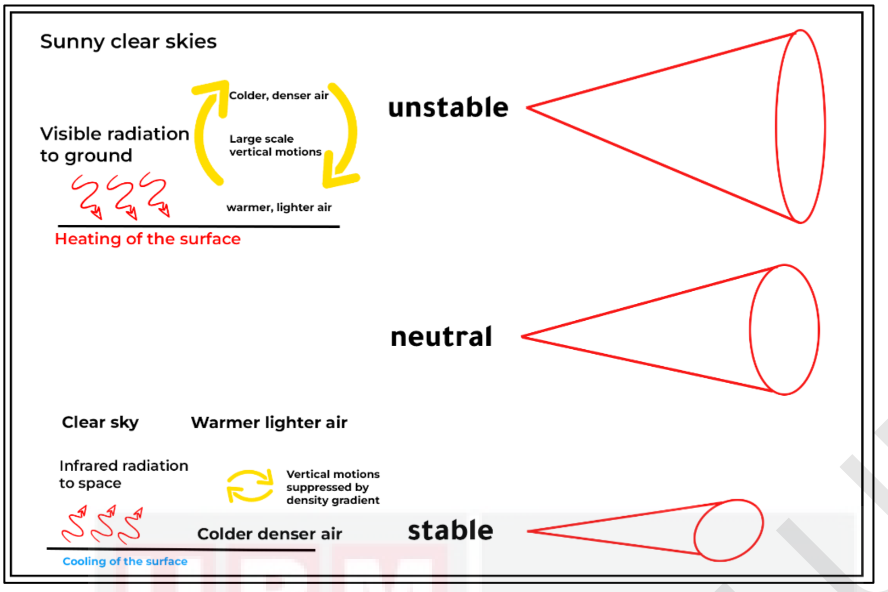

Figure 4.12 : Stability Category Effects on Pollutants Spreading [178]

In the worst-case scenario, turbulent wind conditions lead to vertical and crosswind dispersion, resulting in a broader spread of pollutants. Consequently, Kampung Sungai Chengkeh, which is situated further crosswind but closer downwind, experiences higher pollutant concentrations compared to Kampung Sungai Boh. On the other hand, under the best-case scenario with stable wind conditions, pollutants spread horizontally. As a result, Kampung Sungai Boh, which is positioned at a closer crosswind distance, records higher concentrations than Kampung Sungai Chengkeh. The horizontal dispersion at approximately 200 meters in height also explains why ground-level concentrations are generally lower in the best-case scenario.

4.4 Health Risk Assessment

4.4.1 Average Daily Dose (ADD) for Acute and Chronic Exposure for Worst-Case Scenario

To evaluate the hazard quotient for acute and chronic health effects, the Average Daily Dose (ADD) is determined using equations detailed in Section 2.7.5. Ground-level concentration values, shown in Tables 17–20, serve as the basis for estimating the ADD for both acute and chronic exposures. Table 4.10 and Table 4.11 record the ADD of air pollutants at Kampung Sungai Boh, while Tables 19 and 20 present the ADD for Kampung Sungai Chengkeh.

At Kampung Sungai Boh, the mean ADD values (acute exposure) for adult males, adult females, male children, and female children are 0.103, 0.086, 0.197, and 0.186 mg/kg/day, respectively. For chronic exposure, the mean ADD values for these groups are 0.099, 0.083, 0.189, and 0.179 mg/kg/day, respectively. Meanwhile, at Kampung Sungai Chengkeh, the calculated mean ADD values (acute exposure) for adult males, adult females, male children, and female children are 0.113, 0.096, 0.218, and 0.206 mg/kg/day, respectively. For chronic exposure, the values are 0.109, 0.092, 0.209, and 0.198 mg/kg/day, respectively.

The calculated mean values indicate that male children have the highest exposure risk, followed by female children, adult males, and adult females. This trend can be attributed to two main factors: first, children generally have lower body weight than adults, and second, they possess a larger lung surface area relative to body weight. While adults may inhale more air overall due to larger lung capacity, the air volume passing through lung tissue (per unit of body weight) is relatively higher in children [179, 180].

Among air pollutants, SO_2 has the highest ADD values, followed by CO and NO_2, with PM_{10} showing the lowest ADD values. These results align with expectations, as ADD values are directly proportional to ground-level concentrations, with SO_2

concentrations being the highest, as discussed in Section 4.3.4. Therefore, the higher the ground-level concentration, the greater the ADD intake for individuals exposed to these air pollutants.

Table 4.5 : ADD of Air Pollutants in Kampung Sungai Boh for Acute Health Effects of Worst-Case Scenario (Maximum)

Average Daily Dose (ADD) of Air Pollutants in Kampung Sungai Boh for Acute Health Effects (mg/kg day) of Worst-Case Scenario					
Gas		SO_2	CO	NO_2	PM
Adult	Male	0.200	0.114	0.069	0.027
	Female	0.169	0.096	0.058	0.023
Children	Male	0.384	0.218	0.133	0.052
	Female	0.364	0.206	0.126	0.049

Table 4.6 : ADD of Air Pollutants in Kampung Sungai Boh for Chronic Health Effects of Worst-Case Scenario (Maximum)

Average Daily Dose (ADD) of Air Pollutants in Kampung Sungai Boh for Chronic Health Effects (mg/kg day) of Worst-Case Scenario					
Gas		SO_2	CO	NO_2	PM
Adult	Male	0.192	0.109	0.067	0.026
	Female	0.162	0.092	0.056	0.022
Children	Male	0.370	0.210	0.128	0.050
	Female	0.350	0.198	0.121	0.047

Table 4.7 : ADD of Air Pollutans in Kampung Sungai Chengkeh for Acute Health Effects of Worst-Case Scenario (Maximum)

Average Daily Dose (ADD) of Air Pollutants in Kampung Sungai Chengkeh for Acute Health Effects (mg/kg day) of Worst-Case Scenario					
Gas		SO_2	CO	NO_2	PM
Adult	Male	0.222	0.126	0.077	0.029
	Female	0.187	0.106	0.065	0.024
Children	Male	0.426	0.241	0.148	0.055
	Female	0.403	0.228	0.140	0.052

Table 4.8 : ADD of Air Pollutans in Kampung Sungai Chengkeh for Chronic Health Effects of Worst-Case Scenario (Maximum)

Average Daily Dose (ADD) of Air Pollutants in Kampung Sungai Chengkeh for chronic Health Effects (mg/kg day) of Worst-Case Scenario					
Gas		SO_2	CO	NO_2	PM
Adult	Male	0.190	0.121	0.074	0.028
	Female	0.160	0.102	0.062	0.023
Children	Male	0.366	0.232	0.142	0.053
	Female	0.346	0.220	0.134	0.050

4.4.2 Average Daily Dose (ADD) for Acute and Chronic Exposure of the Best-Case Scenario

The Average Daily Dose (ADD) values for acute and chronic exposures in Kampung Sungai Boh and Kampung Sungai Chengkeh are presented in Tables 4.9, 4.10, 4.11, and 4.12. These values provide insights into the relative exposure risks faced by different demographic groups under typical (best-case) conditions.

Table 4.9 : ADD of Air Pollutants in Kampung Sungai Boh for Acute Health Effects of Best-Case Scenario

Average Daily Dose (ADD) of Air Pollutants in Kampung Sungai Boh for Acute Health Effects (mg/kg day) of Best-Case Scenario					
Gas		SO_2	CO	NO_2	PM
Adult	Male	$4.29e^{-10}$	$7.44e^{-10}$	$1.93e^{-12}$	$9.45e^{-17}$
	Female	$3.62e^{-10}$	$6.27e^{-10}$	$1.63e^{-12}$	$7.96e^{-17}$
Children	Male	$8.25e^{-10}$	$1.43e^{-09}$	$3.71e^{-12}$	$1.82e^{-16}$
	Female	$7.80e^{-10}$	1.35e-09	$3.51e^{-12}$	$1.72e^{-16}$

The ADD of pollutants for acute exposure in Kampung Sungai Boh in Table 4.9, shows that, male children exhibit the highest ADD values across all pollutants, with SO_2 at $8.25e^{-10}$ mg/kg/day, CO at $1.43e^{-09}$ mg/kg/day, NO_2 at $3.71e^{-12}$ mg/kg/day, and PM at $1.82e^{-16}$ mg/kg/day. This elevated ADD suggests that male children are particularly vulnerable to acute health effects under typical conditions, likely due to their higher respiratory rates and lower body mass [181], which increase pollutant intake per kilogram of body weight. In contrast, adult females in Kampung Sungai Boh show the lowest ADD values, with SO_2 at $3.62e^{-10}$ mg/kg/day, CO at $6.27e^{-10}$ mg/kg/day, NO_2 at 1.63e-12 mg/kg/day, and PM at $7.96e^{-17}$ mg/kg/day. This lower exposure in adult females may be attributed to gender-related physiological factors, such as lower respiratory intake relative to body size.

Table 4.10 : ADD of Air Pollutants in Kampung Sungai Boh for Chronic Health Effects of Best-Case Scenario

Average Daily Dose (ADD) of Air Pollutants in Kampung Sungai Boh for Chronic Health Effects (mg/kg day) of Best-Case Scenario					
Gas		SO_2	CO	NO_2	PM
Adult	Male	$4.13e^{-10}$	$7.16e^{-10}$	$1.85e^{-12}$	$9.08e^{-17}$
	Female	$3.48e^{-10}$	$6.03e^{-10}$	$1.56e^{-12}$	$7.65e^{-17}$
Children	Male	$7.93e^{-10}$	$1.38e^{-09}$	$3.56e^{-12}$	$1.75e^{-16}$
	Female	$7.50e^{-10}$	$1.30e^{-09}$	$3.37e^{-12}$	$1.65e^{-16}$

Table 4.10 illustrates the ADD values for chronic exposure in Kampung Sungai Boh. Similar to the acute exposure findings, male children again have the highest ADD, with chronic SO_2 exposure at $7.93e^{-10}$ mg/kg/day, CO at $1.38e^{-09}$ mg/kg/day, NO_2 at $3.56e^{-12}$ mg/kg/day, and PM at $1.75e^{-16}$ mg/kg/day. The consistent pattern of higher chronic exposure in male children compared to other demographics underscores the cumulative risk they face over time. Conversely, adult females present the lowest ADD values, suggesting reduced chronic exposure due to their generally lower pollutant intake.

Table 4.11 : ADD of Air Pollutants in Kampung Sungai Chengkeh for Acute Health Effects of Best-Case Scenario

Average Daily Dose (ADD) of Air Pollutants in Kampung Sungai Chengkeh for Acute Health Effects (mg/kg day) of Best-Case Scenario					
Gas		SO_2	CO	NO_2	PM
Adult	Male	$6.50e^{-12}$	$1.13e^{-11}$	$2.93e^{-14}$	$2.02e^{-21}$
	Female	$5.48e^{-12}$	$9.49e^{-12}$	$2.47e^{-14}$	$1.70e^{-21}$
Children	Male	$1.25e^{-11}$	$2.16e^{-11}$	$5.63e^{-14}$	$3.88e^{-21}$
	Female	$1.18e^{-11}$	$2.05e^{-11}$	$5.32e^{-14}$	$3.67e^{-21}$

While, Table 4.11 reports the ADD for acute exposure in Kampung Sungai Chengkeh. Here, the ADD values for pollutants in male children are notably lower than those observed in Kampung Sungai Boh. For example, acute SO_2 exposure for male children is 1.25e-11 mg/kg/day, and CO exposure is $2.16e^{-11}$ mg/kg/day. These lower values may be due to Kampung Sungai Chengkeh's distance from pollutant sources or other geographic factors. Adult females in Kampung Sungai Chengkeh also exhibit the lowest ADD values, reinforcing the trend observed in Kampung Sungai Boh and indicating a generally lower risk for this demographic.

Table 4.12 : ADD of Air Pollutants in Kampung Sungai Chengkeh for Chronic Health Effects of Best-Case Scenario

Average Daily Dose (ADD) of Air Pollutants in Kampung Sungai Chengkeh for Chronic Health Effects (mg/kg day) of Best-Case Scenario					
Gas		SO_2	CO	NO_2	PM
Adult	Male	$6.25e^{-12}$	$1.08e^{-11}$	$2.82e^{-14}$	$1.94e^{-21}$
	Female	$5.27e^{-12}$	$9.13e^{-12}$	$2.37e^{-14}$	$1.64e^{-21}$
Children	Male	$1.20e^{-11}$	$2.08e^{-11}$	$5.41e^{-14}$	$3.73e^{-21}$
	Female	$1.14e^{-11}$	$1.97e^{-11}$	$5.12e^{-14}$	$3.53e^{-21}$

The ADD for chronic exposure in Kampung Sungai Chengkeh is presented in Table 4.12. Consistent with acute exposure results, male children display the highest ADD values, with chronic SO_2 exposure at $1.20e^{-11}$ mg/kg/day and CO exposure at $2.08e^{-11}$ mg/kg/day. This indicates a heightened vulnerability to long-term health impacts for male children in Kampung Sungai Chengkeh, although the exposure values remain lower than those recorded in Kampung Sungai Boh. The lowest ADD values are again observed in adult females, with chronic SO_2 exposure at $5.27e^{-12}$ mg/kg/day and CO exposure at $9.13e^{-12}$ mg/kg/day, highlighting their comparatively lower risk.

This analysis reveals significant disparities in ADD values across demographics and locations. The consistently higher ADD values in male children compared to other groups reflect their greater vulnerability, particularly in Kampung Sungai Boh. These findings suggest that children, especially male children, are at a higher risk of both acute and chronic health effects from air pollution exposure. This highlights the importance of targeted air quality management strategies and health interventions to protect these vulnerable populations.

4.4.3 Hazard Quotient (HQ) for Acute and Chronic Health Effects of Worst-Case Scenario

ADD values as tabulated in Table 4.9, Table 4.10, Table 4.11, Table 4.12 are used to calculate the hazard quotient (HQ) for acute and chronic health effects of the worst-case scenario. Estimated HQ values for acute health effects at Kampung Sungai Boh are displayed in Figure 4.13, while for chronic health effects are displayed in Figure 4.14. Meanwhile, estimated HQ values for acute health effects at Kampung Sungai Chengkeh are illustrated in Figure 4.15 and for chronic health effects are illustrated in Figure 4.16. As mentioned in Section Air Pollution Health Risk Assessment (AP-HRA)2.7.6, when the HQ values are less than 1, the adverse health effects are unlikely to occur. Hence, an increase in HQ indicates the probability of the development of potential health risk. It is also important to be noted that if the HQ values more than 10, the chronic risk is high [120].

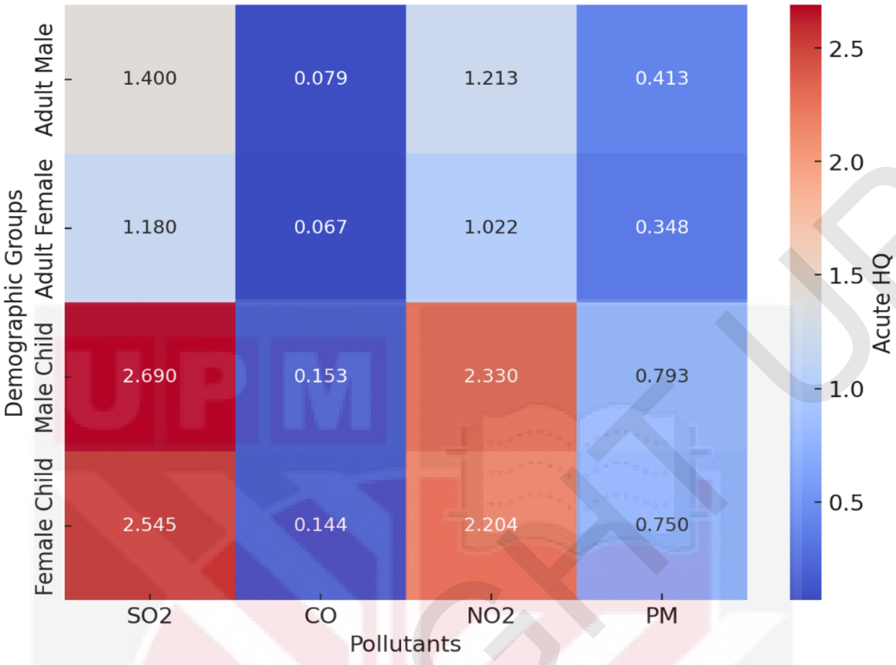

Figure 4.13 : Maximum Acute (Worst-Case Scenario) HQ Values by Group in Kampung Sungai Boh

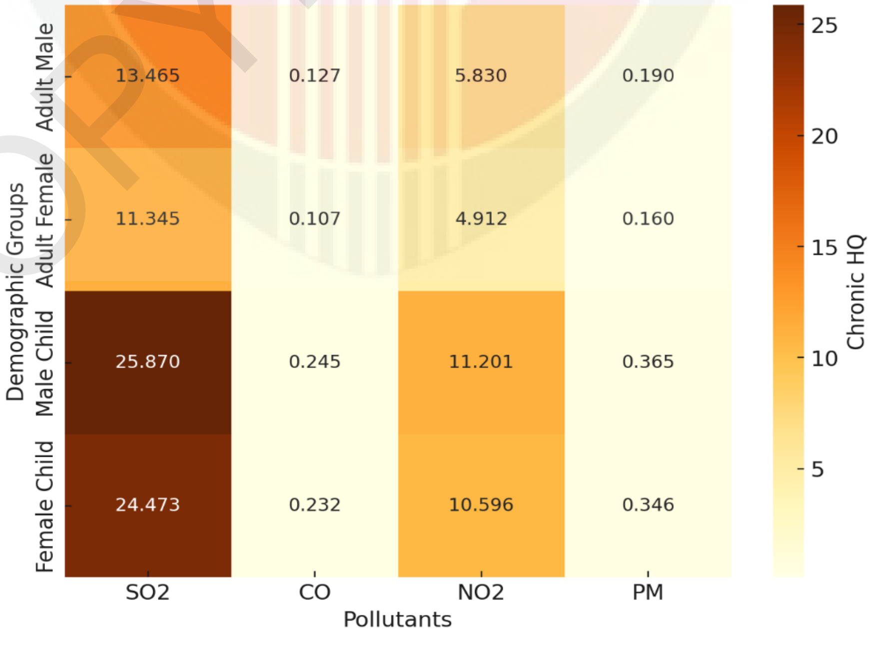

Figure 4.14 : Maximum Chronic (Worst-Case Scenario) HQ Values by Group in Kampung Sungai Boh

As can be observed in Kampung Sungai Boh (Figure 4.13 and Figure 4.14), HQs for adult and children exposed to SO_2 and NO_2 are above 1. Meanwhile, CO and PM_{10} exposure HQs for both adults and children are less than 1. The same result can be seen in Kampung Sungai Chengkeh (Figure 4.15 and Figure 4.16), where HQs for NO_2 and SO_2 exposure are recorded more than 1 for adult and children, while HQs for adult and children exposed to CO and PM_{10} are less than 1 for both acute and chronic health effects. Critically, HQs for all group age of SO_2 exposure in both villages and NO_2 exposure for children in both villages are more than 10, which indicate high chronic risk.

In terms of age group comparison, male children are at higher risk compared to female children, the same as for adults, male are at higher risk compared to female. These results are predicted because the male has a higher inhalation rate compared to female.

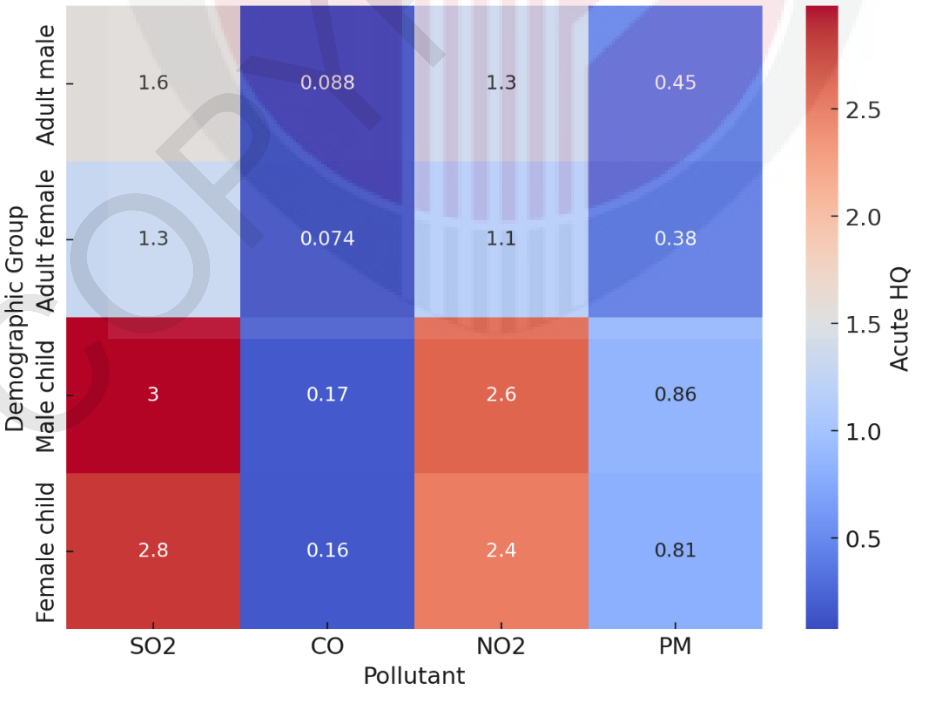

Figure 4.15 : Maximum Acute (Worst-Case Scenario) HQ Values by Group in Kampung Sungai Chengkeh

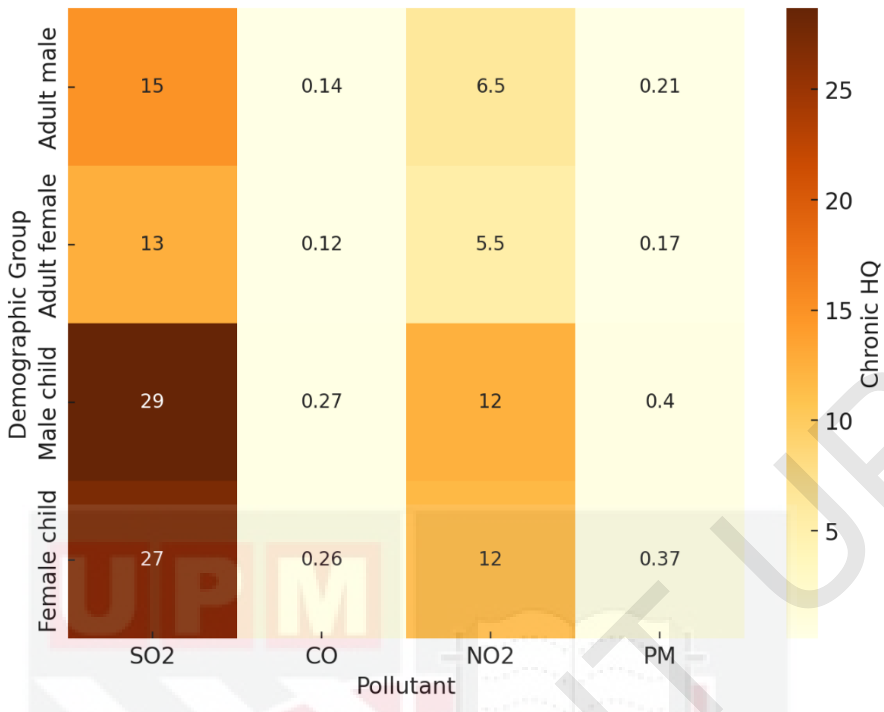

Figure 4.16 : Maximum Chronic (Worst-Case Scenario) HQ Values by Group in Kampung Sungai Chengkeh

Thus, the male is likely to has a higher health risk in air pollution exposures. Furthermore, the results indicate that short and long period exposure to SO_2 are the highest threat for both adults and children. This is due to the high ground level concentration of SO_2 and low RfC values of SO_2. Thus, the HQs for SO_2 are significantly higher compared to other gases. In contrast, RfC values of CO for both acute and chronic exposures are relatively the highest compared to three other gases. Hence, HQs due to CO exposure are the lowest compared to other gases. This result suggested that neither adults nor children would suffer a potential health risk when exposed to only CO and PM_{10}.

In comparison to one of the studies conducted in an urban-industrial area in South Africa where the pollutants originated from a CFPP, metallurgical industries and a manganese smelter, [145] reported that the acute HQ of SO_2 exposure (in the study, it is referring to intermediate worst-case) for child exposure was 0.1 and for adult was 0.07. Meanwhile, for acute HQs of PM_{10} exposure, the child was 0.11 and adult was 0.03. From this study, the acute HQs finding are much lesser compared to the study conducted in South Africa.

Opposing to the chronic HQs, the findings of the study for chronic HQ exposures (in the study, it is referring to chronic worst-case (maximum), were much higher compared to the findings from this study. For example, the chronic HQ of SO_2 exposure for the child was 449 and the adult was 682. Meanwhile, for chronic HQ of PM_{10} exposure for the child was 362 and the adult was 281. The huge differences (almost 100 difference) might be because of the different condition of the pollutant emission such as the study conducted in South Africa had multiple pollutants source and used difference RfC values.

4.4.4 Hazard Quotient (HQ) for Acute and Chronic Health Effects of Best-Case Scenario

ADD values as tabulated in Table 4.9, Table 4.10, Table 4.11, Table 4.12 used to calculate the HQ for acute and chronic health effects of the best-case scenario.

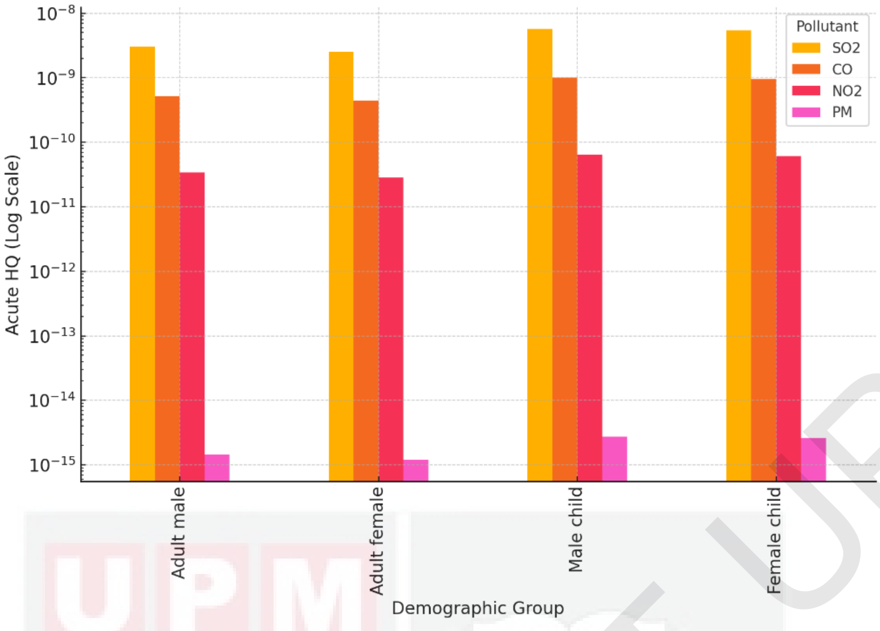

Figure 4.17 : Minimum Acute (Best-Case Scenario) HQ Values by Group in Kampung Sungai Boh

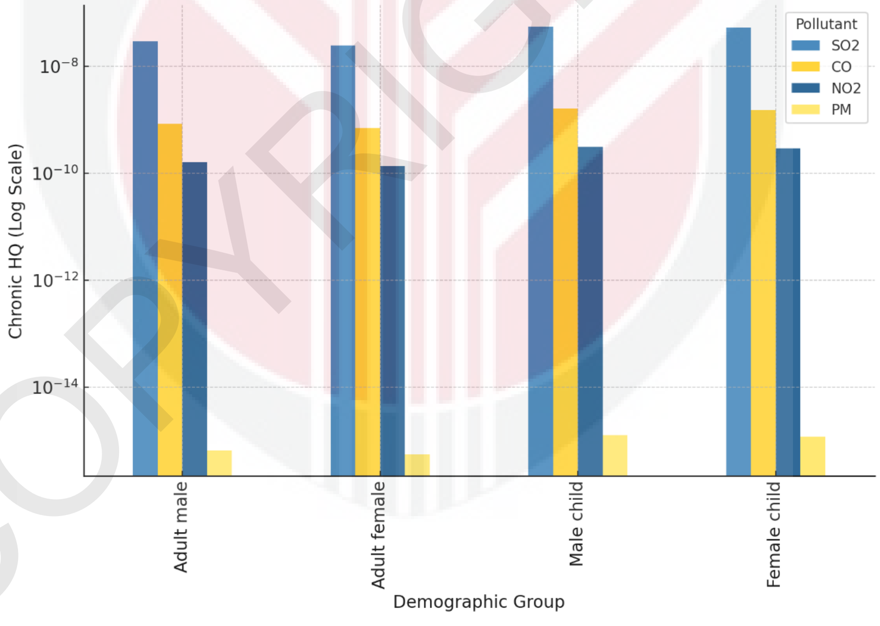

Figure 4.18 : Minimum Chronic (Best-Case Scenario) HQ Values by Group in Kampung Sungai Boh

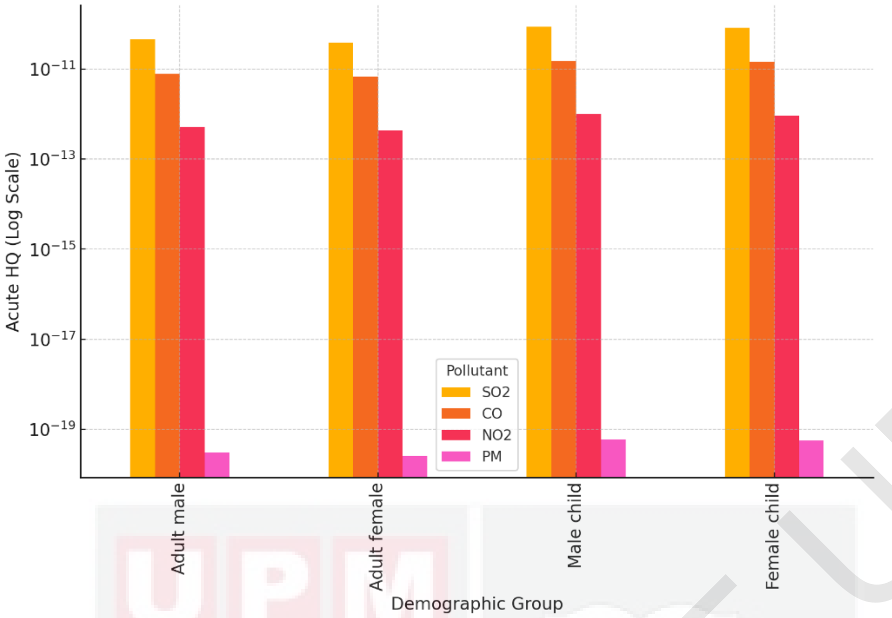

Figure 4.19 : Minimum Acute (Best-Case Scenario) HQ Values by Group in Kampung Sungai Chengkeh

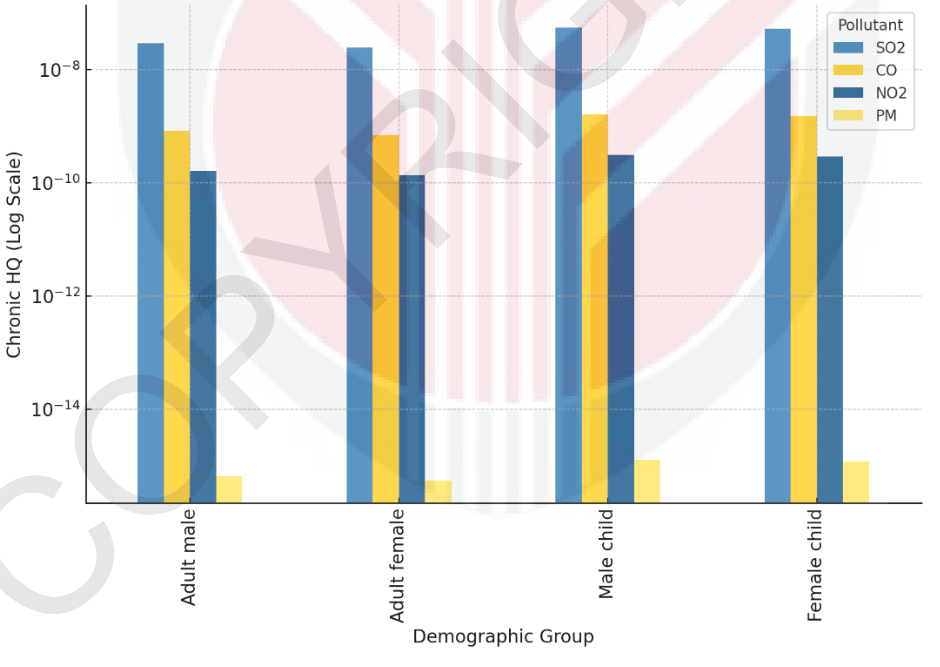

Figure 4.20 : Minimum Chronic (Best-Case Scenario) HQ Values by Group in Kampung Sungai Chengkeh

As can be observed from Figure 4.17, Figure 4.18, Figure 4.19, Figure 4.20, all the HQ values are very low and can be negligible. For the best-case scenario, even though the inhaled ADDs of CO are higher compared to SO_2 ADDs intake, the acute and chronic HQs of SO_2 for both villages are significantly higher compared to CO. This is because the RfC values for SO_2 are 90% lower compared to CO RfC values. HQ is inversely proportional to the RfC values.

4.4.5 Hazard Index (HI) for Acute and Chronic Health Effects

Hazard indexes (HIs) are estimated using the HQ values to obtain the deposited dose to the studied groups' exposure to air pollutants. Figure 4.21 below shows a comparison of acute exposure HI for different studied groups at Kampung Sungai Boh with population lives at Kampung Sungai Chengkeh. Meanwhile, for chronic exposure, estimated HIs for all studied group live at Kampung Sungai Boh and Kampung Sungai Chengkeh are displayed in Figure 4.22.

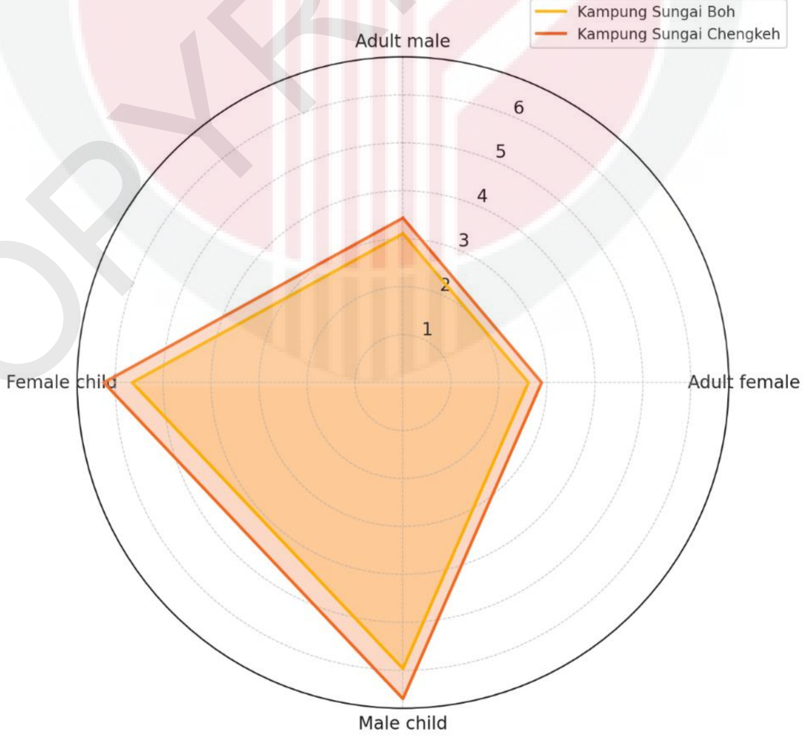

Figure 4.21 : Comparison of Acute Exposure HI in Kampung Sungai Boh with Kampung Sungai Chengkeh

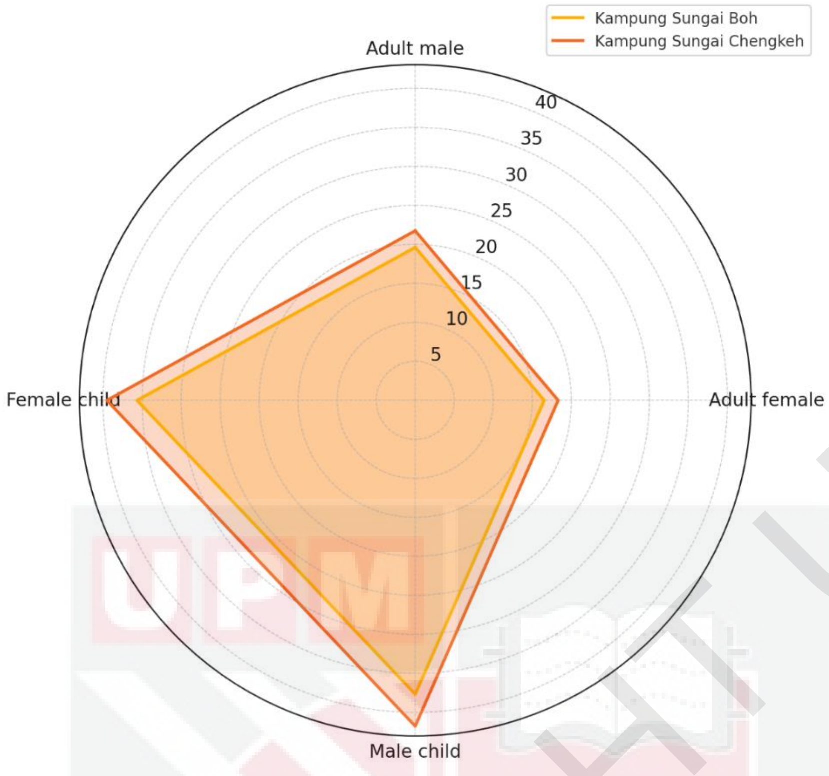

Figure 4.22 : Comparison of Chronic Exposure HI in Kampung Sungai Boh with Kampung Sungai Chengkeh

According to the HQs acute values as recorded in Figure 4.18 and Figure 4.20, SO_2, NO_2, PM_{10} and CO accounted for approximately 45%, 39%, 13% and 3% respectively of the HI values for the adult male, male child, adult female and female child at both threat areas. Meanwhile, for chronic exposure HIs, SO_2 exposure HQ values are accounted more than 50% compared to NO_2 (30%), CO (0.65%) and PM_{10} (1%) for all studied groups.

HI acute values estimated at Kampung Sungai Chengkeh are 9.5% higher compared to HIs acute values evaluated at Kampung Sungai Boh. While, for chronic health effects, calculated HIs value at Kampung Sungai Chengkeh is 9.8% higher compared to Kampung Sungai Boh for all studied groups. These results are in line with the consistency of ground level concentration where Kampung Sungai Chengkeh has about 10% higher estimated concentration values than Kampung Sungai Boh as stated in Section 4.3.4.

Based on the findings recorded below, it is concerning as the estimated HI values for all studied groups are remarkably above 1 which indicates negative health outcomes are probable. HI for SO_2, NO_2 and CO exposures are targeting cardiovascular and respiratory system [182]. Therefore, all the studied groups who are living in Kampung Sungai Boh and Kampung Sungai Chengkeh have a high tendency to experience cardiovascular diseases and respiratory diseases.

The HI values for the best-case scenario are not displayed in this document as the values are significantly low. The range of acute HIs of both villages is from $4.54e^{-11}$ (adult female who live in Kampung Sungai Chengkeh) to $6.84e^{-09}$ (the male child who live in Kampung Sungai Boh). Same for chronic HI values, adult female who lives in Kampung Sungai Chengkeh has the lowest value ($3.81e^{-10}$) and male children who live at Kampung Sungai Boh has the highest value ($5.74e^{-08}$). These findings are affected by the ADD values in discussion Section 4.4, where male children who live in Kampung Sungai Boh have the highest values and women who live in Kampung Sungai Chengkeh have the lowest ADD values.

4.5 Conclusion

This chapter highlights the critical findings from the emission data analysis, modeling, and health risk assessment. Historical data analysis revealed that SO_2 emissions were consistently the highest among pollutants, followed by CO, NO_2, and PM_{10}, with notable variability across sampling periods. ALOHA and Gaussian Plume Dispersion simulations showed significant differences (almost 100 difference) between worst-case and best-case scenarios, with worst-case conditions yielding higher ground-level pollutant concentrations, particularly for SO_2.

The health risk assessment demonstrated that children, especially male children, are the most vulnerable group due to higher ADD values. SO_2 consistently presented the greatest health risk, with Hazard Quotient (HQ) and Hazard Index (HI) values indicating potential respiratory and cardiovascular effects for all groups at both Kampung Sungai Boh and Kampung Sungai Chengkeh in worst-case conditions. These findings emphasize the need for targeted interventions to mitigate air pollution exposure in these communities.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, this study successfully achieved all of its objectives, with two of the three hypotheses being accepted. The first hypothesis, stating that ALOHA software is suitable for predicting ground-level pollutant concentrations, is validated. The simulated concentrations align well with observed real-world data, demonstrating the model's accuracy. A comprehensive sensitivity analysis further confirmed the model's stability and reliability, supporting its use for estimating pollutant dispersion from CFPP emissions. The reliable predictions provided by this model are valuable for policymakers, as they highlight the potential impact of increasing coal consumption on air quality, particularly in regions like Southeast Asia, where electricity demand is projected to grow post-COVID-19.

The second hypothesis, which anticipated that acute and chronic health risks would remain within acceptable levels for SO_2 and NO_2 exposures, was rejected. The findings reveal that hazard quotients (HQ) for both acute and chronic exposure to SO_2 and NO_2 exceed acceptable limits in both Kampung Sungai Boh and Kampung Sungai Chengkeh. This suggests significant health risks for residents, particularly in Kampung Sungai Chengkeh, where pollutant concentrations were found to be 10% higher than in Kampung Sungai Boh. However, it should be noted that these results are influenced by factors such as atmospheric conditions and emission rates, which vary over time.

The third hypothesis, asserting that children are more vulnerable to air pollution than adults, is accepted. Analysis shows that male children are the most susceptible, followed by female children, adult males, and adult females. These results highlight the pressing health risks posed by CFPP emissions, particularly to younger populations, underscoring the need for protective measures.

This research provides critical evidence of the health impacts of CFPP emissions on nearby communities. Despite adherence to the Malaysian Ambient Air Quality Guidelines (MAAQG), the emissions from CFPPs in the worst-case scenario still pose a substantial risk to public health in both villages. Therefore, it is essential for both the government and CFPP management to develop both short- and long-term strategies to mitigate these risks. This includes not only ensuring compliance with MAAQG standards but also implementing stricter controls on the release timing and concentrations of pollutants such as SO_2, CO, NO_2, and PM_{10} to protect the health and well-being of vulnerable communities.

5.2 Recommendations

Several recommendations can be made to enhance this study. First, it is advised to use meteorological data from stations closer to the studied CFPP site, as air dispersion modeling is significantly influenced by atmospheric data quality. High-quality meteorological data would yield more accurate pollutant modeling results, which should be communicated to authorities and CFPP management to guide decision-making and address worst-case health scenarios for nearby communities. To further reduce emissions and enhance environmental compliance, the CFPP should consider investing in advanced scrubber technology, as seen in Germany's industrial best practices. Scrubbers are effective at removing harmful pollutants such as chlorine, sulfur dioxide, hydrogen chloride, and hydrogen sulfide. Germany's commitment to greenhouse gas neutrality by 2045, through its "Energiewende" (energy transition) strategy, serves as a model for balancing economic growth with sustainability by phasing out coal-fired plants and promoting renewable energy.

Secondly, it is recommended to simulate multiple pollutant sources, as several nearby sources may contribute significantly to ambient pollution levels. Including multiple sources in the model would allow for a more comprehensive assessment of exposure levels and health risks. Finally, for calculating the Average Daily Dose (ADD), it is beneficial to account for human activities in various microenvironments, such as indoor spaces like homes or stores, where pollutant concentrations are generally lower than outdoors. While this consideration may refine short-term exposure estimates, it is essential to address the core issue—pollutants emitted from the CFPP. Investing in cleaner technologies to reduce SO_2, CO, NO_2, and PM_{10} concentrations remains vital for protecting public health in the long term.

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APPENDICES

Appendix A

Sample Calculation of Wind Power Law

Wind speed at 200m with wind speed at 37.8 reference height for the worst-case scenario:

Data input	
Power law	0.07
Stability class	B
Wind speed at 37.8m, u_2 (m/s)	2
Stack height, z_1 or h (m)	200

$$u_1 = (\frac{z_1}{z_2})^n \times u_2 = (\frac{200m}{37.8m})^{0.07} \times \frac{2m}{s} = 2.25m/s$$

Appendix B

Sample ALOHA Input Simulation

The diagram below shows ALOHA input simulation of the worst-case scenario for SO_2 emission and threat point in Kampung Sungai Chengkeh.

```
Text Summary
SITE DATA:
  Location: KUKUP, MALAYSIA
  Building Air Exchanges Per Hour: 0.44 (unsheltered single storied)
  Time: March 11, 2020  1200 hours ST (user specified)

CHEMICAL DATA:
  Chemical Name: SULFUR DIOXIDE
  CAS Number: 7446-9-5                    Molecular Weight: 64.06 g/mol
  AEGL-1 (60 min): 0.524 mg/(cu m)   AEGL-2 (60 min): 1.965 mg/(cu m)   AEGL-3 (60 min): 78.602 mg/(cu m)
  IDLH: 100 ppm
  Ambient Boiling Point: -10.0° C
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 2.25 meters/second from 120° true at 200 meters
  Ground Roughness: open country          Cloud Cover: 7 tenths
  Air Temperature: 28.3° C                Stability Class: B
  No Inversion Height                     Relative Humidity: 82%

SOURCE STRENGTH:
  Direct Source: 3414.73 kilograms/hr    Source Height: 200 meters
  Release Duration: 60 minutes
  Release Rate: 56.9 kilograms/min
  Total Amount Released: 3,415 kilograms
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT AT POINT:
  Concentration Estimates at the point:
  West: 1.72 kilometers                   North: 1.24 kilometers
  Max Concentration:
     Outdoor: 0.992 mg/(cu m)
     Indoor:  0.274 mg/(cu m)
```

Appendix C

Sample Calculation of Gaussian Plume Dispersion of PM_{10}

C.1 : Initial Buoyancy Flux for Plume Rise, F_b

The data are obtained from the historical data.

Data input	
Initial velocity of gas flow, w_0 (m/s)	15.26
Initial stack radius, R_0 (m)	7.5
Initial plume temperature at the stack height T_{p0}, (K)	364
Initial ambient temperature at the stack height, T_{a0}, (K)	301.3

$$F_b = \frac{W_0 {R_0}^2 g}{T_{P0}(T_{P0} - T_{a0})} = (\frac{\frac{15.26m}{s} \times 7.5m^2 \times \frac{9.8m}{s^2}}{364K(364K - 301.3K)} = 0.369m^4 s^{-3}$$

C.2 : Plume rise, Δh

$$\Delta h = \frac{21.425 \times \ {F_b}^{0.75}}{u} = \frac{21.425 \times 0.369^{0.75}}{2.25} = 4.53m$$

C.3 : Downwind and crosswind Distance at Kampung Sungai Boh

Data input	
Coordinate X (km) (from Marplot and ALOHA)	2.33
Coordinate Y (km) (from Marplot and ALOHA)	1.23
Angle from centre to receptor, θ (degree)	297.83◦
Wind direction, *WD* (degree)	120◦

$$r(hypothenus\ source\ to\ receptor) = \sqrt{2.33^2 + 1.23^2} = 2.635km$$

$$x(receptor) = rsin\theta = 2.635 \sin(297.83) = -2.33km$$

$$y(receptor) = rcos\theta = 2.635 \sin(297.83) = 1.23km$$

$$x = -x(receptor) \sin(WD) - y(receptor) \cos(WD)$$
$$= -(-2.33 \sin(120)) - 1.23 \cos(120) = 2.6328km$$

$$y = x(receptor)\cos(WD) - y(receptor)\sin(WD)$$
$$= (-2.33\sin(120)) - 1.23\cos(120) = 0.0998km$$

C.4 : Vertical Settling of Particulate Matter10, h_v

Data input	
Particle diameter for particulate, ρ (μm)	10
Particle density, ρ_ρ (g/cm^3)	1.65
Downwind distance, *x* (m) of Kampung Sungai Boh	2632.84
Wind speed at the effective release height (assume same as wind speed at 200m), *u* (m/s)	2.25

$$h_v = \frac{3\times10^{-5}\times x\times {d_\rho}^2\times\rho_\rho}{u} = \frac{3\times10^{-5}\ \times\ 2632.8\times10^2\times1.65}{2.25} = 5.792\ m/s$$

C.5 : Plume Rise, *H*

$$H = (h + \Delta h - h_v) = (200 + 4.53 - 5.792) = 198.73m$$

C.6 : Ground Level Concentration at Threat Point, Kampung Sungai Boh

Data input	
Stability class	B
Pollutants emission (kg/s)	0.1187

Passquill-Gifford Dispersion Coefficients:

$$\sigma_y = 0.337x^{0.88} = 0.337\times2632.8^{0.88} = 344.83m$$

$$\sigma_z = 10^{(-1.25+1.09\log(x)+0.0018\ (logx)^2}$$

$$\sigma_z = 10^{(-1.25+1.09\log(2632.8)+0.0018\ (log2632.8)^2} = 315.73m$$

Ground level concentration at z=0

$$c(x,y,0) = \frac{Q}{\pi u\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2{\sigma_y}^2}\right)\exp\left(-\frac{(-H)^2}{2{\sigma_Z}^2}\right)$$

$$c(x,y,0) = \frac{0.1187}{\pi \times 2.25 \times 344.83 \times 315.73} \exp\left(-\frac{99.79^2}{2 \times 344.83^2}\right) \exp\left(-\frac{(-198.73)^2}{2 \times 315.73^2}\right)$$

$$= 1.21E - 7\frac{kg}{m^3} \; or \; 0.121 \; mg/m^3$$

Appendix D

Average Daily Dose (ADD) Sample Calculation

Sample calculation of ADD for the worst-case scenario of PM_{10} chronic exposure (men) is shown as follows:

Data input	
Inhalation rate, *IR* (m^3/h)	0.63
Exposure time, *ET* (hour)	24
Body weight, *BW* (kg)	68
Exposure frequency, *EF* (day/year)	350
Exposure duration, *ED* (year)	59

$$ADD(chronic, men) = \frac{Ca \times IR \times ET \times EF \times ED}{BW \times AT}$$

$$= \frac{0.121mg/m^3 \times 0.63m^3/h \times 24h \times 350day/year \times 59year}{68kg \times (59year \times \frac{365days}{year})}$$

$$= 0.026mg/kgday$$

Appendix E

Chronic Hazard Quotient (HQ) Sample Calculation for the Worst-Case Scenario of PM_{10} Emission

Reference dose calculation where the relative value is default adult.

RfC= 0.48 mg/m^3

$$\mathbf{RfD = RfC \times \frac{20m^3/day}{70kg} = 0.137\ mg/kgday}$$

Hazard quotient sample calculation:

$$HQ = \frac{ADD}{RfD} = \frac{0.026\ mg/kgday}{0.137\ mg/kgday} = 0.190$$

Appendix F

Chronic Hazard Index (HI) Sample Calculation for Male Adult Who Live in Kampung Sungai Boh

Worst-case scenario of chronic hazard quotient	
Sulfur dioxide (SO_2)	13.465
Carbon monoxide	0.127
Nitrogen dioxide (NO_2)	5.830
Particulate matter 10	0.190

$$HI = \sum HQ_i = 13.465 + 0.127 + 5.83 + 0.190 = 19.61$$

BIODATA OF STUDENT

Ts. Mohd Shahril Kamarudin holds a bachelor's degree (honours) in Biochemical-Biotechnological Engineering from the International Islamic University Malaysia. Ts. Mohd Shahril Bin Kamarudin is an experienced professional with 13 years of progressive experience in chemical operations, safety, and environment within various industries including Combined Cycle Gas Turbine (CCGT) and Coal Fired Power Plants, Oil & Gas, and Utilities. He has also obtained several professional certifications and trainings including Lead Auditor for Integrated Management System, Certified Sustainability (ESG) Practitioner, and Certified Professional in Environmental Pollution Control System under Department of Environment Malaysia.

His passion and interest in research and development pursue him to further his study in environmental engineering. He is now a postgraduate candidate for Department of Chemical and Environmental Engineering in Faculty of Engineering University Putra Malaysia

Currently, Ts. Mohd Shahril is working as Chemical Services & Environmental Manager at one of energy company in Kuala Lumpur, Malaysia. In this role, he is responsible for developing and implementing environmental management systems, monitoring environmental performance, ensuring compliance with environmental regulations, providing environmental training and awareness, and responding to environmental incidents. He also manages the cycle chemistry control of 2 units of power plants and the laboratory for water, wastewater, oil, and gas analysis.

In summary, Ts. Mohd Shahril is a highly skilled and experienced professional with expertise in chemical operations, safety, and environment. He has a strong track record of successfully managing environmental programs, ensuring compliance with regulations, and providing technical support in various industries. His leadership and mentoring skills make him a valuable asset to any organization.

LIST OF PUBLICATIONS

Mohd Shahril Kamarudin et.al (2024). Health Risk Assessment of Pollutant Emissions from Coal-fired Power Plant: A Case Study in Malaysia. Pertanika J. Sci. & Technol. 32 (1): 161 - 184 (2024)

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