

**[HUMAN HEALTH RISK ASSESSMENT OF INDUSTRIAL
AIR POLLUTANT EMISSIONS UNDER DIFFERENT
MITIGATION SCENARIOS USING DISPERSION
MODELING]**

BY

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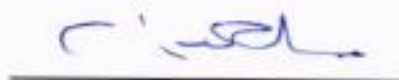
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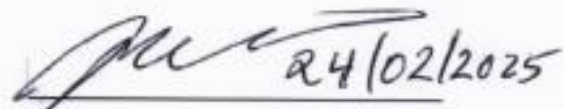
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DEDICATION

I would like to dedicate this research to my parents who guarded my learning; strived with me to reach and improve my level of knowledge; watched me and taught me the origins of life, being eager to see my achievements; wept at my frustration and raised me on the correct path. Dedication is also extended to my brother, my friends, and my colleagues from VEKR Environmental Services Est. for their everlasting contributions and help. Furthermore, I dedicated this work to the field of Artificial Intelligence, which has enriched my research capabilities and meticulously aided in grammar checking and enhancing the precision of this research. I also extend my gratitude to my teachers in the Department of Geosciences and to Dr. Bassam Tawabini and Dr. Ismail Anil for their continuous support and patience with me.

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LIST OF ABBREVIATIONS

ABL	: Atmospheric Boundary Layer
ADD	: Average Daily Dose
ADM	: Air Dispersion Modelling
AQ	: Air Quality
AQI	: Air Quality Index
AQMS	: Air Quality Monitoring Station
C	: Concentration
CO	: Carbon Monoxide
D	: Diameter
HHRA	: Human Health Risk Assessment
HI	: Hazard Index
HQ	: Hazard Quotient
hr	: Hour
I	: Index Break Point
Km	: Kilometer
KSA	: Kingdom of Saudi Arabia
m	: Meter
m/s	: Meter per Second
MEWA	: Ministry of Environment, Water, and Agriculture
MM5	: Fifth-Generation Penn State/NCAR Mesoscale Model
MODON	: Saudi Authority for Industrial Cities and Technology Zones
NCEC	: National Center for Environmental Compliance
NO ₂	: Nitrogen Dioxide
PM ₁₀	: Particulate Matter with Diameter of 10 Microns
PM _{2.5}	: Particulate Matter with Diameter of 2.5 Microns
ppb	: Part per Billion
ppm	: Part per Million
r	: Radius

RfD	: Reference Dose
SO ₂	: Sulfur Dioxide
µg/m ³	: Microgram per Meter Cube
US-EPA	: United States Environmental Protection Agency
UTM	: Universal Transverse Mercator
VOCs	: Volatile Organic Compounds
WHO	: World Health Organization
WRF	: Weather Research and Forecasting Model

ABSTRACT

Full Name :[Waleed Talal Omar Alafif]
Thesis Title :[Human Health Risk Assessment of Industrial Air Pollutant Emissions
Under Different Mitigation Scenarios Using Dispersion Modeling]
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This study provides a detailed assessment of air pollutant emissions and mitigation strategies in the industrial regions of the Kingdom of Saudi Arabia, focusing on the use of advanced dispersion modeling techniques. A comprehensive analysis was conducted to evaluate various mitigation scenarios using the CALPUFF dispersion modeling system and the United States Environmental Protection Agency's (US EPA) methodologies. The air pollutants assessed include CO, SO₂, NO₂, PM_{2.5}, and PM₁₀. Emission parameters for more than 90 industrial stacks and meteorological data from three monitoring stations within a 150-km radius were utilized to predict 1-hour, 24-hour, and annual average pollutant dispersions. Two scenarios were modeled along with the current situation: (1) increasing stack height, and (2) fuel change from diesel to natural gas. The results revealed that: CO average concentrations were reduced by 68.6% under the stack height scenario. NO₂ concentrations showed reductions of 36.4% under increased stack height and 46.9% under fuel change. Results also showed that SO₂ concentrations significantly reduced by 97.2% with fuel change. Moreover, increasing the stack height lead to a reduction of 59.3% and 60.7% of PM_{2.5} and PM₁₀ concentrations respectively. In general, the results of this study demonstrated higher reductions in the pollutant concentrations and lower human health risks when changing the fuel to natural gas. Significant reductions were observed for key pollutants, particularly SO₂ and NO₂, highlighting the potential of cleaner energy sources to enhance air quality in industrial regions. This study underscores the importance of integrated strategies to reduce industrial emissions and improve air quality.

Keywords: Air Pollution, Atmospheric Dispersion Modeling, CALPUFF, Air Quality Index, Health Risk Assessment, Kingdom of Saudi Arabia

ملخص الرسالة

الاسم الكامل : وليد طلال عمر العفيف

عنوان الرسالة : تقييم مخاطر انبعاثات ملوثات الهواء الصناعية على صحة الإنسان في ظل سيناريوهات التخفيف المختلفة باستخدام نمذجة التشتت

التخصص : ماجستير العلوم في العلوم البيئية

تاريخ الدرجة العلمية : 2025/02م

تقدم هذه الدراسة تقييماً شاملاً لانبعاثات ملوثات الهواء واستراتيجيات التخفيف في المناطق الصناعية في المملكة العربية السعودية، مع التركيز على استخدام تقنيات نمذجة الانتشار المتقدمة. تم إجراء تحليل شامل لتقييم سيناريوهات التخفيف المختلفة باستخدام نظام نمذجة انتشار الهواء CALPUFF ومنهجيات وكالة حماية البيئة الأمريكية (US EPA). تشمل ملوثات الهواء التي تم تقييمها: أول أكسيد الكربون (CO)، وثاني أكسيد الكبريت (SO₂)، وثنائي أكسيد النيتروجين (NO₂)، والجسيمات الدقيقة (PM_{2.5}) و (PM₁₀)، تم استخدام بيانات الانبعاثات لأكثر من 90 مدخنة صناعية وبيانات الأرصاد الجوية من ثلاث محطات مراقبة ضمن دائرة نصف قطرها 150 كيلومتراً للتنبؤ بانتشار الملوثات على مدار ساعة واحدة، و24 ساعة، وسنوياً. تم تصميم سيناريوهين مع الوضع الحالي: (1) زيادة ارتفاع المدخنة، و (2) تغيير الوقود من الديزل إلى الغاز الطبيعي. كشفت النتائج أن: متوسط تراكيز CO انخفضت بنسبة 68.6% في سيناريو زيادة ارتفاع المداخل. أظهرت تراكيز NO₂ انخفاضاً بنسبة 36.4% في سيناريو زيادة ارتفاع المداخل، وبنسبة 46.9% في سيناريو التحول من الديزل إلى الغاز الطبيعي. انخفضت تراكيز SO₂ بشكل كبير بنسبة 97.2% مع التحول في الوقود من الديزل إلى الغاز الطبيعي. وعلاوة على ذلك، فإن زيادة ارتفاع المدخنة تؤدي إلى انخفاض تركيزات PM_{2.5} و PM₁₀ بنسبة 59.3% و 60.7% على التوالي. وبشكل عام، أظهرت نتائج هذه الدراسة انخفاضاً أكبر في تركيزات الملوثات وانخفاض مخاطر الصحة البشرية عند تغيير الوقود إلى الغاز الطبيعي مقارنة بزيادة ارتفاع المدخنة. وقد لوحظت انخفاضات كبيرة للملوثات الرئيسية، وخاصة SO₂ و NO₂ مما يسلب الضوء على إمكانات مصادر الطاقة النظيفة لتحسين جودة الهواء في المناطق الصناعية. وتؤكد هذه الدراسة على أهمية الاستراتيجيات المتكاملة للحد من الانبعاثات الصناعية وتحسين جودة الهواء.

الكلمات المفتاحية: تلوث الهواء، نمذجة انتشار الغلاف الجوي، CALPUFF، مؤشر جودة الهواء، تقييم المخاطر الصحية، المملكة العربية السعودية.

CHAPTER 1

INTRODUCTION

1.1 Overview

In the last few decades, Saudi Arabia has become one of the countries striving for rapid industrialization to fulfill its development objectives through the establishment of numerous factories and industries. This has helped produce a significant number of work opportunities and boost the country's overall economy (Al-Dawood, 2000). However, it also relates to some health risks for the persons who are employed in those factories and for the surrounding environment. As the risk of occupational and environmental health hazards increases with the increase of industrialization, Saudi occupational health authorities and other responsible agencies are currently emphasizing prevention, through implementation of the 1995 Occupational Safety, Health and Working Environment Ordinance. Industries are established primarily to produce goods and to benefit the national economy, but those industries may expose their workers to a variety of health hazards (Ballal, 2016). Incorrectly operated industries also pose a danger to their surroundings. Health is endangered when hazardous waste enters the environment with no previous treatment and containment. The environment is part of human survival and is required for human health (Bertsimas et al., 2023). When small particles penetrate the lungs and enter the bloodstream, it causes further harmful effects on the respiratory and circulatory systems. In regard to inorganic particles, it has potential negative effects on the lungs and other organs. Organic chemicals are ubiquitous in the environment. They are emitted as a result of fuels combustion and during the crude oil refining processes. These pathogenic chemicals may cause respiratory diseases, cardiac illnesses, malodorous impacts on sensitive receptors, cancer in exposed persons and other susceptible activities (Tawabini et al., 2023).

It's noticed that the fuel consumption rate (diesel & gas) has been significantly increasing as it is the main energy source in different industries and domains. Main fuel combustion emitters are found in the energy producing sector, such as power plants and domestic heating furnaces, industries producing cement and steel, and road traffic, with

particular regional differences (Munsif et al., 2021). As a matter of fact, there are some gases and particles that are generated from the industrial activities and emitted to the ambient air. Anthropogenic emissions from the combustion of fossil fuels (PM_{2.5}, PM₁₀, NO_x, SO₂, and CO) causes variability, and increases the frequency and intensity of extreme weather events. These emissions, originating from human activities, have a profound impact on our planet's delicate balance as they lead to an increase in air pollutants and the formation of dust in the surrounding area and lead to visual pollution of the area (Ayompe et al., 2020). Besides, it has great effects on human health. As it naturally affects the human respiratory system, which causes multiple health problems resulting from asthma, heart disease and cancer.(Bashawri & Salama, 2016). There are many industrial activities in the kingdom that are distributed around its regions that consume the diesel and gas for its production process.

Air quality is a public health challenge in many of the rapidly developing and heavily industrialized cities of the world. In Saudi Arabia, air quality levels in numerous metropolitan areas frequently surpass the thresholds set by the World Health Organization (WHO) and the more stringent US regulations (Dano et al., 2023). Air pollution has increased in Saudi Arabia and has become a major challenge due to the rapid increase in the country's industrial and mobile pollution sources.

Although long-term exposure to air pollution is linked to smoking, occupational exposures, and genetic factors, it can have several significant long-term and short-term effects on human health. Poor urban air quality still remains one of the main unresolved environmental issues, and inadequate resources, weak legislative controls and poor awareness are the key reasons for current pollution limitations and standards (Saleh et al., 2022). Saudi Arabia also has experienced rapid development and urbanization, leading to high air pollution levels and related health hazards. Several studies have assessed the degree of air pollution and its impacts in its cities, indicating the necessity of taking effective measures to control the air quality. Computer-based atmospheric dispersion models are useful tools to predict the concentration of air pollutants in residential areas exposed to industrial activity during the planning and permission phase, as well as to help ensure that new or modified sources emit air pollutants that comply with local and international regulations. During this research, it was found that most studies have some

limitations regarding the Air Dispersion Modelling, including the representation of sources, meteorological data, and model validation.

This research will help provide baseline support for those studying air contaminants in Saudi Arabia. In industrial areas, where multiple pollution sources are present and emissions fluctuate throughout the day, CALPUFF's ability to model these changing conditions makes it highly effective. For instance, in factories using large combustion processes, the emissions of SO₂ and NO₂ might peak during specific production times, with dispersion patterns shifting as wind speeds and directions change. CALPUFF can track these emissions from the point of release, considering not only immediate local dispersion but also how pollutants may travel across regions, affecting downwind communities. This capability is vital for industries looking to optimize pollution control technologies or meet stricter environmental regulations, as it provides an accurate forecast of where pollutants will end up under different scenarios. Moreover, CALPUFF excels in long-range pollutant tracking, which is particularly important in regions where pollution from one area can significantly affect another. In scenarios where pollutants like PM₁₀ and SO₂ can be carried by strong winds across vast distances, CALPUFF can predict the downwind effects on air quality in neighboring areas or even across borders. This makes it indispensable in regional air quality management, where policymakers need to understand the cumulative effects of both local and transported pollution. It does not only inform decision-makers about current pollution levels but also helps forecast future pollution episodes, guiding actions such as temporary industrial shutdowns or emission reduction measures during peak pollution periods. Ultimately, CALPUFF's strength lies in its ability to simulate complex, real-world conditions with a high degree of accuracy, offering insights into pollutant behavior that simpler, steady-state models cannot provide (Scire et al., 2000). Its use in areas with mixed pollution sources, fluctuating weather patterns, and intricate geography makes it a robust tool for both industrial and regional air quality management, ensuring a comprehensive approach to pollution mitigation and regulatory compliance.

1.2 Statement of the Problem

Due to the escalating pace of human development, which has resulted in increased consumption of fuels such as diesel and gas, ambient air pollutants are continuously dispersing, exerting direct and indirect effects on human health across vast geographical regions. Consequently, there is an imperative to gather data and formulate precise estimates that integrate both current and projected dispersion patterns of pollutants within specific geographic areas. Furthermore, it is essential to assess the potential human health risks associated with emissions of industrial air pollutants across various mitigation scenarios, utilizing the predicted dispersion patterns of pollutants.

1.3 Significance of Research

The significance of this research lies in its originality on the assessment of human health risk industrial air pollutant emissions. By employing a comprehensive approach that integrates advanced dispersion modeling technique of CALPUFF model with US EPA methodologies, this study provides an insight into the health risks associated with air pollution.

This research aligns with Saudi Arabia's Vision 2030, emphasizing sustainable development and public health, thus offering a framework for policymakers and local authorities to implement evidence-based interventions.

Moreover, the study serves as a foundational resource for future research in air quality management, facilitating a deeper understanding of the interactions between industrial emissions and human health. By addressing both short- and long-term air quality challenges, this research not only aims to protect the health of local communities but also contributes to broader environmental sustainability efforts, ultimately promoting a healthier and more resilient urban ecosystems.

1.4 Objectives of the Research

The overall objective of the research is to identify the distribution patterns of several air pollutants using CALPUFF software and assess the human health risk that may be affected by pollutants. The specific objectives include:

1. To obtain dispersion model input parameters comprising meteorological and stack emission data.
2. To predict the atmospheric dispersion of air pollutants, including NO₂, PM_{2.5}, PM₁₀, SO₂, and CO being emitted from an industrial city, using the CALPUFF model.
3. To generate pollutant concentration and air quality index (AQI) distribution maps over a selected domain based on the results of the CALPUFF model.
4. To assess human health risk for the receptor domain by use of the CALPUFF model results of the current emission conditions and two emission mitigation scenarios.

CHAPTER 2

LITERATURE REVIEW

Air Quality (A.Q.) refers to the condition and cleanliness of the air we breathe each day, and which has a direct impact on human health worldwide (Morsy et al., 2021). The main objective of any country is to protect its people particularly from environmental pollutions that affects the air, and water quality. Air pollution is mainly associated with public health. For the regulatory organization, the Air Quality from location to location may differ and it can be measured using Air Quality Index (AQI). The AQI is a tool through which we can know the levels of pollution in a specific area. The purpose of the AQI is to monitor air quality for the health of sensitive recipients of in general, and it helps in avoiding any humanitarian disasters that may affect human health. AQI can be used for environmental safety and atmosphere protection in the disaster management cycle of any country. As mentioned, the air quality varies from one region to another, so the AQI will vary from one place to another even in its calculations. Therefore, international organizations establish fixed levels to measure the air quality index, including the World Health Organization (WHO), as well as the Environmental Protection Agency (US-EPA), and also the Ministry of Environment, Water and Agriculture in Saudi Arabia (MEWA). Also, with the AQI, Health risk assessment is the estimation of the adverse health effects of environmental pollutants in terms of their nature and potential hazard for human health. The EPA has outlined basic steps for risk assessment which are: hazard identification, dose-response relationship, exposure assessment, and risk characterization (USEPA). According to the World Health Organization (WHO), air pollution is the change in the natural properties of air through the influence of the indoor and outdoor environment. Air pollution is the greatest environmental risk for human disease. (World Health Organization).

The Saudi AQI has created simple maximum permissible average concentration values for criteria substances. Karar et al. in 2020 mentioned that Air Quality in Saudi Arabia and the Kingdom's main cities were calculated and modeled using Saudi data and the theoretical AQI functions. Threshold levels of AQI were presented along with the effect on human health (Karar et al., 2020). AQI was designed to help people understand the

impact of air pollution on their health and the quality of the air. The AQI is based on the concentration of pollutants, which may cause health concerns, as per the USEPA. Five main air pollutants are measured by the AQI: ground-level ozone (O_3), Particulate Matter 2.5 ($PM_{2.5}$), sulfur dioxide (SO_2), carbon monoxide (CO), and nitrogen dioxide (NO_2). An index between 0-100 is used by the AQI to measure the level of risk posed by the chief pollutants and the cautionary measures required. An equivalency of this index translates to six distinct levels: 0 – 50 (Good), 51 – 100 (Moderate), 101 – 150 (Unhealthy for Sensitive individuals), 151 – 200 (Unhealthy), 201 – 300 (Very Unhealthy), and over 300 (Hazardous). (USEPA, 2013)

There is a close relationship between the high levels of pollutants and human activity, which includes vehicle movement, industry, and others. The movement of vehicles and industry generates emissions that lead to a rise in pollutants in the surrounding air. The proof of this fact was the pandemic period. During the pandemic, vehicles stopped working and the level of pollution from industry was reduced for a period of time which helped the AQI level to be decreased by significantly. Morsy et al., (2021) reported that there was a significant decrease in concentration rates during the pandemic, compared to the pre-pandemic period, by 26.34% for sulfur dioxide, 28.99% for nitrogen dioxide, 26.24% for carbon dioxide, 11.62% for O_3 , and 30.03. % for PM_{10} . they also mentioned that vehicular traffic activities represent 25-30% of the total air pollution load in the city of Makkah. The sources of air pollution are different, but the main cause is the anthropogenic activities, majorly industrial activities. The cities are mainly affected by the industries' emissions such as PM, CO, NO_x , and SO_2 . (Ardusso & Fernández-Caldas, 2018). Even the pollutants levels were affected during the outbreak of the Coronavirus, as their concentrations decreased in most of the measurement sites (Anil & Alagha, 2021; Cheval et al., 2020; Resmi et al., 2020; Sethi & Mittal, 2020) which been measured by the monitoring stations distributed around the eastern province in KSA (Anil & Alagha, 2021). (Karar et al., 2020), mentioned that Deaths resulting from the negative health effects of air pollution in the Middle East region reach to about 500 thousand people. In the short term, air pollution can effectively act as an irritant to the eyes, nose, throat, and lungs, resulting in coughing, sneezing, tears, shortness of breath, headaches, dizziness, malaise, lightheadedness, and nervousness, swelling of airways. The movement of air pollutants occurs through air

carriers, including the air itself, as well as dust and insects. Where pollutants are transferred from the source and may even penetrate into the blood leading to decreased blood oxygen levels (Hussain et al., 2022; Maheswari et al., 2020; Mauliku et al., 2021). Talwar & Bharati, (2012) evaluated the levels of PM particles around industrial area and they found that chemical characterization of the particles contributed to particle toxicity effect on human and occupational health. This represents the need for more evaluation and monitoring of the pollution that might come from the surrounding environment.

In order to monitor the movement of these pollutants, it is necessary to obtain data recorded from previous years in order to know the movement of pollutants, and the best way to collect them is by using satellite data. Satellite data are one of the main supports in observation of atmospheric changes, which observes the changes in metrological data in different seasons. Farahat et al., (2015) used satellite data to study the aerosols characteristics and dynamics over the Saudi Arabia. They reported the presence of higher air pollution levels over the region with intensive oil and gas activities. The main reason for using it is the lack of ground level data which can support the actual conditions analysis. There are different types of data that can also be a cause to change in the observation of atmospheric conditions such as terrain data, metrological data, and pollutants data. The change in the scenarios of data types can affect the actual level's observation also, which can affect human health.

ElSharkawy & Ibrahim, (2019) reported that air pollutants that have been emitted by the Industrial City can affect the surrounding environments. They reported that the mean conc. of PM₁₀ exceeding the local and international standards were levels of SO₂ and NO₂ were lower than air quality guidelines. Salama et al., (2016) assessed air quality levels in King Abdulaziz Port. They found that air quality parameters such as NO₂, SO₂, O₃, VOCs and PM₁₀ were in high significant concentrations from all the stations within the port. Bashawri & Salama, (2016) studied the effect of traffic air pollutants on blood coagulation and found that when these pollutants are in higher concentrations in the ambient air, the risk to human health is the appearance of some changes in blood coagulation parameters. The impact on humans from industrial activities depends mainly on the distance between the source of pollution and the areas of residence (receptors), which will be affected mainly by the metrology of geographical nature.

Using the air modeling tool is one of the means that contributes to knowing the areas affected by pollutants resulting from industrial works. Some solutions must be found that contribute to reducing emissions levels during the process of their spread in the air. (Wierzbńska, 2019) stated that the concentration decreases with increasing emitter height. However, the percentage decrease in concentrations may be insufficient to reduce emission levels sufficiently. Therefore, it may be necessary to find other solutions, such as changing the type of fuel used during power generation and industrial operations. It was found that the use of coal in power plants shows high results for carbon dioxide and PM_{2.5} emissions (Anggarani et al., 2020).

The results from various studies on air pollution dispersion modeling emphasize the significant impact of pollutants such as PM_{2.5}, PM₁₀, CO, NO₂, and SO₂ in industrial regions. For instance, Purwanto et al., (2024) analyzed SO₂ and NO₂ emissions from a lime factory using AERMOD, a Gaussian-based model, to simulate pollutant dispersion. The study demonstrated that emissions of SO₂ and NO₂ were influenced by local environmental factors, including wind speed and topography. Similarly, Zhang et al., (2023) investigated air pollution trends in Eastern Xinjiang, focusing on PM_{2.5}, PM₁₀, CO, NO₂, and SO₂ concentrations over five years. Their findings highlighted the influence of seasonal meteorological conditions, with increased pollution levels during winter due to coal combustion for heating, and during spring due to frequent dust storms. Both studies provide valuable insights into the sources and behavior of pollutants but rely on steady-state models like AERMOD and HYSPLIT, which have limitations when modeling complex environments and varying atmospheric conditions.

Shan et al., (2023) examined the impact of emission reduction policies on air quality in Qinhuangdao, focusing on major industries like iron and steel, cement, and flat glass. They developed a 2016 emission inventory and assessed two scenarios: Business-as-Usual (BAU) and Peak Production Capacity (PPC), which incorporates ultra-low emission (ULE) standards. Under the BAU scenario, concentrations of SO₂, NO_x, and PM₁₀ ranged from 4.42 to 11.64 µg/m³, 10.84 to 63.27 µg/m³, and 36.95 to 118.52 µg/m³, respectively. The PPC scenario significantly reduced these values to 2.35–6.04 µg/m³ for SO₂, 6.57–35.70 µg/m³ for NO_x, and 18.99–55.32 µg/m³ for PM₁₀. The study highlights the effectiveness of ULE policies in reducing pollution and improving air quality (Shan et al., 2023).

In another study, Wu et al., (2018) investigated the spatial-temporal variations and source contributions of key pollutants, including PM₁₀, SO₂, and NO_x, using the WRF/CALPUFF modeling system to simulate pollutant concentrations in Benxi, China which is heavily industrialized with steel and coal companies. The results showed that daily average concentrations of PM₁₀ (210 µg/m³), SO₂ (180 µg/m³), and NO_x (160 µg/m³) significantly exceeded national air quality standards, particularly in urban centers (Wu et al., 2018).

In 2021, Xie et al., 2021 conducted a study to assess the impact of emissions from the brick and tile industry on air quality. Using the CALPUFF model, they simulated pollutant concentrations, focusing on SO₂, NO_x, and PM_{2.5}. The 24-hour average concentration peaks during different seasons were measured, with the highest levels recorded in winter. The average daily concentrations of SO₂ were 40.52 µg/m³, NO_x at 36.68 µg/m³, and PM_{2.5} at 2.66 µg/m³ across all seasons. These findings highlight the significant seasonal variation in pollutant levels, with winter showing the highest pollutant concentration due to lower wind speeds and temperature inversions that limit dispersion (Xie et al., 2021).

Jittra et al., (2015) compared the predictions of sulfur dioxide (SO₂) and nitrogen dioxide (NO₂) concentrations between different models. For SO₂, the CALPUFF model predicted an average concentration of 38.6 µg/m³, which was compared against the observed data with a mean standard deviation of 49.14 µg/m³. Similarly, for NO₂, CALPUFF showed an average concentration of 40.8 µg/m³ with a mean standard deviation of 40.59 µg/m³. (Jittra et al., 2015).

In this context, the use of CALPUFF could significantly enhance the accuracy and scope of these findings. CALPUFF is specifically designed to handle long-range transport of pollutants, making it more suitable for regions with complex topography and variable meteorological conditions, such as Xinjiang. Zhang et al., (2023) noted that the air quality in Eastern Xinjiang is influenced by both local emissions and long-range transport, especially during dust storms. CALPUFF can simulate how pollutants like PM₁₀ and SO₂ are transported across regions, considering the temporal variations in wind patterns, temperature, and humidity. This would allow for a more detailed analysis of transboundary pollution, as well as the interplay between natural and anthropogenic emission sources.

In industrial areas, such as the lime factory studied by (Purwanto et al., 2024), CALPUFF could provide more nuanced simulations of pollutant dispersion, particularly under changing atmospheric conditions, offering a more comprehensive understanding of ground-level concentrations over time.

By integrating CALPUFF into these studies, researchers could overcome the limitations of steady-state models and capture the dynamic nature of pollutant dispersion. For example, in the case of SO₂ and NO₂ emissions from industrial chimneys, CALPUFF could simulate the plume rise and dispersion over varying time frames, providing more accurate predictions under both normal and extreme meteorological conditions. Likewise, for particulate matter like PM_{2.5} and PM₁₀ in Xinjiang, CALPUFF's ability to account for both local and long-range pollutant transport could lead to a better understanding of the contributions of regional dust storms and industrial activities to overall air quality. Incorporating CALPUFF into future research would not only validate current findings but also offer more robust predictions of long-term environmental and health impacts, making it a valuable tool for improving air quality management strategies

This research conducts an extensive assessment of human health risks associated with some air pollutant emissions. It analyzes various mitigation scenarios through a unified approach that integrates the CALPUFF dispersion modeling system, the United States Environmental Protection Agency's (US EPA) preferred model, air quality indices (AQI), and the EPA's human health risk assessment methodology.

Research Gap

Previous researches have explored air quality concerns in Saudi Arabia, there remains a lack of focused analysis on the specific health impacts of distinct emission reduction strategies; such as increasing stack heights or changing fuel types. On pollutants like SO₂, NO₂, CO, PM_{2.5}, and PM₁₀ within localized industrial Areas. Additionally, the unique meteorological and geographical characteristics of the study area further emphasize the need for a detailed understanding of how mitigation efforts influence pollutant dispersion and concentration patterns. This thesis addresses these gaps by using CALPUFF air dispersion modeling to simulate pollutant behavior under different mitigation scenarios and applying the U.S. EPA's health risk assessment framework to identify potential health impacts on surrounding communities.

CHAPTER 3

METHODOLOGY

To ensure a comprehensive and reliable assessment, the methodology was designed with a clear and methodical framework. Each phase was thoroughly executed to ensure accuracy, consistency, and alignment with the study's goals. The process is revealed systematically through the following key steps:

1. **Site Selection** – Identifying a suitable location for the air quality study, considering factors such as population density, industrial activity, and proximity to sensitive environments.
2. **Selection of Air Modelling Software** – Choosing appropriate software for air dispersion modeling, such as AERMOD or CALPUFF, based on project requirements and data availability.
3. **Data Collection and Setting of Modelling Parameters** – Gathering necessary data, including meteorological information, emission rates, and terrain details, and configuring model parameters accordingly.
4. **Running the Model** – Inputting the collected data into the selected software to simulate pollutant dispersion over time and space.
5. **Generation of Air Quality Index Maps** – Producing maps that visually represent air pollutant concentrations, often in the form of an Air Quality Index (AQI), to assess air quality across the study area.
6. **Assessing the Human Health Risk** – Evaluating the impact of predicted pollutant concentrations on human health.
7. **Checking the Scenarios Results** – Comparing the AQI maps, and human health risk assessment results for the current conditions and suggested scenarios to improve air quality levels within the receptor domain.
8. **Conclusion and Recommendations** – Summarizing the findings and providing recommendations for mitigating air quality impacts and improving environmental and public health outcomes.

3.1 Site Selection

A site with industrial activities in the Kingdom of Saudi Arabia was selected as the study site for this research. The chosen site represents a diverse industrial zone with multiple types of industries and a number of factories, making it an ideal candidate for assessing pollutant dispersion and mitigation strategies. The study area was defined by covering a square region around the selected site with a radius of 150 km to evaluate pollutant dispersion patterns effectively. This approach ensures a generalized framework that can be applied to similar industrial areas across Saudi Arabia.

3.2 Air Dispersion Modelling: CALPUFF

CALPUFF is a sophisticated air dispersion modeling software with a multi-layered, multi-type, non-steady-state framework that includes algorithms for both sub-grid scale and long-range effects. It simulates the impact of changing meteorological conditions on pollution transfer, transformation, and removal. This makes it particularly suited for long-distance transportation of pollutants and areas with complex terrain. CALPUFF is especially valuable for study domains larger than 50 km in radius, where steady-state models like AERMOD may not provide sufficient accuracy. The model can handle diverse scenarios, making it ideal for simulating pollutant dispersion in larger industrial zones or regions with varied topography and meteorology.

The CALPUFF modeling system requires two main data processors: CALMET and CALPOST. CALMET is a 3D meteorological and micrometeorological model that accounts for onshore and offshore boundary layers, incorporating coastal effects, dynamic terrain influences, terrain blocking effects, divergence reduction, and slope flows. This enables precise simulation of pollutant behavior in areas with complex landscapes. On the other hand, CALPOST is a post-processing package designed to compute time-averaged concentrations, visual effects, and deposition flux, offering a detailed analysis of pollutant impacts over time. In order to run CALPUFF efficiently, the system demands robust computational capabilities, including a good operating system and processor. Additionally, access to hourly surface data, upper air, and precipitation data is essential for accurate modeling results. These inputs ensure that CALPUFF can handle both the intricate meteorological variables and the physical transport mechanisms of pollutants across long distances. For the atmospheric dispersion study of pollutants emitted from an Industrial City, CALPUFF was chosen due to the large geographical area being able to be analyzed, which exceeded the 50 km radius. Under such conditions, the dynamic, non-steady-state nature of CALPUFF provides more accurate simulations compared to simpler models. It accounts for both the immediate local impacts and the long-range transport of pollutants, making it a comprehensive tool for environmental assessments. EPA's CALPUFF Dispersion Model was used under different scenarios described in the "Scenarios" section to assess the dispersion and deposition of pollutants across the study domain. Below is an

overview of the CALPUFF Modeling System, illustrating its key components and capabilities

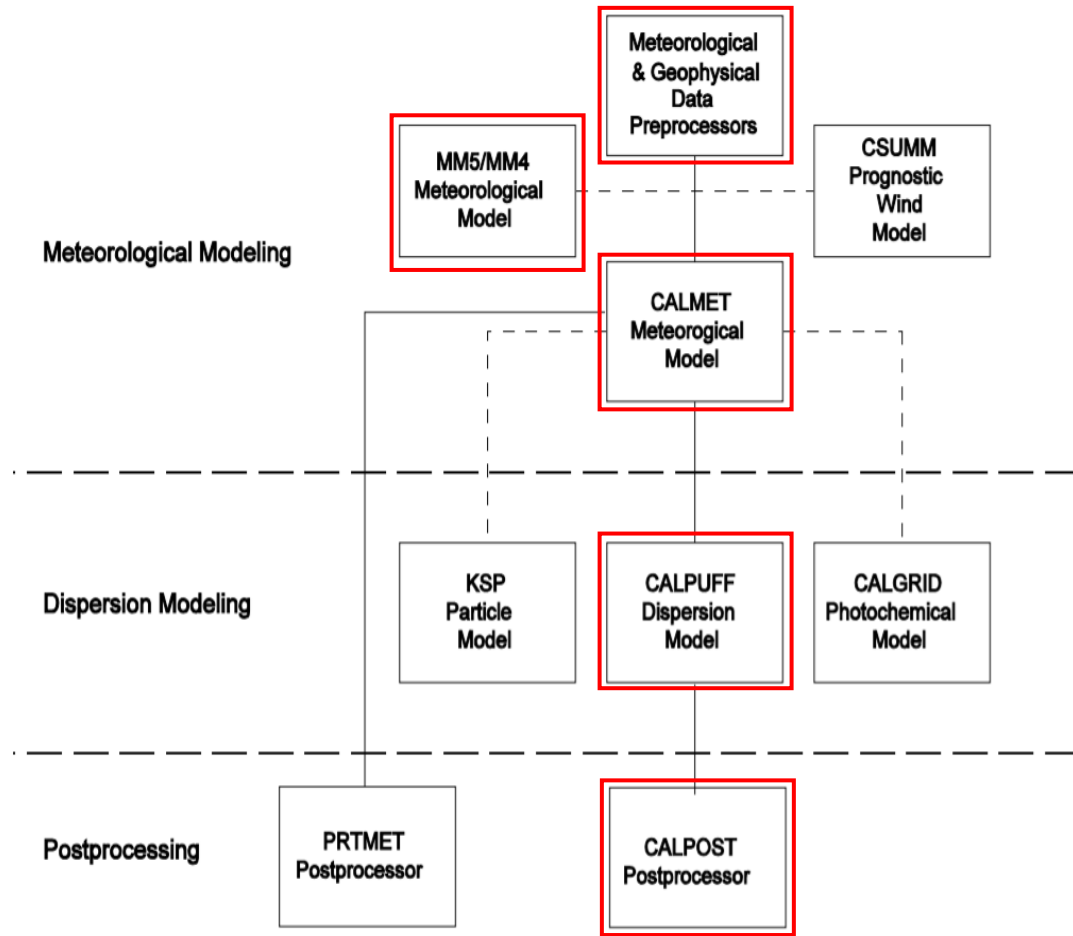


Figure 3-1: Overview of CALPUFF Modelling System
(The tools used in the thesis are in red boxes)

CALPUFF can be used to measure the atmospheric boundary layer (ABL) as it was used in observations and tracing experiments by Cui et al., 2020, impact of ships on the meteorology by Bai et al., 2020, and for air quality modeling to assess particulate emissions from power plants or to support modeling results for research into the air quality process itself. Air modeling data is also used to monitor ports and airports, ship passenger traffic data, meteorological data, and more. Some may ask why the use of modeling software is

different, and the answer is because each researcher has a purpose during the measurement process as answered by Ridzuan et al., 2020. The following table shows the characteristics of CALPUFF (Table 3-1):

Table 3-1: CALPUFF Characteristics

Class	Air quality modelling tool
Components	- CALMET - CALPUFF - CALPOST
visualization	2 Dimension
Range	>50 km

3.3 Data Collection

3.3.1 Air Emission Data Collection

In the Kingdom of Saudi Arabia, there are regulatory bodies responsible for monitoring the emissions of the industrial facilities and the extent of their environmental compliance.

The study utilized emissions data obtained through cooperation with a confidential source, who facilitated access to pollutant reports for stack emissions within an industrial Zone. The data includes stack emissions from 2016 to 2021. During this period, the regulatory bodies enforced regulatory measures requiring factories to progressively reduce their emission levels, resulting in the lowest recorded emissions in 2021.

For the purposes of this analysis, data from the latest reports in 2021, encompassing more than 90 stacks, were used to model emissions and their dispersion within the surrounding areas. The collected parameters included concentrations of key pollutants, specifically CO, SO₂, NO₂, PM_{2.5}, and PM₁₀, with emissions measured on an hourly basis to provide a detailed temporal profile.

3.3.2 Meteorological Data Collection

Meteorological inputs, including wind speed, wind direction, temperature, and humidity, were sourced from three regional stations within a 150-kilometer radius. This hourly meteorological data, along with upper-air measurements, was incorporated into the CALPUFF model to ensure accurate simulation of pollutant dispersion under varying atmospheric conditions.

CALPUFF dispersion model requires both ground level and upper-layer meteorological data. Hourly ground level meteorological data including wind speed and direction, ambient cloud cover, and temperature that covering the whole year of the study period (2021) were from three weather stations using Wunderground Data Base (<https://www.wunderground.com/>) with respect to the Industrial Area. Vertical meteorological data (Upper Air Data) were taken from NOAA/ESRL Radiosonde Database (<https://ruc.noaa.gov/raobs/>). It provides vertical structure of the atmosphere. Measurement of Radiosonde includes pressure, wind speed and direction, height, dew point, and temperature. Both ground level and upper-air data are further processed by (CALMET) which is the meteorological processor of the CALPUFF model and produced outputs such as surface friction velocity, sensible heat flux, vertical potential temperature gradient in the 500-m layer above the planetary boundary layer, convective velocity scale, convective mixing height, Monin-Obukhov length, mechanical mixing height, surface roughness length, albedo, and Bowen ratio.

3.4 Running the Model CALPUFF

3.4.1 CALMET Input Data

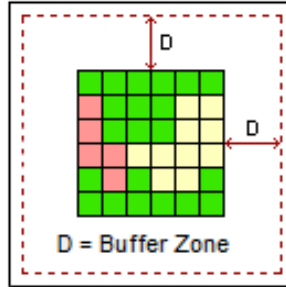
The preparations for running the program to study the area for the sake of implementing appropriate mitigation strategies for this thesis were done using the geophysical processor with the following details:

- The mode used in this thesis was refined mode as the Refined Mode, with considering the gridded base of geophysical and meteorological data generated from digital elevation maps, land use maps, surface, and upper air meteorological stations, and prognostic model results (e.g. MM5, WRF data).
- The version used was Version 7 as it's the updated version at the time were the software been running.
- The period selected was the year 2021 and the time zone selected was +3 zone as needed in the study domain.
- UTM is the project coordination system used also.
- UTM zone is 39 in the north hemisphere.
- Reference point was the middle of Industrial City.
- Cell Faced Height were in default sittings.
- Grid spacing was 1 Km, X length: 200 Km, and Y length: 200 Km.
- Terrain files & Land use files were generated using Laked satellite data.

After the pre-sittings for starting to sit the coordinates using the geophysical processor, the Met processor was used. The meteorological data was prepared in SAMSON formats for 3 different meteorological stations as mentioned previously along with the upper air data that been downloaded as (.fsl) formats and were uploaded to CALMET.

The period selected was from 01/12/2020 up to 31/01/2022 as CALMET did not recognize that the stations were in (+3 zone).

The stations were processed using SMERGE and the buffer zone selected was 100 Km (The buffer zone is the distance beyond the met grid that CALPUFF View want to search for meteorological stations).



After that the upper air input file (.fsl) was processed using READ62 to generate UP.DAT file.

Note that precipitation data was not processed as the precipitation was very low in the study domain in 2021.

3.4.2 CALPUFF Preparations

There were four runs generated using CALPUFF. Each one has its own preparations as this thesis focus on looking for the mitigation scenarios for the stacks' emissions, which are:

1. The current year for the stacks in the Industrial City (2021).
2. First three (3) months of the original case for the stacks (2021 first quarter).
3. Scenario 1- Increasing the stack height
4. Scenario 2- Fuel Shifting

3.4.2.1 Current Conditions (2021)

The source data collected from regulatory bodies has been carefully reviewed and manually input into the CALPUFF model. This process ensures that the data is accurately represented and integrated into the system for precise analysis. By manually entering the data, every relevant detail is thoroughly considered, allowing the model to generate more reliable predictions regarding the environmental impact of industrial emissions. The manual data entry approach further guarantees that any potential discrepancies or errors are identified and corrected, enhancing the overall accuracy and credibility of the modeling process.

3.4.2.1 Reference: The 3 Months Input Data (Q1-January-March 2021)

The same input data used for the original case was applied in this case, with the only modification being an adjustment to the run period, which was set to cover the first quarter of the year 2021. This change ensures that the CALPUFF model reflects the environmental conditions and emissions specific to this time frame, providing a more focused analysis of the potential impacts during that period. By aligning the run period with the first quarter of 2021, the study aims to capture any variations or trends in industrial emissions, enhancing the overall understanding of their environmental effects during that specific timeframe.

3.4.2.2 Scenario 1- Increasing the Stack Height

Providing adequate stack height is the minimum to prevent pollutant drift during periods of high wind speed. With stacks less than twice the height of the main power station structure, experience has shown that during high-speed winds wind vapors may be captured in the turbulent vortex sheath and transported to ground level in relatively high concentrations near the station and sometimes re-enter the building air supply. Extensive wind tunnel tests and field experience have demonstrated that backwashing is not a problem where the stack height is at least 1.5 times the height of the power station or other adjacent structure and sufficient flow velocities are provided.

All Stacks heights were checked, and they were below 50 m height. So, in this scenario, all stacks heights were changed to be 50 m in order to check the difference between three (3) months case and the current scenario results.

3.4.2.3 Scenario 2- Change of the Combustion Fuel

Burning natural gas produces less NO_x, soot and greenhouse gases than other petroleum fuels such as diesel. EPA's AP-42 emission factors were used to compare NO₂ emissions resulting from diesel and natural gas combustion in order to calculate the emissions using the emission factor for each type of pollutant. Factor used in this thesis are mentioned below:

Table 3-2: Emission Factor for The Uncontrolled Pollutants

Pollutant	Diesel (a) g/m ³	Gasoline (b) g/m ³	Distilled oil (c) g/m ³	Natural Gas (d) g/m ³
CO	16046	15942	235	6.31
SO ₂	4898	1353	624	9.6×10^{-3}
NO ₂	74486	26247	12054	51.8
PM _{2.5}	-	-	-	0.63
PM ₁₀	5236	1610	384	630×10^{-3}

Table 3-3: Factors Used to Change Each Type of Fuel into Natural Gas

Pollutant	Diesel / Natural Gas (a/d)	Gasoline / Natural Gas (b/d)	Distilled oil / Natural Gas (c/d)
CO	390×10^{-6}	0.4×10^{-3}	27×10^{-3}
SO ₂	2×10^{-6}	7×10^{-6}	15×10^{-6}
NO ₂	0.7×10^{-3}	2×10^{-3}	4.3×10^{-3}
PM _{2.5}	120×10^{-6}	390×10^{-6}	1.6×10^{-3}
PM ₁₀	120×10^{-6}	390×10^{-6}	1.6×10^{-3}

This calculation provided a more accurate estimate of the total emissions for each pollutant. By combining the fuel emission ratios with actual stack emissions data, the study was able to offer a clear indication of any environmental concerns.

3.4.3 Reduction Equation

The Reduction Percentages were calculated by comparing the pollutant concentrations for each scenario to the concentrations in the **reference scenario**, which is treated as the baseline (100%).

The formula used for calculating the percentage reduction is:

$$\text{Percentage Reduction} = \left(\frac{\text{Reference Scenario Value} - \text{Targeted Scenario Value}}{\text{Reference Scenario Value}} \right) \times 100 \quad (3.1)$$

3.5 AQI index Mapping

Equation 3.2 and Table 3-4 were used to calculate AQI values of the selected pollutants for the study area. AQI index values per each grid cell were generated for each selected pollutant based on the results of CALPUFF air dispersion model within the study domain. Following these, calculated AQI values of the pollutants coupled with the respective geographical coordinate were converted to AQI maps within the study domain using the QGIS software.

AQI equation (EPA Office of Air Quality Planning, 2024) :

$$AQI = \left(\frac{I_{high} - I_{low}}{C_{high} - C_{low}} \times (C - C_{low}) \right) + I_{low} \quad (3.2)$$

Where;

C = Pollutant concentration measured at the station

C_{low} = concentration breakpoint that is ≤ C

C_{high} = concentration breakpoint that is ≥ C

I_{low} = index breakpoint corresponding to C_{low}

I_{high} = index breakpoint corresponding to C_{high}

Table 3-4: AQI categories and ranges. (EPA Office of Air Quality Planning, 2024)

Category	Good	Moderate	Unhealthy for Sensitive Groups	Unhealthy	Very Unhealthy	Hazardous	
AQI	0-50	51-100	101-150	151-200	201-300	301-400	401-500
8-hr O₃ (ppm)	0.000-0.064	0.065-0.084	0.085-0.104	0.105-0.124	0.125-0.374	use 1-hr	use 1-hr
1-hr O₃ (ppm)	---	---	0.125-0.164	0.165-0.204	0.205-0.404	0.405-0.504	0.505-0.604
24-hr PM_{2.5} (µg/m³)	0.0-15.4	15.5-35.4	35.5-55.4	55.5-150.4	150.5-250.4	250.5-350.4	350.5-500.4

Category	Good	Moderate	Unhealthy for Sensitive Groups	Unhealthy	Very Unhealthy	Hazardous	
24-hr PM₁₀ (µg/m³)	0-54	55-154	155-254	255-354	355-424	425-504	505-604
8-hr CO (ppm)	0.0-4.4	4.5-9.4	9.5-12.4	12.5-15.4	15.5-30.4	30.5-40.4	40.5-50.4
24-hr SO₂ (ppm)	0.000-0.034	0.035-0.144	0.145-0.224	0.225-0.304	0.305-0.604	0.605-0.804	0.805-1.004
1-hr NO₂ (ppm)	---	---	---	---	0.65-1.24	1.25-1.64	1.65-2.04

The EPA's AQI ranges, categories, and meanings used in this study are given in Table 3-5. The AQI ranges from 0 to 500, categorized by color groups. Green (0-50) indicates good air quality; Yellow (51-100) signifies moderate conditions. Orange (101-150) warns of unhealthy levels for sensitive groups, while Red (151-200) indicates unhealthy air for everyone. Purple (201-300) poses very unhealthy risks, and Maroon (301-500) signifies hazardous conditions requiring immediate action. The same color scale system indicated in Table 3-5 is used for the color scale of AQI maps generated in this study.

Table 3-5: AQI levels and meaning (EPA Office of Air Quality Planning, 2024)

AQI	Category	Meaning
0 - 50	Good	None
51 - 100	Moderate	Unusually sensitive people should reduce prolonged or heavy exertion
101 - 150	Unhealthy for Sensitive Groups	Sensitive groups should reduce prolonged or heavy exertion
151 - 200	Unhealthy	Sensitive groups should avoid prolonged or heavy exertion; general public should reduce exertion
201 - 300	Very Unhealthy	Sensitive groups should avoid all physical activity outdoors; public should reduce exertion
301 - 500	Hazardous	Everyone should avoid all physical activity outdoors

3.6 Human Health Risk Assessment

Receptors that have the potential to be affected by the toxicity of pollutants in the atmosphere are the local residents. Inhaling of pollutants is considered the main exposure way. US EPA prepared the Health Evaluation Manual and Supplemental Guidance for Inhalation Risk Assessment (Part and Full) (K. J. Maji, A. K. Dikshit et al., 2017).

3.6.1 Exposure Assessment

In this research, risk characteristics of air emissions (pollutants emissions) generated by industrial activities were presented. The health problems that could be caused by the emission of pollutants are identified. A flow chart illustrates the EPA HHRA process is given in Figure 3-2 (USEPA, 2024).

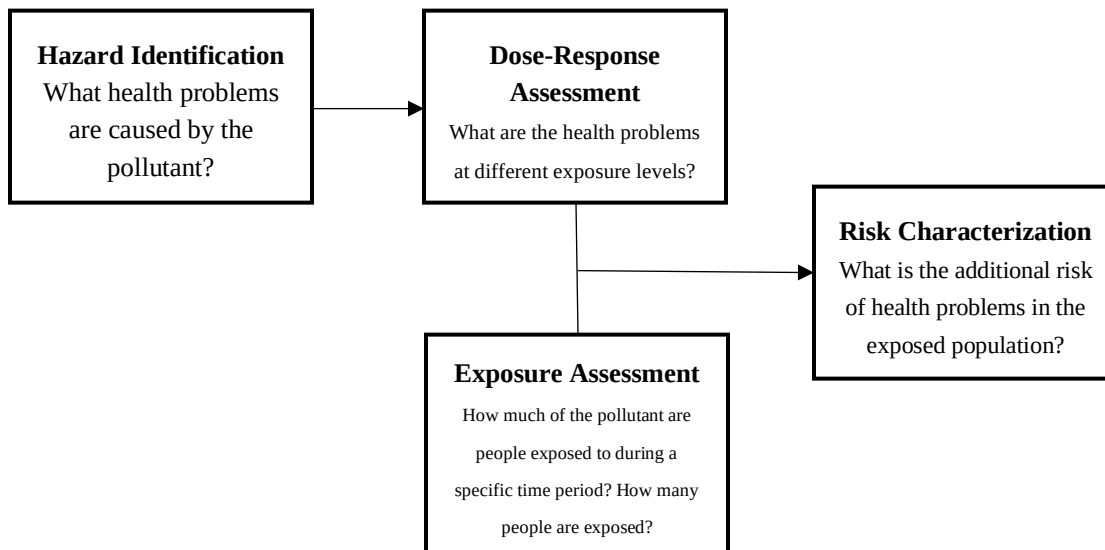


Figure 3-2: The 4 steps risk assessment process. (USEPA, 2024)

For noncarcinogen risk assessment, the toxicity is important only during the time of exposure. Recall that for a cancer risk calculation, the dose is averaged over an assumed 70-year lifetime.

The hazard quotient has been defined so that if it is less than 1.0, there should be no significant risk of systemic toxicity. Ratios above 1.0 could represent a potential risk, but there is no way to establish that risk with any certainty.

When exposure involves more than one chemical, the sum of the individual hazard quotients for each chemical is used as a measure of the potential for harm. This sum is called the hazard index:

$$\text{Hazard index (HI)} = \text{Sum of the hazard quotients} \quad (3.3)$$

Hazard quotient is calculated for each chemical using the following equation:

$$\text{Hazard Quotient (HQ)} = \frac{\text{Average daily dose during exposure period (mg/kg-day)}}{\text{Reference Dose (mg/kg-day)}} \quad (3.4)$$

Average daily dose (ADD) of each pollutant was computed using the equation given below:

$$\text{ADD (mg/kg-day)} = \frac{\text{Concentration } \left(\frac{\text{mg}}{\text{m}^3}\right) \times \text{Daily intake (m}^3\text{)}}{\text{body weight (kg)}} \quad (3.5)$$

Reference doses (RfD) of PM_{2.5}, PM₁₀, CO, NO₂, and SO₂ were calculated using the following equation based on their limit values suggested by WHO given in Table 3-6.

$$\text{RfD (mg/kg-day)} = \frac{\text{Limit concentration } \left(\frac{\text{mg}}{\text{m}^3}\right) \times \text{Daily intake (m}^3\text{)}}{\text{body weight (kg)}} \quad (3.6)$$

Where daily intakes and body weights were adopted from the table below Table 3-6. EPA Exposure Factors Recommended for Risk Assessment.

Table 3-6: EPA Exposure Factors Recommended for Risk Assessment
(Epa & Risk Assessment, 1989)

Land Use	Exposure Pathway	Daily Intake	Exposure Frequency, Days/Year	Exposure Duration, Years	Body Weight, kg
Residential	Ingestion of potable water	2 L (adult)	350	30	70 (adult)
		1 L (child)	350	6	15 (child)
	Ingestion of soil and dust	200 mg (child)	350	6	15 (child)
		100 mg (adult)	350	24	70 (adult)
		20 m ³ (adult)	350	30	70 (adult)
		12 m ³ (child)	350	30	15 (child)
Industrial and commercial	Ingestion of potable water	1 L	250	25	70
	Ingestion of soil and dust	50 mg	250	25	70
	Inhalation of contaminants	20 m ³	250	25	70
		(workday)			
Agricultural	Consumption of homegrown produce (fruit)	42 g	350	30	70
	Consumption of homegrown produce (veg.)	80 g	350	30	70
Recreational	Consumption of locally caught fish	54 g	350	30	70

3.6.2 Severity and Probability

Severity and Probability will be evaluated to know the damage and the likelihood of the affected people from the polluted air that will be assessed .

Severity classification:

- Catastrophic - 4: emissions from industrial pollutants that may kill or have major issues, which requires immediate action.
- Critical - 3: emissions from industrial pollutants commonly cause severe issues or major damage which require immediate corrective action.
- Marginal - 2: emissions from industrial pollutants may cause minor issues, without major damage.
- Negligible - 1 emissions from industrial pollutants will result in no damage.

Probability classification:

- Frequent - 5: Occurrence is likely to happen
- Probable - 4: Occurrence will be several times
- Occasional - 3: Occurrence will be likely sometime
- Remote - 2: Occurrence will be unlikely
- Improbable - 1: Occurrence will be so unlikely

3.6.3 Assessment for Risk

The risk rating values will be determined by multiplying the scores of the probability and severity values together. The higher the risk rating, the higher the overall risk of air pollutants to human health.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Meteorological Results

Running CALMET resulted in finding the meteorological pathways that will affect the domain with references to the 3 meteorological stations. The analysis of wind data from the 1st station indicates that the prevailing wind direction for the year 2021 was consistently towards the southeast, shaping a significant trend for the region. The maximum wind frequency occurred for speeds ranging between 3.6 m/s and 5.7 m/s, with a notable frequency rate of 29.4%. This pattern highlights the predominance of moderate wind speeds in this region. Likewise, the 2nd station showed a similar wind direction, primarily towards the southeast. In this case, the highest wind frequency was for slightly lower speeds, between 2.1 m/s and 3.6 m/s, which also accounted for 29.4% of the time. This suggests that, despite the difference in wind speed ranges, both stations experienced a dominant southeastward wind flow.

The wind data from the 3rd station further reinforces this trend, with the wind also blowing predominantly towards the southeast. The highest frequency was observed for wind speeds between 3.6 m/s and 5.7 m/s, reaching a maximum frequency of 30.1%, slightly higher than the other stations. This consistency in wind direction across the three stations indicates a regional wind pattern that could have significant implications for air quality and pollutant dispersion in the area.

CALMET model results provide further insights, allowing for a more thorough assessment of how wind patterns change with altitude, which is critical for predicting how emissions and pollutants might spread through the atmosphere at various heights. Together, these figures and data offer a comprehensive view of the region's wind dynamics, forming a critical foundation for air quality assessments and environmental impact studies.

Overall, the comprehensive wind data from the stations, combined with CALMET's multi-level analysis, offers a robust foundation for any future long-term environmental planning.

4.2 Dispersion Modelling Results

Emissions from the stacks were integrated into the CALPUFF model for the original case scenario, and subsequent modifications were applied to observe variations in concentration levels. This process enabled a detailed examination of how different scenarios influence pollutant dispersion and concentration.

The results provide peak average concentrations for each scenario, along with their specific geographic coordinates, for three distinct averaging periods: 1-hour, 24-hour, and all-hour periods. This detailed analysis offers insight into both short-term and long-term impacts of emissions under various scenarios. By comparing these peak concentrations and their locations, the study can identify areas with the highest pollutant levels and assess how changes in emissions or operational conditions affect air quality.

This comprehensive evaluation helps to understand the spatial distribution of pollutants and environmental impacts associated with different industrial activities. The findings are crucial for developing effective air quality management strategies and making informed decisions about emission control measures.

4.2.1 Current Conditions Case – 2021

The dispersion modeling results for the current conditions, representing the entire year of 2021, demonstrate the impact of industrial emissions on pollutant concentrations in the study area. Key pollutants, including CO, SO₂, NO₂, PM_{2.5}, and PM₁₀, were analyzed across various averaging periods. The results of this scenario provide a baseline for evaluating the effectiveness of proposed mitigation strategies in reducing pollutant concentrations.

4.2.2 Three Months Case (Q1-2021)

The results for the three-month revealed notable reductions in pollutant concentrations compared to the full-year. The varied reductions among pollutants and averaging periods were as follows:

- NO₂ concentrations showed reductions of approximately 10% for 24-Hour periods and 50% for 1-Hour periods.
- SO₂ concentrations experienced reductions of around 32% for 24-Hour periods and 53% for 1-Hour periods.
- CO concentrations exhibited a reduction of approximately 39% for the 1-Hour and 18% for 24-Hour periods.
- PM₁₀ and PM_{2.5} concentrations showed reductions of 57% and 56.6%, respectively, for 24-Hour periods.

Despite these reductions, concentrations of NO₂ and SO₂ for shorter averaging periods indicated the need for effective mitigation strategies. These findings highlight the potential for achieving significant improvements in air quality through targeted interventions.

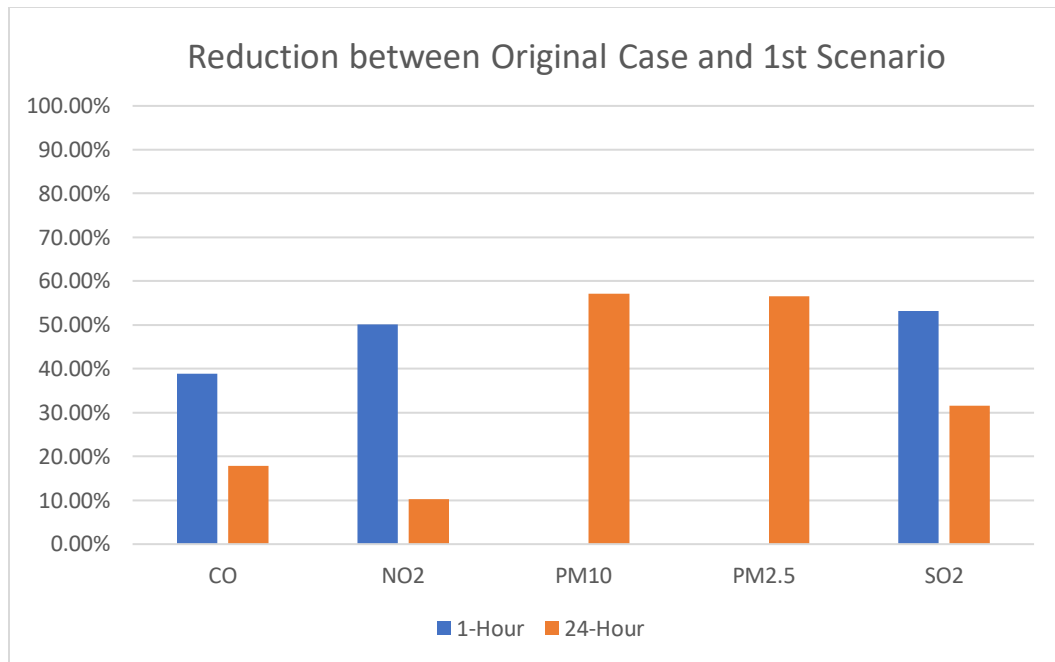


Figure 4-1: Reduction (%) between Original Case and 1st Quarter.

4.2.3 Scenario 1- Increasing the Stack Height

The results of the scenario involving increased stack heights indicate slight reductions in pollutant concentrations compared to the three-month case.

The percentage reductions observed in this scenario are as follows:

- NO₂ concentrations:
 - A reduction of almost 36% for 3-month average period.
 - Approximately 17% reduction for 24-Hour periods.
 - Around 15% reduction for 1-Hour periods.
- SO₂ concentrations:
 - A reduction of almost 34% for 3-month average period.
 - Approximately 29% reduction for 24-Hour periods.
 - Around 9% reduction for 1-Hour periods.
- CO concentrations:
 - A reduction of almost 69% for 3-month average period.
 - Significant reduction of 47% for 1-Hour
 - And 68% for 24-Hour periods.

- PM_{10} and $PM_{2.5}$ concentrations:
 - Reductions of around 61% and 59%, respectively, for 3-Month period.
 - Reductions of around 68% and 71%, respectively, for 24-Hour periods.
 - Reductions of around 81% and 82%, respectively, for 1-Hour periods.

This scenario shows improvements in overall concentrations. But also, the limited effectiveness of stack height increases suggests that this mitigation measure alone may not be sufficient for addressing the exceedances in this case.

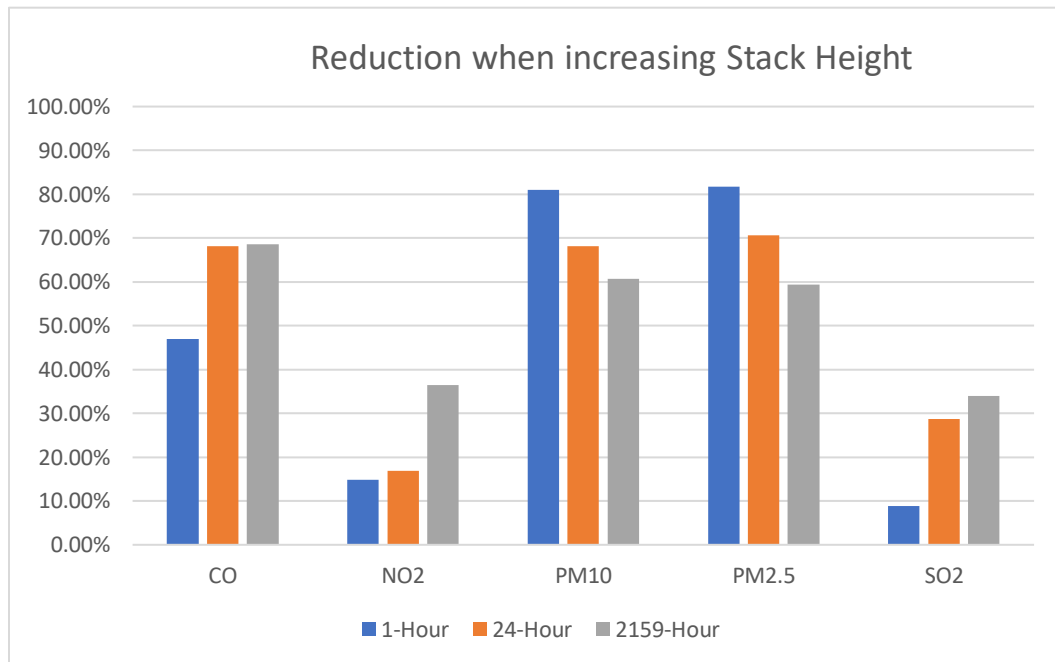


Figure 4-2: Reduction (%) when increasing Stack Height.

4.2.4 Scenario 2- Fuel Shifting

The fuel-shifting scenario demonstrates notable reductions in pollutant concentrations compared to both the three-month case and the stack height increase scenario. This approach results in significant improvements.

The percentage reductions observed are as follows:

- NO₂ concentrations:
 - A reduction of almost 47% for a 3-month average period.
 - Approximately 55% reduction for 24-Hour periods.
 - Around 39% reduction for 1-Hour periods.
- SO₂ concentrations:
 - A reduction of almost 97% for a 3-month average period.
 - Approximately 97% reduction for 24-Hour periods.
 - Around 97% reduction for 1-Hour periods.
- CO concentrations:
 - A reduction of almost 11% for a 3-month average period.
 - Reductions of around 2% for 24-Hour periods
 - And 1% for 1-Hour periods
- PM₁₀ and PM_{2.5} concentrations:
 - Reductions of around 19% and 12%, respectively, for 3-Month period.
 - Reductions of around 2.7% and 3.3%, respectively, for 24-Hour periods.
 - Reductions of around 0% and 0%, respectively, for 1-Hour periods.

Compared to increasing stack heights, fuel shifting shows a dramatic improvement, particularly for SO₂ concentrations. This scenario highlights the substantial effectiveness of transitioning to cleaner fuel sources as a mitigation strategy for improving air quality in industrial regions.

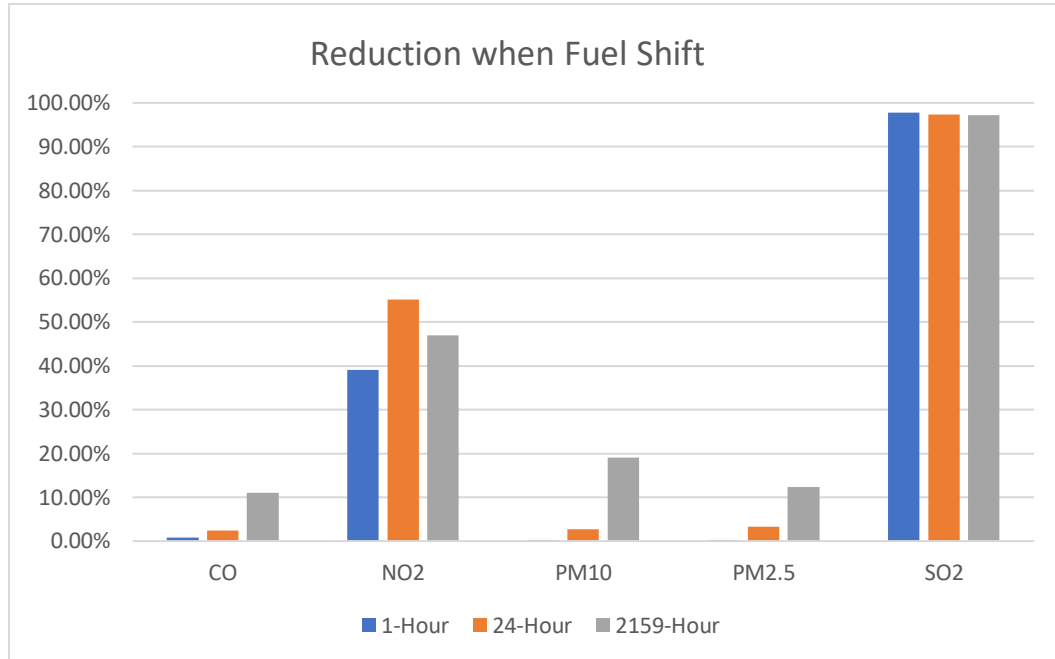


Figure 4-3: Reduction (%) when Fuel Shift.

4.2.5 Dispersions Comparison

In this section, the effectiveness of increasing stack height (Scenario 1) and fuel shifting (Scenario 2) on emission reductions is discussed. The reductions in pollutant concentrations resulting from these scenarios have been calculated based on the concentrations in the three-month reference scenario. The comparative results highlight distinct differences in their effectiveness across pollutants and averaging periods.

Increasing stack height demonstrates moderate reductions in short-term pollutant concentrations. While these reductions are notable, the effectiveness of increasing stack height is limited for certain pollutants such as NO_2 and SO_2 , which exhibit smaller percentage decreases.

Fuel shifting demonstrates significantly greater reductions in pollutant concentrations compared to increasing stack height. Fuel shifting proves highly effective in reducing SO_2 concentrations due to the low sulfur content in natural gas compared to other fuels. Additionally, the notable reductions in NO_2 highlight the potential of cleaner-burning fuels to address nitrogen oxides.

A comparison for all pollutants' reductions under scenario 1 (stack height) and 2 (fuel shifting) using annual averages is shown in Figure 4-4.

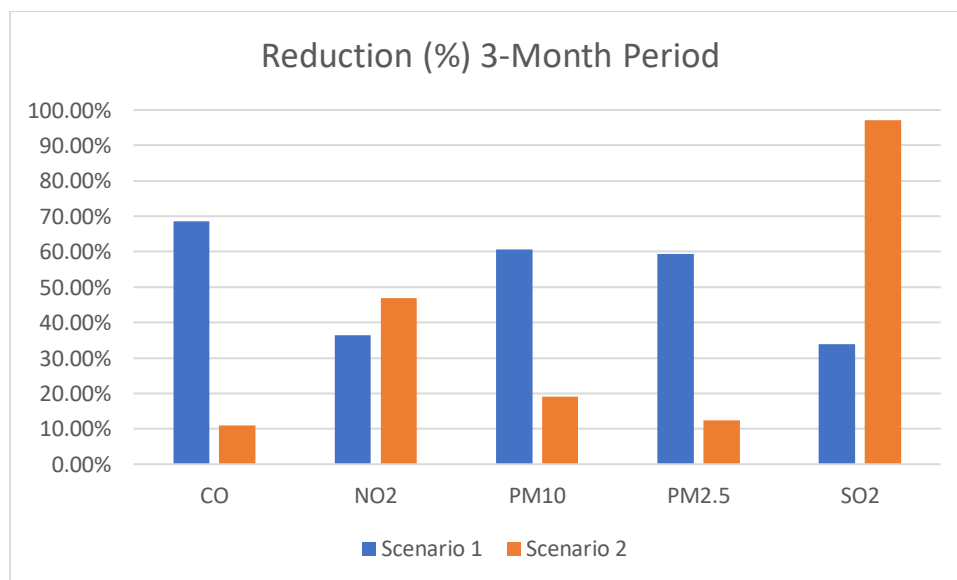


Figure 4-4: Comparing all pollutants' reductions under scenario 1 and 2.

The dramatic reduction in SO₂ emissions under the fuel-shifting scenario underscores its effectiveness for long-term air quality improvements. This is attributed to the minimal sulfur content in natural gas, which nearly eliminates SO₂ emissions. In contrast, CO reductions are less pronounced, as they depend more on combustion conditions rather than the fuel's sulfur content.

While increasing stack height shows moderate effectiveness for particulate matter (PM_{2.5} and PM₁₀) and CO, it is less effective for pollutants like NO₂ and SO₂. Fuel shifting, on the other hand, offers a comprehensive reduction across pollutants, particularly for SO₂ and NO₂.

Overall, these results indicate that while increasing stack height can moderately reduce particulate matter and CO concentrations, fuel shifting is crucial for achieving significant reductions in SO₂ and NO₂ in both short-term and long-term contexts. A combined mitigation strategy that incorporates both approaches could provide the most effective solution for improving air quality in industrial regions.

4.3 AQI Maps

The AQI equation has been used to convert CALPUFF emissions results into AQI values and mapped using QGIS software.

The AQI results indicate that CO, PM_{2.5}, and PM₁₀ are “Good” in all scenarios around the source. NO₂ has a slight increase in AQI values near the source which indicates a “Moderate” condition. SO₂ has a clear increase in AQI values around the source which indicates a “unhealthy” condition and “Unhealthy for Sensitive Groups” at the Industrial City. Even when compared with the scenarios, it will be found that changing the fuel type will have a huge impact on reducing the AQI values which leads in a good and healthy environment for the people and workers in the Region related to the pollutants that are emitted from stacks of factories.

The results of AQI values are shown below for each type of pollutant (in 24-Hour averaging period) in order to see the differences between scenarios.

4.3.1 AQI for CO

The AQI maps of CO for each scenario are depicted. The AQI for CO in the first scenario ranged from 0 to 8.79 and these values are below 50, which represents a good condition for the AQI. Even after shifting the fuel scenario, the values show that the AQI is maximum 8.58 and it is in good condition.

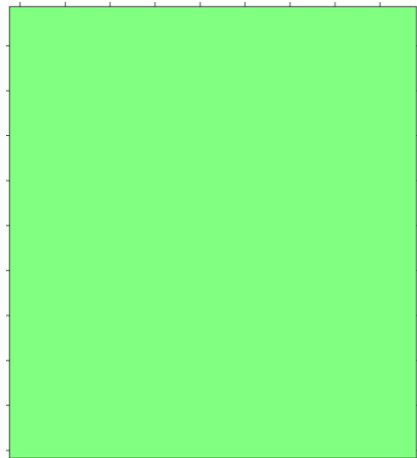


Figure 4-5: CO AQI map for first quarter of 2021

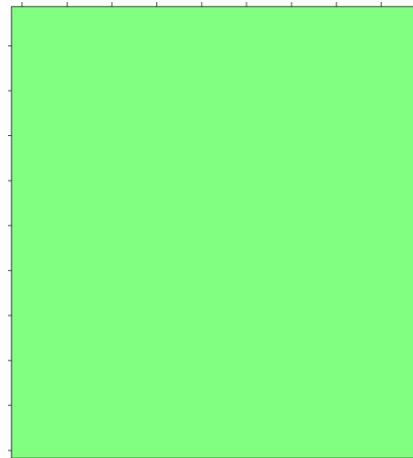


Figure 4-6: CO AQI map for Scenario 1

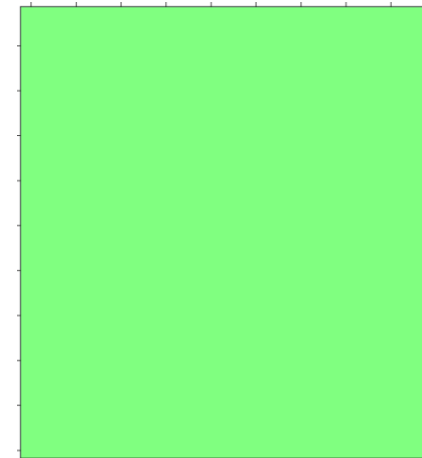


Figure 4-7: CO AQI map for Scenario 2

4.3.2 AQI for NO₂

The AQI map for NO₂ presents a mixed picture of air quality across the different scenarios. In the original case, AQI values for NO₂ ranged from 0.07 to 107.78, with certain areas near emission sources exceeding the threshold for "moderate" air quality and entering the "unhealthy for sensitive groups" category. These areas reflect the high NO₂ emissions concentrated near the industrial zones, with the highest values occurring within a 10 km radius. The prevailing winds in the region, which tend to disperse pollutants southeastward, play a key role in determining these concentrations.

When comparing Scenario 1 to Scenario 2 (fuel shift), a substantial reduction in NO₂ concentrations can be observed. In Scenario 2, AQI values decrease significantly, with a maximum of 58.86, indicating a shift to "moderate" air quality across most areas. The fuel shifting scenario reduces NO₂ emissions by 46.9%, which is reflected in the improved AQI readings. The fuel shift effectively lowers the risk to sensitive groups in the vicinity of the industrial areas, bringing most locations back into the "good" to "moderate" AQI range. This scenario demonstrates the impact of cleaner fuel usage in reducing NO₂ levels, especially in heavily industrialized areas where NO₂ levels are traditionally a concern for both environmental and public health.

Despite these improvements, some localized areas near emission sources still hover in the "moderate" category, underscoring the need for continued mitigation strategies to ensure long-term air quality improvements. The gradual decline in NO₂ levels also suggests that combining fuel shifting with additional measures, such as stack height increases, could further improve air quality in the affected regions.

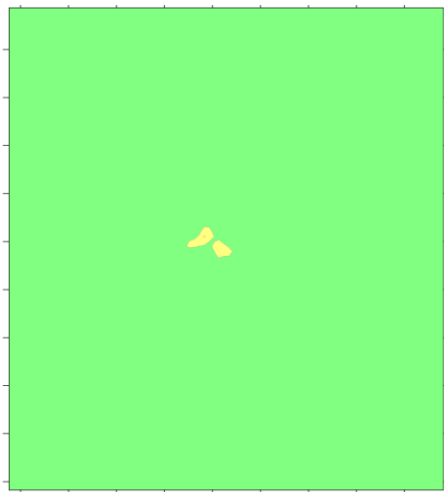


Figure 4-8: NO₂ AQI map for first quarter of 2021

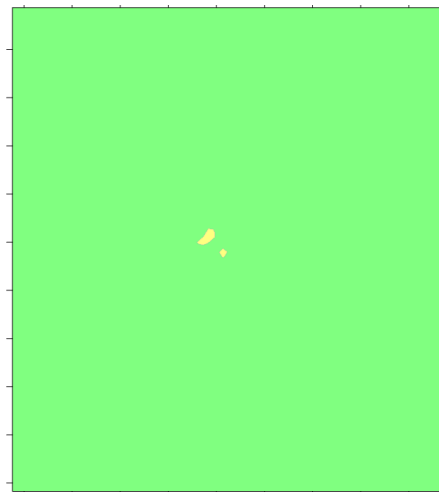


Figure 4-9: NO₂ AQI map for Scenario 1

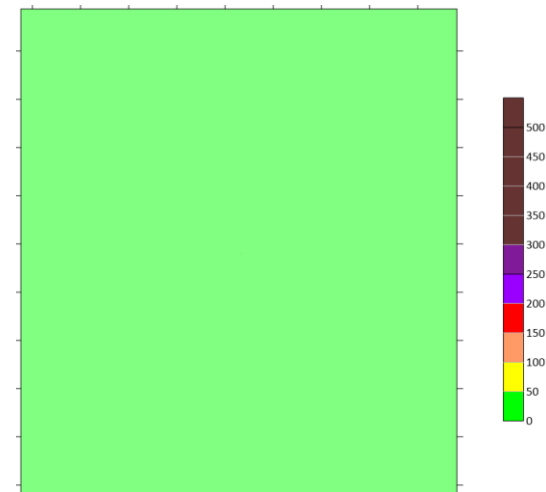


Figure 4-10: NO₂ AQI map for Scenario 2

4.3.3 AQI for SO₂

The SO₂ AQI maps show even more pronounced improvements across the different scenarios. In the original case, SO₂ concentrations reached concerning levels, with AQI values ranging from 0.13 to 182.72. This placed parts of the receptor area in the "unhealthy" range, especially in zones immediately surrounding the industrial stacks. Such elevated SO₂ levels are attributed to the combustion of high-sulfur fuels, which results in significant sulfur emissions.

Scenario 1 (increased stack height) provided some relief, reducing SO₂ concentrations slightly and shifting most of the affected areas to the "moderate" or "unhealthy for sensitive groups" range. However, Scenario 2 (fuel shifting) had the most dramatic impact on SO₂ levels. In this scenario, AQI values dropped sharply, with a maximum reading of just 18.27, firmly within the "good" range. This reduction of over 90% in SO₂ concentrations highlights the effectiveness of transitioning to cleaner, low-sulfur fuels in mitigating sulfur emissions.

The fuel shifting scenario, which replaces traditional fuel sources with cleaner alternatives such as natural gas, led to a 97.2% reduction in SO₂ emissions. This not only significantly improves air quality but also drastically reduces the health risks associated with SO₂ exposure, particularly near industrial areas. The AQI maps for Scenario 2 show that even the areas closest to the industrial sources now experience "good" air quality, with SO₂ concentrations well below harmful levels.

This improvement highlights the importance of adopting cleaner energy sources in industrial operations, not only for compliance with environmental regulations but also for the protection of public health. The near-total elimination of "unhealthy" AQI levels for SO₂ across the receptor area illustrates the potential for fuel shifting to bring about long-term improvements in air quality, especially in regions where industrial activities contribute heavily to air pollution.

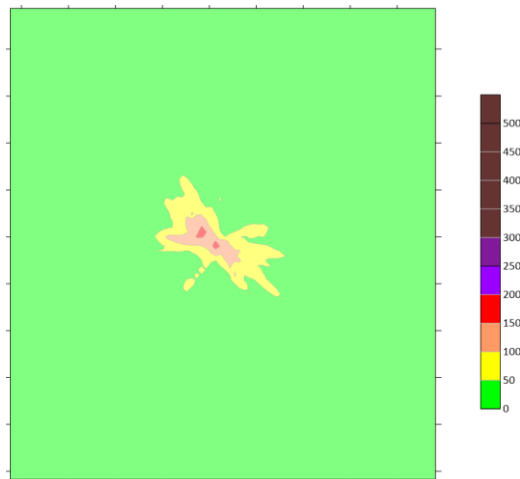


Figure 4-11: SO₂ AQI map for first quarter of 2021

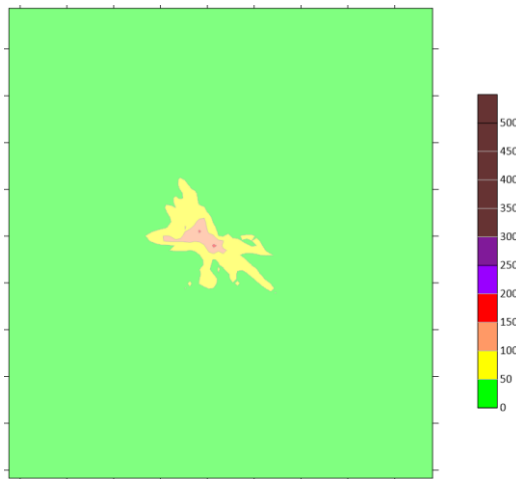


Figure 4-12: SO₂ AQI map for Scenario 1

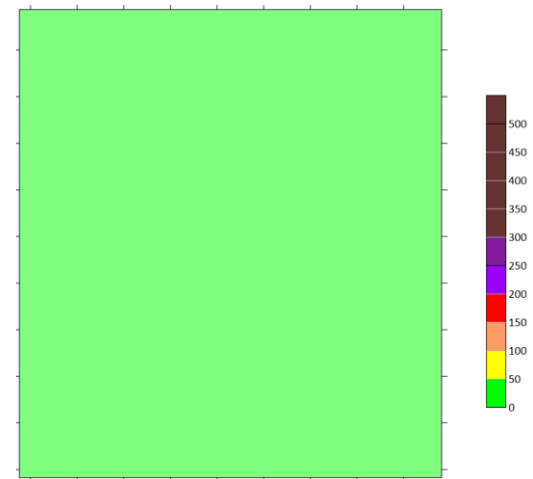


Figure 4-13: SO₂ AQI map for Scenario 2

4.3.4 AQI for PM_{2.5}

PM_{2.5} concentrations remained mostly in the "moderate" range across scenarios. In 1st quarter case, AQI values peaked at 95.19 near the industrial site, representing a moderately polluted environment. After implementing fuel shifting in Scenario 2, the AQI values were slightly reduced to a maximum of 92.91, still within the "moderate" category, but showing no significant degradation in air quality. In contrast, Scenario 1 (Stack Height Increase) provided more significant improvements in AQI results, particularly for PM_{2.5}. The increased stack height allowed for better dispersion of pollutants, reducing their ground-level concentrations.

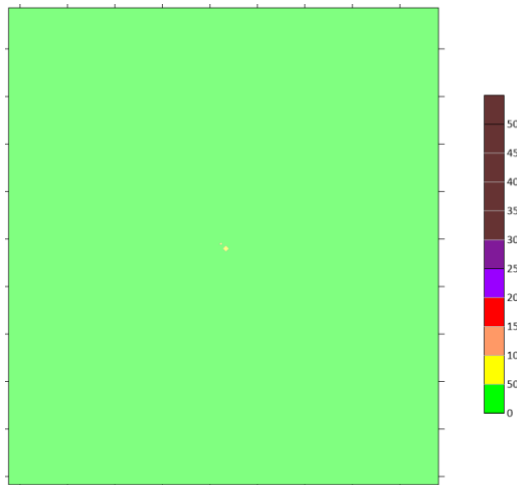


Figure 4-14: PM_{2.5} AQI map for first quarter of 2021

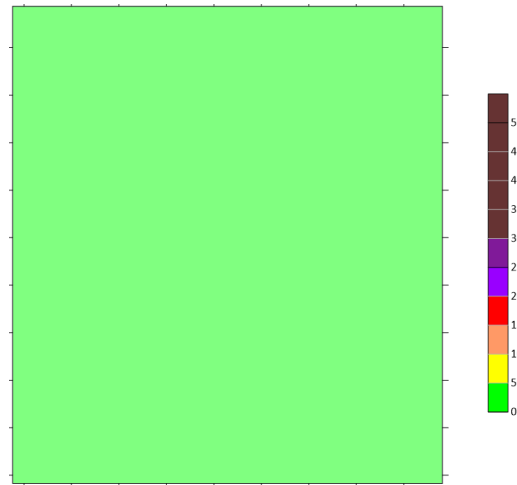


Figure 4-15: PM_{2.5} AQI map for Scenario 1

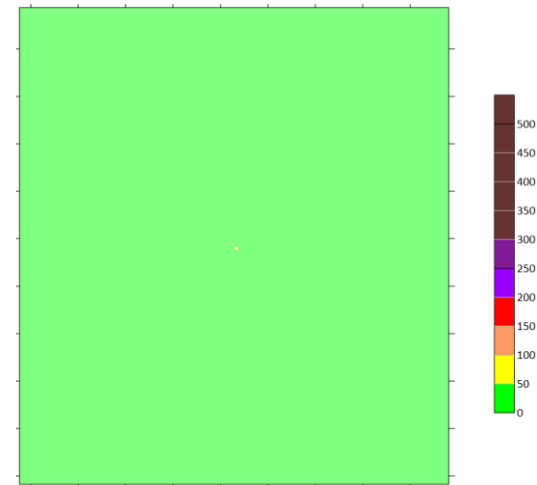


Figure 4-16: PM_{2.5} AQI map for Scenario 2

4.3.5 AQI for PM₁₀

The AQI for PM₁₀ remained consistently below 50 across all scenarios, indicating "good" air quality. In 1st quarter case, AQI values ranged from 0.01 to 44.85, and after mitigation measures, including fuel shifting, the values only dropped slightly to 43.66. This shows that PM₁₀ emissions, while present, pose minimal health risks in the evaluated domain.

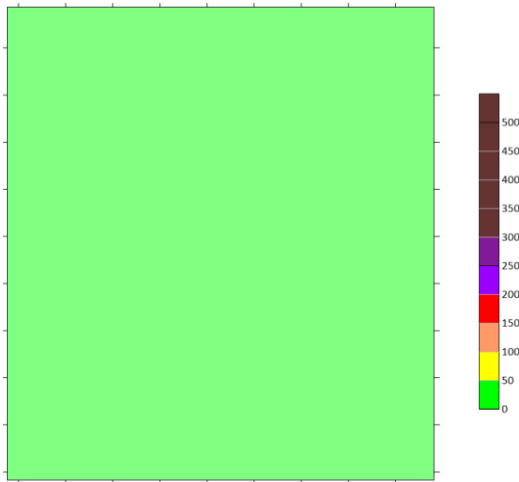


Figure 4-17: PM₁₀ AQI map for first quarter of 2021

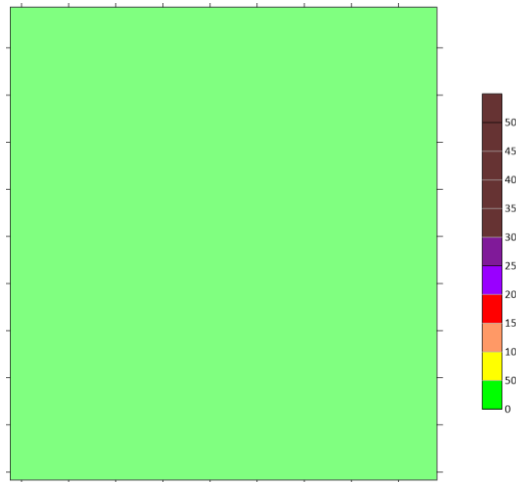


Figure 4-18: PM₁₀ AQI map for Scenario 1

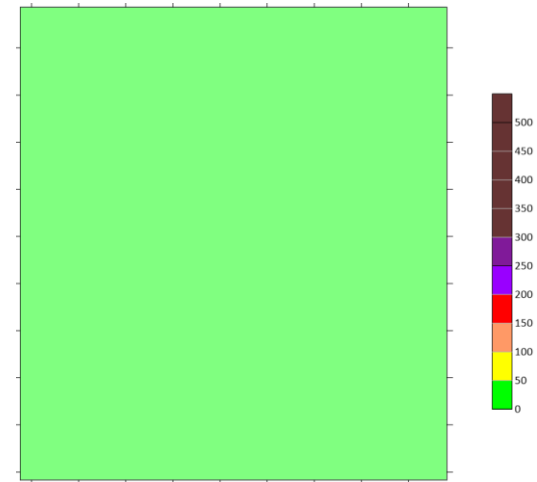


Figure 4-19: PM₁₀ AQI map for Scenario 2

4.4 Human Health Non-Cancer Risk Assessment Results

As mentioned in section 3.6.1 (Exposure Assessment) Hazard quotients (HQ) and hazard indexes (HIs) were assessed near the source location using daily average concentrations of pollutants dispersion scenarios.

In Scenario 1, the HI is reduced by 28.6%.

The changes in HQs show a slight improvement:

- SO₂ remains the largest contributor, with an HQ reduction of 27.8%.
- NO₂ shows a reduction in HQ of 27.5%.

Fuel shifting, Scenario 2, proves to be the most effective mitigation strategy, with the HI dropping by 72.4%. This indicates that the health risks associated with pollutant exposure are substantially mitigated. The HQs for each pollutant reflect this improvement:

- SO₂ sees the most dramatic reduction, with an HQ reduction of 97.2%, effectively eliminating it.
- NO₂ also shows a significant reduction, with an HQ reduction of 51.9%, though it still represents the most considerable contributor to the remaining HI.

The following table outlines the health impact severity, population exposure, susceptibility of the population, and the calculated risk rating for each pollutant.

Table 4-1: Health Impact Assessment

Pollutant	Health Impact Severity	Population Exposure	Susceptibility of Population	Risk Rating
SO₂	Critical (3) - Respiratory and cardiovascular impacts	Frequent (5) - Common in industrial areas	High - Affects vulnerable groups severely	15
NO₂	Critical (3) - Causes respiratory inflammation and reduces lung function	Frequent (5) - Widespread exposure near traffic and industrial sources	High - Affects asthmatics and the elderly significantly	15
PM₁₀	Marginal (2) - Causes respiratory issues but less penetration than PM _{2.5}	Probable (4) - Ubiquitous presence in urban and industrial settings	Moderate - Impacts are severe in sensitive individuals	8
PM_{2.5}	Critical (3) - Penetrates deeply into the lungs and cardiovascular system	Frequent (5) - Ubiquitous presence in urban and industrial settings	High - Especially dangerous for children and the elderly	15
CO	Marginal (2) - Primarily affects cardiovascular function and can impair cognitive function at high levels	Occasional (3) - High levels typically occur in enclosed areas with poor ventilation	Moderate - Significant effects on people with pre-existing heart conditions	6

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

- This research aimed to assess the impact of industrial emissions in the Kingdom of Saudi Arabia by analyzing key pollutants such as NO₂, SO₂, PM_{2.5}, PM₁₀, and CO using the CALPUFF dispersion model.
- The study evaluated the effectiveness of two mitigation scenarios (increasing stack height, and fuel shifting) to reduce pollutant concentrations. The mitigation strategies demonstrated varying degrees of effectiveness, with fuel shifting showing the most significant reductions in pollutant concentrations, particularly for NO₂ and SO₂, while increasing stack height achieved notable but comparatively moderate reductions across all pollutants, highlighting the need for integrated approaches to fully address industrial emissions.
- The reductions, particularly in NO₂ and SO₂, brought AQI levels to well below critical thresholds, with most areas achieving "good" air quality (AQI below 50). SO₂, was even effectively reduced to safe levels under the fuel shifting scenario, nearly eliminating its contribution to the Hazard Index by 97.2% reduction.
- Fuel shifting proved to be the most effective mitigation measure, achieving substantial reductions across pollutants, particularly for SO₂ and NO₂. These reductions contribute to significant improvements in air quality and align with the goals of sustainable development.

- This study underscores the critical importance of employing effective mitigation strategies to reduce industrial emissions.
- Fuel shifting demonstrated substantial improvements in air quality, making it a key solution for reducing pollutants such as SO₂ and NO₂.
- Increasing stack height provided moderate reductions but was less effective for pollutants with short-term high concentrations.
- By using advanced dispersion modeling techniques, this research provides actionable insights for policymakers and industries in the Kingdom of Saudi Arabia to implement effective emission reduction strategies.
- These findings support Saudi Arabia's Vision 2030 objectives for sustainable development, highlighting the need for cleaner technologies and comprehensive air quality management.
- The study sets the stage for further research into integrated approaches to air quality improvement, ensuring healthier communities and a more sustainable environment.

5.2 Recommendations

5.2.1 Air Quality Improvement

- Fuel shifting is the most effective way to reduce NO₂ and SO₂ emissions. Transitioning to cleaner fuels like natural gas should be prioritized to achieve significant reductions in pollutant concentrations.
- Increasing stack height can help reduce ground-level pollutant concentrations, especially for PM_{2.5}, PM₁₀, and CO. This measure should be considered where fuel shifting is not immediately feasible.
- A centralized database for real-time industrial emissions data should be used to support air quality modeling and ensure compliance with environmental regulations.
- Hourly meteorological data should be made available in the right format from the authorities to improve the accuracy of air dispersion models and support more effective pollution control strategies instead of using satellite data.
- Future air quality models should integrate building data to account for downwash effects and improve predictions of pollutant dispersion.
- Installing more continuous monitoring equipment for the industries who have potential of affecting the surrounding environment to track real-time pollutant levels, allowing for quick responses to pollution spikes and ensuring effective mitigation.
- Enforce stricter emission controls on SO₂ and NO₂ to encourage cleaner technologies and ensure compliance with air quality standards.

5.3 Limitations of the research

This research has provided important insights into the mitigation of air pollutants from industrial sources. However, several limitations should be noted as they frame the context in which these conclusions are drawn. These limitations include:

5.3.1 Lack of Model validation

One significant limitation is the absence of model validation, which was primarily due to the unavailability of Air Quality Monitoring Station (AQMS) data. This restriction may affect the accuracy of the dispersion modeling, as calibration aligns the model outputs with observed data, enhancing the predictive reliability of the modeling.

5.3.2 Modeling Constraints

The CALPUFF modeling system used in this study does not support parallel computing, which significantly increases the time required for each model run. This limitation restricted the ability to include seasonal variations in the analysis, as conducting multiple runs to cover different seasons would have been prohibitively time-consuming given the computational resources required.

5.3.3 Greenhouse Gases and Temperature Impacts

While the focus of the study was on air pollutants, the effects of greenhouse gases and indirect temperature-related impacts were not deeply integrated into the model's results. The interaction between air quality and climate change factors such as greenhouse gas emissions and rising temperatures could provide additional layers of complexity and accuracy to the study's findings.

5.4 Contributions of the Research

Despite the limitations, the research makes several unique contributions to the field of environmental science and industrial pollution control:

5.4.1 Integration of Multiple Scenarios

The research proposed various mitigation scenarios within a single thesis, offering a comprehensive analysis of potential interventions. This approach allows for a detailed comparison of the effectiveness of different strategies, providing valuable insights for policymakers and environmental managers.

5.4.2 Comprehensive Analysis of Different Pollutants

This study uniquely presents the effects of multiple pollutants, including SO₂, NO₂, PM₁₀, PM_{2.5}, and CO, within a single investigative framework. This comprehensive approach provides a holistic view of the air quality challenges faced by industrial regions and the combined health impacts of various pollutants.

5.4.3 Extensive Study Domain and Source Evaluation

The research covered a large geographic domain and considered emissions from a significant number of sources. This extensive coverage ensures that the results are robust and reflective of complex industrial activities, making the findings relevant for wide-scale air quality management and planning.

5.5 Future Research Directions

- Secure AQMS data to validate and calibrate air dispersion models.
- Utilize more efficient computing resources to study seasonal effects on pollutant dispersion.
- Research the combined effects of air quality and climate variables like greenhouse gases and temperature.

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WORK EXPERIENCE

- | | | |
|--------------------------------|---|-----------------------|
| Jan 2023 /
Now | VEKR Environmental Services Est. | Khobar, Saudi Arabia |
| | <ul style="list-style-type: none">• Established the Environmental Consultancy Department• Department Manager Projects Manager• Archival of the Company's Digital Files• Environmental Consultant• Investigations, environmental site analysis and sampling expert• Developed the department to achieve Class (A) with NCEC• Finished Around (19) Environmental Technical Reports for Projects related to NCEC• Support (4) clients to establish their certificates in NCEC system• Finished Around (04) Projects with MWAN• Support (2) clients to establish total (6) certificates in MWAN system• Support in other departments development. | |
| Oct 2021 /
Dec 2022 | Saudi Ecodem for Environmental Services Co. Ltd. | Dhahran, Saudi Arabia |
| | <ul style="list-style-type: none">• Management of the company's Environmental Aspects and Documents• Procurement Coordinator for Materials and Services for Saudi Aramco Project• Assistant Sales Engineer• Vendors Management and Registration• Archival of the Company's Digital Files• Aramco Portal User Assistant | |
| Oct 2018 /
Sep 2021 | Arabian Environmental Science Ltd Co. | Khobar, Saudi Arabia |
| | <ul style="list-style-type: none">• Indore Air quality, noise, soil and ground water investigations• Undertaking monitoring of noise levels during the construction, commissioning, and operational stages of projects• Writing Environmental studies including Baseline and Environmental Impact Assessments• Environmental Auditing• General environmental management• Environmental field surveys | |

- Reviewer to environmental studies and reports
- Investigations, environmental site analysis and sampling
- Project Manager Assistant
- Project Manager for Several EIAs and Environmental Registers
- NCEC & NCWM (MWAN now) (GAMEP/PME) systems user.

June, 2023	Attended a 2-Day Online Course (16 hours) on CALPUFF Air Dispersion Modeling by Lakes
March, 2023	Attended a 2-Day Online Course (16 hours) on AERMOD Air Dispersion Modeling by Lakes.
January, 2023	Attended Environmental management with AERMOD Air Pollution Model by EPA, 5hrs.
June 27, 2022	Active Volunteer with Environmental Friends in various activities.
Jul 01, 2021	Presented a lecture about “Environmental Noise Pollution” to IAU undergraduate students.
March 30, 2021 – May 03, 2021	Completed the course (Hydrological studies preparation and hydraulic structure design using WMS, Hyfran, Global Mapper, HEC-HMS, HEC-RAS, Culvert Master, Flow Master, SewerGEMS, software's, 40 hrs) by HB Academy - Jordan.
September 02, 2020	Completed the training program (Fundamentals of environmental auditing for industrial facilities, 02 hrs) by Scientific Endowment at King Abdulaziz University in Jeddah.
February 2019	Completed the course (W504 – Asbestos and Other Fibers, 30 hrs) by Faculty of Occupational Hygiene.
June 2018	Institution of Occupational Safety and Health (IOSH) Certificate
April 14, 2018	Done the Academic IELTS Test with an overall band score 5.5 / 9.0
November 2017	Provide an environmental awareness on E-Waste with Saudi DAZ E-Waste Recycling Plant.
November 2017	Founding member of Environmental Engineering Club in Imam Abdulrahman Bin Faisal University.
October 19, 2017	1st Place (Under Graduate Level) in the 5th Water Arabia Conference & Exhibition with the poster title “Solar Based Tertiary Effluent Treatment for Agricultural Reuse: Towards Sustainable Water Management in Saudi Arabia”