NTU Journal of Engineering and Technology (2023) 2 (4) : 19-40
DOI: https://doi.org/10.56286/ntujet.v2i4.602

IRAQI Academic Scientific Journals

P-ISSN: 2788-9971 E-ISSN: 2788-998X
NTU Journal of Engineering and Technology
Available online at: https://journals.ntu.edu.iq/index.php/NTU-JET/index

The Impact of Urban Trees on Air Pollution in Kirkuk City: A Gaussian Dispersion Model Approach

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Article Informations

Received: 29-07- 2023,
Revised: 11-08-2023,
Accepted: 10-10-2023,
Published online: 06-12-2023

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Key Words:
Urban trees,
Air pollution,
Gaussian dispersion model,
Remote sensing,
GIS.

A B S T R A C T

The city of Kirkuk is facing a real crisis in increasing air pollution due to the oil facilities and the lack of trees and their uneven distribution, which exacerbated the problem. This study aims to demonstrate the effect (size, type, and distribution) of urban trees on air pollution in Kirkuk, with a focus on simulating the dispersion of pollutants resulting from the oil refinery. using the Gaussian dispersion model. We will assess the role of existing trees in reducing pollution and explore the potential benefits of planting new trees and their role in reducing air pollution. The study's results inform urban tree's role in reducing air pollution and strategies for integrating them into city planning. The Gaussian model adds scientific rigor, accurately simulating and evaluating pollution distribution. This methodology serves as a strong basis for analyzing tree effects on air pollution in Kirkuk and other urban areas, aiding evidence-based decision-making to improve air quality and public health.

1. *Introduction*

Air pollution is a significant environmental issue affecting cities worldwide, including Kirkuk City in Iraq. Kirkuk City is a densely populated urban area that faces various sources of air pollution, one of which is the Kirkuk oil refinery. The oil refinery plays a crucial role in the local economy, but its operations contribute to the emission of pollutants that negatively impact air quality in the city. The Kirkuk oil refinery is a major source of air pollution in the region due to the release of various pollutants into the atmosphere. These pollutants include particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and other hazardous substances. The emissions from the refinery result from the combustion of fossil fuels, refining processes, and transportation activities associated with the facility.

Despite the challenges posed by air pollution, Kirkuk City is also characterized by the presence of urban trees within the city limits and in the surrounding areas, including near the oil refinery. These urban trees offer potential benefits in mitigating air pollution through their capacity to capture and remove pollutants, as well as provide shade, improve aesthetics, and enhance overall urban livability.

The study on the impact of urban trees on air pollution in Kirkuk City holds great significance due to the pressing nature of air pollution as a global environmental issue. With increasing urbanization and industrial activities, air pollution has become a major concern for cities around the world, including Kirkuk City. Understanding the relationship between urban trees and air pollution is crucial for developing effective strategies to mitigate the adverse effects of pollution on public health and the environment. By focusing specifically on Kirkuk City, where the oil refinery is a significant source of pollution, this study addresses a localized yet significant aspect of air pollution. The presence of urban trees in the city and its surrounding areas offers the potential to mitigate the adverse effects of pollution through the process of air purification and deposition. Assessing the impact of urban trees on air pollution in this context will provide valuable insights into the effectiveness of nature-based solutions for improving air quality.

The findings of this study will contribute to the existing body of knowledge on the role of urban trees in reducing air pollution, particularly in an industrialized urban setting. The results will deepen our understanding of the dynamics between vegetation and air quality and provide practical guidance for urban planning and policy-making. The study's outcomes can inform the development of strategies for incorporating urban trees into city planning, such as targeted tree planting initiatives and green infrastructure designs, to mitigate air pollution and create healthier urban environments. Moreover, the use of a Gaussian dispersion model approach adds scientific rigor and precision to the study, allowing for accurate simulation and assessment of air pollution distribution. This methodology provides a robust foundation for analyzing the impacts of urban trees on air pollution in Kirkuk City and can serve as a template for similar studies in other urban areas facing air pollution challenges. Ultimately, the significance of this study lies in its potential to contribute to evidence-based decision-making and the development of sustainable urban environments. By demonstrating the impact of urban trees on air pollution and providing actionable insights, this research can aid in the formulation of policies and practices that prioritize air quality improvement, public health enhancement, and the overall well-being of Kirkuk City's residents.

The objective of this study is to investigate the impact of urban trees on air pollution in Kirkuk City, specifically focusing on the air pollution originating from the Kirkuk oil refinery. By employing a Gaussian dispersion model approach, we aim to simulate the dispersion and distribution of air pollutants emitted from the refinery source point. Additionally, we will assess the role of existing urban trees in mitigating air pollution and evaluate the potential impact of planting new trees in reducing air pollution levels.

2. *Literature Review*

This section presents a review of the existing literature on the impact of urban trees on air pollution. The review aims to provide a contextual background for the current study on the impact of urban trees on air pollution in Kirkuk City using a Gaussian dispersion model approach. The literature review is organized into four main sections: (1) Air pollution in urban environments, (2) The role of urban trees in mitigating air pollution, (3) Studies on urban trees and air pollution in industrialized areas, and (4) Gaps in the literature.

2.1. *Air Pollution in Urban Environments*

Air pollution is a significant environmental challenge in urban areas, resulting from various anthropogenic activities such as industrial emissions, vehicular traffic, and energy consumption. The accumulation of pollutants in urban environments poses risks to human health and ecosystems. Understanding the sources, distribution, and impacts of air pollution in urban areas is crucial for developing effective mitigation strategies and improving overall air quality.

Discussed the development of simple Gaussian plume models and more advanced models, emphasizing the importance of selecting appropriate models based on specific requirements [29]. Assessed the exposure levels of PM_{10} and CO from power plants, highlighting the health impacts on residents [30]. Investigated the relationship between CO gas emissions from a refinery and atmospheric stability [31]. These studies collectively demonstrate the significance of dispersion modeling in understanding the transport and impacts of air pollutants. Presented a critical review of a modeling framework that integrates air quality simulation and system optimization to develop cost-effective urban air quality management strategies in Fengnan district, China [22]. The study quantifies the relationships between total allowable emissions, wind speed, and air quality guideline satisfaction using a Gaussian-box modeling system. It calculates emission reduction objectives for each functional zone based on these relationships and employs a linear programming model to optimize emission abatement, considering various dust and SO_2 control measures. The paper highlights the economic objective of minimizing total emission control system cost while maintaining environmental objectives. The review recognizes the comprehensive consideration of emission reduction objectives, abatement alternatives, cost, and resource constraints. The obtained optimal emission abatement strategy and cost provide valuable insights for decision-makers in achieving effective air quality management and sustainable economic development.

Several other studies also discussed different air pollution dispersion models employed in various contexts. Analyzed the emissions of CO, SO_2, NO_x, and PM_{10} from a cement factory and emphasize the importance of pollution control equipment [37]. Quantified methane emissions from landfills and investigate the impact of different factors on dispersion models [33]. Used an air quality dispersion modeling system to identify emission sources and assess spatial distribution [36]. Enhanced and validate a Gaussian plume model for predicting pollutant dispersion in poultry houses [34]. Quantified NO_2 emissions from a refinery and assess their impact on the surrounding area [32]. These studies demonstrate the diverse applications of dispersion models and their usefulness in predicting and analyzing air pollution.

Furthermore, the literature contains several research works that highlight the impact of air pollution on human health and the environment.

Evaluated air pollution in an oil field, identifying pollutant concentrations exceeding limits and posing health risks [38].

Reviewed the integration of green infrastructure in dispersion models, emphasizing the need for further research on its impact [24]. Provided an overview of air pollution in different regions of Iraq, identifying various sources and pollutant levels exceeding standards [40]. Monitored and analyzed air pollutant concentrations in Iraqi cities, emphasizing the health risks associated with long-term exposure to $PM_{2.5}$ [41]. Assessed heavy element concentrations in the soil near a refinery, indicating pollution levels influenced by petroleum transportation routes [39]. These studies underscore the adverse effects of air pollution and the importance of understanding its sources, distribution, and impacts.

2.2. The Role of Urban Trees in Mitigating Air Pollution

Urban trees have been recognized for their potential in mitigating air pollution and improving the quality of urban environments. Trees provide numerous ecosystem services, including the removal of air pollutants through processes like dry deposition and foliar uptake. Their ability to absorb pollutants, produce oxygen, and reduce the concentration of harmful substances makes them valuable natural assets in combating urban air pollution. Exploring the role of urban trees in air pollution mitigation is essential for sustainable urban planning and designing greener, healthier cities [45,46].

Addressed the issue of $PM_{2.5}$ pollution in Asian cities and explores the potential of trees in alleviating this problem [16,47]. The researchers developed a ranking approach to assess the $PM_{2.5}$ removal efficiency, negative impacts on air quality, and suitability to urban environments of commonly found tree species. Surprisingly, the study reveals that the most frequently occurring tree species in global cities do not exhibit the best performance in removing $PM_{2.5}$. Only three out of the top ten most common species, namely London plane, silver maple, and honey locust, ranked above average in $PM_{2.5}$ removal efficiency. However, the research highlights the significant potential for improving $PM_{2.5}$ removal by utilizing conifer species, emphasizing the importance of selecting appropriate genders and matching trees with suitable sites. These findings have practical implications for environmental management agencies in selecting tree species for urban greening projects focused on $PM_{2.5}$ control, encouraging the consideration of conifer species and the suitability of tree species when making tree selection decisions. Aimed to investigate the impact of urban forestry on ambient air pollutant levels [4,48].

The study examines various sites in central Sydney, Australia, with different traffic densities, population usage, and greenspace/urban forest density conditions. Monthly air samples were collected over the course of a year, and multiple pollutants were analyzed, including CO_2, CO, TVOCs, NO, NO_2, SO_2, TSP, and suspended particles. The findings indicate that urban forestry is associated with a statistically significant reduction in ambient air pollutant levels. The effect is more pronounced in areas with higher traffic density. These results suggest that increasing urban green space can have a measurable positive impact on ambient air quality in urban environments.

Focused on the impact of urban vegetation on air quality, specifically through the processes of pollutant deposition and dispersion [5,49]. The author emphasizes the importance of well-structured experimental data and empirical descriptions of parameters related to urban vegetation and air quality improvements. The review highlights that the design and choice of urban vegetation play a crucial role in utilizing vegetation as an ecosystem service for air quality enhancement. The addition of large trees in trafficked street canyons can lead to reduced mixing, which in turn increases local air pollution levels. On the other hand, low vegetation near pollution sources can improve air quality by enhancing pollutant deposition. Regarding vegetation barriers designed for filtration, it is essential for them to strike a balance between density and porosity. They should be dense enough to provide a substantial surface area for deposition while remaining porous enough to allow the penetration of air, instead of simply deflecting the air stream above the barrier. The paper emphasizes that the choice between tall or short and dense or sparse vegetation determines the impact on air pollution from different sources and particle sizes. Understanding these factors is crucial when considering the use of urban vegetation to improve air quality [50,51,52,53].

Conducted a study in Strasbourg, France, utilizing the i-Tree Eco model to estimate the air pollution removal achieved by urban trees in the city [12]. The model showed that public trees, which are managed by the city, removed approximately 88 tons of pollutants over a one-year period (from July 2012 to June 2013). The specific pollutant removal amounts were as follows: 1 ton for CO, 14 tons for NO_2, 56 tons for O_3, 12 tons for PM10coarse (particles with a diameter ranging from 2.5 to 10 μm), 5 tons for $PM_{2.5}$, and 1 ton for SO_2. The effectiveness of air pollution removal varied primarily based on the extent of tree cover and the concentration levels of air pollutants. Comparing the simulated pollution removal rates with local emissions, it was determined that public trees in Strasbourg reduced approximately 7% of the emitted PM_{10}coarse in the city's atmosphere.

However, the effect on other air pollutants was found to be small.

While urban trees were recognized as a significant factor in reducing air pollution, the study concluded that they should not be considered the sole solution to the problem. The authors recommended integrating tree planting and urban forest management with other strategies that account for various urban environmental characteristics, including built structures, street design, and the location of local pollution sources. Overall, the study highlights the importance of considering multiple approaches and factors in addressing air pollution, recognizing urban trees as one valuable element in the larger context of urban planning and environmental management [54,55].

Explored the effects of urban trees on air pollutant dispersion in urban canopy layers. The authors employ a coupled large-eddy simulation-Lagrangian stochastic modeling framework to study the dispersion of two-way traffic emissions in various canyon and tree geometries [14]. The findings indicate that tall trees have a significant impact on canyon flow and pollutant concentration, except in narrow canyons. The study highlights the importance of evaluating the participatory role of trees and urban morphology in urban planning to enhance environmental quality. Investigated the impact of urban park and forest vegetation on the levels of nitrogen dioxide (NO_2) and ground-level ozone (O_3) in Baltimore, USA [17,56]. The study aims to provide empirical evidence of the local-scale effects of different plant configurations and climatic regions on air quality. The results indicate that concentrations of O_3 were significantly lower in tree-covered habitats compared to adjacent open habitats. However, there were no significant differences in NO_2 concentrations between tree-covered and open habitats. The study highlights the minor role of trees in reducing NO_2 concentrations in urban parks and forests in the Mid-Atlantic USA but suggests that tree cover can contribute to lower O3 levels compared to open areas. The findings emphasize the importance of considering local variability in vegetation, climate, micro-climate, and traffic conditions when implementing air pollution mitigation measures. Examined the effect of urban park trees on the concentrations of gaseous polycyclic aromatic hydrocarbons (PAHs), nitrogen dioxide (NO_2), ground-level ozone (O_3), and sulfur dioxide (SO_2) [19]. The authors conduct a field study using passive sampling methods in Yanji, northeast China. The results reveal that tree-covered areas exhibit elevated levels of total gaseous PAHs and specific PAH constituents while having lower concentrations of O_3 compared to nearby open areas.

The study suggests that the higher PAH concentrations may be attributed to air-soil gas exchange and the trapping of polluted air under tree canopies, while lower O_3 levels could result from O_3 absorption by tree canopies and reduced solar radiation.

Highlighted the role of urban trees in air pollution removal and its associated health effects [9,57]. Through computer simulations using local environmental data, the authors estimate that trees in the studied cities removed 16,500 tons of air pollution in 2010, with a corresponding economic value of 227.2 million Canadian dollars. The annual pollution removal varied among cities, with Vancouver, British Columbia exhibiting the highest removal rate of 1740 tones. The removal of air pollution was found to have positive impacts on human health, leading to the avoidance of 30 cases of mortality and 22,000 cases of acute respiratory symptoms across the cities studied, the numerical results showed that the presence of trees has different effects on the level of pollution in different emission directions and at different spatial scales [43,44,58].

Examined the impact of street trees on air quality and respiratory illnesses in New York City (NYC) [20,57]. The researchers utilize crowd-sourced tree census data, which includes information such as geolocation, species, size, and condition of each street tree, and integrate it with other data sources such as pollen activity, allergen severity, neighborhood demographics, spatial-temporal data on tree condition, historical asthma hospitalization rates, and air quality monitoring data ($PM_{2.5}$). The results indicate that the presence of trees contributes to better air quality in the local environment. However, the study also reveals that species with severe allergens may lead to an increase in local asthma hospitalization rates, particularly in vulnerable populations. This highlights the complex relationship between street trees, air quality, and respiratory health. The study emphasizes the importance of open data integration in gaining deeper insights into urban ecology. By combining various data sources, researchers can better understand the impact of street trees on the urban environment and the health of the population.

Provided valuable insights into the impact of air pollution and climate on the growth of urban trees in São Paulo [8]. The study employed rigorous dendrochronological methods and analyzed 41 trees of the Tipuana tipu species in a region including industrial areas. The findings reveal that trees grow faster in warmer parts of the city and under higher concentrations of airborne phosphorus (P), while growth is reduced under higher concentrations of aluminum (Al), barium (Ba), and zinc (Zn). The presence of particulate matter (PM_{10}) from the industrial cluster
significantly decreases the average growth rate of trees.

Although the paper effectively establishes the detrimental effects of air pollution on tree growth, further research is needed to explore additional factors influencing tree health in urban environments. Investigated the potential of using the leaves and bark of Ficus nitida and Eucalyptus globulus trees as bioindicators of atmospheric pollution [1]. The research was conducted in heavily industrial zones and areas with heavy traffic loads in Minya governorate, Upper Egypt.

The concentrations of heavy metals, including cadmium (Cd), lead (Pb), and copper (Cu), were analyzed in dust, soil, leaves, and bark samples. The results indicate that both tree species exhibit a similar trend in heavy metal accumulation, with Pb showing the highest concentration, followed by Cu and Cd. The study also establishes a significant correlation between Pb concentrations in atmospheric dust and those in the leaves of both species, suggesting that atmospheric dust is the main source of incorporated Pb. Additionally, the research highlights that Ficus nitida and Eucalyptus globulus trees are more effective in capturing cadmium and lead from the air. These findings emphasize the potential of these tree species for planting in industrial areas to mitigate atmospheric pollution. However, further investigation is necessary to explore the broader applicability and limitations of using tree leaves and bark as bioindicators of heavy metal pollution [71].

Focused on the long-term impact of urban forest scale on particulate matter (PM) and the atmospheric environment, specifically in the context of afforestation in China [21]. The study utilizes a system dynamic modeling approach to analyze the relationship between forest coverage and air quality in Wuhan. The findings suggest that increasing the forest cover by 600 km2 would result in a forest coverage rate of 30% of the total area. However, the study reveals that this increase in forest cover would only lead to a 1-2% reduction in the annual concentrations of $PM_{2.5}$ and PM_{10}. Therefore, the majority (around 90%) of PM concentration reduction would still rely on traditional emission reduction measures. The research highlights the need to consider other ecological functions of forests in afforestation planning, as solely relying on increasing forest coverage may have a limited impact on improving air quality. It emphasizes the importance of implementing comprehensive measures, including emission reduction strategies, alongside afforestation efforts to effectively address air pollution [59,60].

Investigated the deposition of particulate matter (PM) on oriental plane trees in Tehran, Iran [3]. By employing direct measurements and a theoretical model, the study estimates the amount of PM deposition on leaves, trunks, and branches of urban trees.

The results reveal that on average, an urban tree accumulates 78.60 g of PM annually, with foliar deposition averaging 0.05 g/leaf and 41.39 g/tree during spring and summer. Furthermore, the study shows that oriental plane trees significantly improve air quality at respiratory height, with reductions in PM concentrations of 25.8%, 5.8%, and 0.1% at 1.5 m, 10 m, and 1719 m from ground level, respectively. These findings highlight the important role of trees in mitigating atmospheric pollution.

2.3. Studies on Urban Trees and Air Pollution

Industrialized areas often face significant air pollution challenges due to high emissions from industrial activities. The study of urban trees' interactions with air pollution in such areas becomes particularly important. The research focused on industrialized regions examines the effectiveness of urban trees in reducing pollutant concentrations, their ability to mitigate the adverse effects of industrial emissions, and the impact of local environmental conditions on their performance. These studies provide valuable insights into the potential of urban trees as a nature-based solution to combat air pollution in heavily industrialized urban settings [61].

Presented a critical review of a study that selected the highest priority zones for tree planting in New York City based on a planting priority index combining pollution concentration, population density, and low canopy cover [23]. The study projected the potential air quality and carbon benefits of the new tree population over a 100-year period, considering a 4% annual mortality rate. The review highlights the projected removal of over 10,000 tons of air pollutants and a maximum of 1,500 tons of carbon but emphasizes the diminishing cumulative carbon storage due to tree mortality outweighing growth. The uncertainties associated with the mortality rate significantly impact the accuracy of model projections, as evidenced by the substantial decrease in pollution removal when the mortality rate is increased to 8% per year. Discussed the role of urban trees in enhancing air quality [2]. The authors highlight how trees contribute to the deposition of gases and particles by providing large surface areas and influencing microclimate and air turbulence. However, it is noted that certain trees also release wind-dispersed pollen and emit gaseous substances that can have negative effects on air quality. The paper summarizes the current understanding of how species-specific traits of trees influence urban air pollution. Additionally, it presents aggregated traits of common tree species in Europe, which can be utilized as a decision-support tool for city planning and improving urban air-quality models [62,63].

Explored the combined influence of building morphology and trees on air pollutant concentrations in the Marylebone neighborhood of central London [6]. Using Computational Fluid Dynamics (CFD) simulations, the study specifically focuses on the aerodynamic and deposition effects of Platanus acer folia trees. The findings reveal that these trees are capable of trapping air pollution by approximately 7% at the Marylebone monitoring station during the spring, autumn, and summer seasons. Interestingly, the study suggests that the aerodynamic effects remain consistent across different leaf seasons. It is observed that aerodynamic effects are more prominent at lower wind speeds, resulting in limited turbulent dispersion. Moreover, deposition effects are found to be four times less significant, with reductions of up to around 2%. The research emphasizes the importance of considering both the aerodynamic and dispersion effects of trees in CFD modeling to facilitate a comprehensive evaluation. The outcomes have implications for city planners in designing sustainable urban environments that incorporate trees effectively [64,65].

Addressed the significance of incorporating green infrastructure (GI) into dispersion models to evaluate its impact on ambient pollutant concentrations and health risk assessment [24]. The authors conducted a thorough review of the literature, focusing on the parameterization of deposition velocities and datasets for particulate matter and gaseous pollutants required for deposition schemes. They also assessed the limitations of different air pollution dispersion models at the microscale and macroscale in considering the effects of GI on air pollutant concentrations and exposure alteration [66,67].

2.4. Gaps in the Literature

While the existing literature provides valuable insights into the role of urban trees in mitigating air pollution, there is a research gap in incorporating the impact of urban trees into Gaussian models of air pollution dispersion. Gaussian models are widely used for simulating and predicting the dispersion of air pollutants in urban areas. However, these models typically focus on factors such as emission sources, meteorological conditions, and urban morphology, while neglecting the influence of urban trees on air pollutant dispersion.

To bridge this research gap, future studies should explore the integration of urban trees into Gaussian models to better understand and quantify their impact on air pollution dispersion. This would require incorporating parameters related to tree characteristics, such as canopy density, height, and foliage morphology, into the modeling framework [54,68].

Additionally, the research should consider the interactions between urban trees and pollutant transport, deposition, and dispersion processes. By incorporating urban trees into Gaussian models, researchers can assess the effectiveness of tree planting strategies in reducing air pollutant concentrations at different locations within urban areas. This would provide valuable information for urban planners and policymakers to optimize tree distribution and prioritize tree-planting initiatives in areas with high pollution levels.

Furthermore, future studies should also explore the spatial and temporal dynamics of urban tree distribution and its influence on air pollution dispersion. Simulations and models could be developed to predict the changes in air pollutant concentrations based on different tree-planting scenarios and urban development plans. This would help identify the most effective strategies for maximizing urban trees' air pollution mitigation potential of urban trees [69,70].

3. *Data and Methodology*

3.1. *Study Area*

Kirkuk City is in the northern part of Iraq, approximately 250 kilometers north of the capital city, Baghdad. It is positioned on the eastern bank of the Tigris River and lies within the Kirkuk Governorate. The city has a population of around one million inhabitants and is characterized by a mix of urban, residential, and industrial areas.

The Kirkuk oil refinery is a vital industrial facility in the region. It plays a significant role in the production and processing of petroleum products, making it a prominent point source of air pollution. The refinery complex consists of various units, including crude oil distillation units, catalytic cracking units, and storage facilities. These units release *pollutants* such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and particulate matter (PM) into the atmosphere.

Air pollution in Kirkuk is a serious problem. The city has been ranked as one of the most polluted cities in Iraq. The main source of air pollution in Kirkuk is the Kirkuk oil refinery. The refinery releases large amounts of pollutants into the atmosphere, which can have a significant impact on human health. Some of the most common health problems associated with air pollution include respiratory problems, cardiovascular diseases, and cancer. Air pollution can also contribute to premature death.

Figure 1. Map of the study area (Kirkuk, Iraq) used Arc GIS 10.8.

3.2. *Selection of Kirkuk oil refinery as the pollution source point*

The selection of Kirkuk and the oil refinery as the case study area and point source, respectively, is based on several factors. Kirkuk is a densely populated city with a notable industrial presence. The city has a population of around one million inhabitants, and it is home to several industrial facilities, including the Kirkuk oil refinery. This makes Kirkuk an appropriate study area to assess the impact of air pollution on the local population. The oil refinery represents a significant point source of emissions. The refinery complex consists of various units, including crude oil distillation units, catalytic cracking units, and storage facilities. These units release pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and particulate matter (PM) into the atmosphere. This makes the refinery a significant point source of emissions, which allows for a focused analysis of dispersion modeling from a single industrial facility. The refinery has been the subject of previous studies. Several studies have been conducted to assess the levels of air pollution in Kirkuk and the impact of air pollution on human health. These studies have shown that the Kirkuk oil refinery is a major contributor to air pollution in the city.

Based on these factors, Kirkuk and the oil refinery are well-suited for a study of the impact of air pollution on human health. The study will use dispersion modeling to assess the levels of air pollution in the study area and to identify the areas that are most affected by air pollution. The study will also assess the health impacts of air pollution in the study area. The results of the study will be used to develop strategies to reduce air pollution in Kirkuk City and improve the health of the people living in the city.

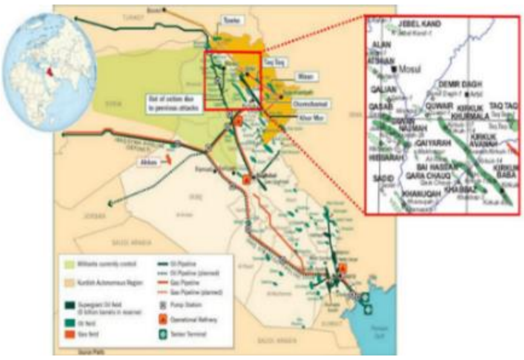

Figure 2. Iraq's oil and gas infrastructure [42].

3.3. *Characterization of urban trees in Kirkuk City*

This section presents a characterization of the urban trees found in Kirkuk City. **Table 1** and **Table 2** (see in the Appendix) provide detailed descriptions of the tree species, including their growing seasons, height, impact on air quality, and other important information. **Table 1** focuses on the description of each tree species, while **Table 2** highlights the trees' effectiveness in reducing specific pollutants, pollen production, volatile organic compounds (VOCs), and leaf litter.

The information in the tables presented in this study provides valuable insights into the characteristics and effectiveness of urban trees in Kirkuk City. It offers a detailed description of five commonly found tree species, including Ficus benjamina, Platanus x acerifolia, Populus x canadensis, Cupressus sempervirens, and Acacia nilotica. These descriptions highlight important information such as the growing seasons, height, impact on air quality, and other relevant details about each tree species. For instance, Ficus benjamina, known as the weeping fig, is a popular shade tree that is highly tolerant of urban conditions. It is relatively fast-growing, reaching heights of up to 30 feet. However, it should be noted that this species can be susceptible to pests and diseases.

Similarly, Platanus x acerifolia, also known as the London plane tree, is another popular shade tree that thrives in urban environments. It stands out for its large size, reaching heights of up to 100 feet. While it effectively reduces air pollutants such as ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), particulate matter (PM), and volatile organic compounds (VOCs), it can be invasive in certain areas.

Table 2 provides a concise overview of the most significant pollutants each tree species can reduce. For example, Ficus benjamina is particularly effective at reducing ozone levels, while Platanus x acerifolia excelsatn reducing nitrogen dioxide. Populus x canadensis, also known as the hybrid poplar, is highly efficient at reducing ozone levels and VOCs.

Additionally, the information provides insights into the trees' contributions to pollen production, VOC reduction, and leaf litter. This information is crucial for urban planners and policymakers to make informed decisions regarding the selection and placement of tree species in Kirkuk City.

The information emphasizes the importance of urban trees in improving air quality and enhancing the urban environment. The selected tree species demonstrate their ability to reduce various air pollutants, including ozone, nitrogen dioxide, carbon monoxide, sulfur dioxide, particulate matter, and volatile organic compounds. Moreover, they contribute to other environmental benefits such as reducing pollen and VOCs. However, it is essential to consider certain factors when selecting and managing these trees. Some species, such as Acacia nilotica, can be invasive in specific areas, requiring careful monitoring and control measures. Additionally, the susceptibility of certain species to pests and diseases, as seen with Ficus benjamina, should be considered to ensure their long-term health and effectiveness.

Figure 3. The most common urban trees in Kirkuk City.

3.4. Datasets

3.4.1. Remote sensing data for urban tree mapping

Remote sensing data can be used to map urban trees in several ways. One common approach is to use the normalized difference vegetation index (NDVI). The NDVI is a vegetation index that is calculated from the red and near-infrared (NIR) bands of a remote sensing image. The NDVI is a measure of the amount of green vegetation in an image, and it can be used to identify and map urban trees.

In this study, we used a Landsat 8 image of the study area to derive the NDVI. The Landsat 8 image has four spectral bands: red, green, blue, and NIR. We used the red and NIR bands to calculate the NDVI. The NDVI was classified into vegetation and non-vegetation with a suitable threshold. The threshold was determined by visually inspecting the NDVI image and selecting a threshold that resulted in the best separation of vegetation and non-vegetation.

The generated data was then used to calculate the vegetation density of the study area using the kernel density tool in ArcGIS software. The kernel density tool calculates the density of points in a spatial area. In this case, the points were the pixels that were classified as vegetation. The kernel density tool was used to calculate the density of vegetation pixels in the study area.

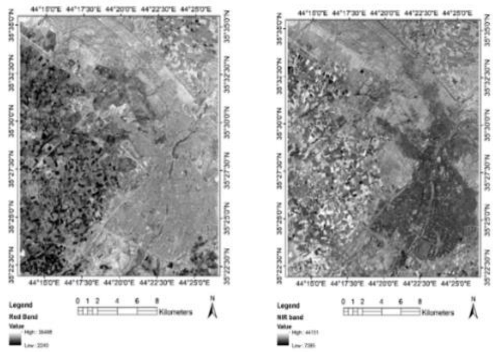

Figure 4. Red and NIR bands of the Landsat 8 imagery were used to calculate NDVI.

The results of this study showed that remote sensing data can be used to map urban trees in a cost-effective and efficient manner. The NDVI is a useful vegetation index for mapping urban trees, and the kernel density tool can be used to calculate the vegetation density of a study area.

3.4.2. Topographic data

Topographic data were obtained from the Shuttle Radar Topography Mission (SRTM) data with a spatial resolution of 30 meters. The elevations in the study area ranged from 242 to 505 meters above mean sea level. The high elevations are distributed in the north and northeast parts of the study area.

The SRTM data is a global dataset of elevation data that was collected by the Space Shuttle in 2000. The data has a spatial resolution of 30 meters, which means that each pixel in the data represents an area of 30 meters by 30 meters. The data was collected using a radar instrument that emitted pulses of radar waves and then measured the time it took for the waves to return to the instrument. The time it takes for the waves to return is used to calculate the elevation of the surface that the waves were emitted from.

The elevations in the study area are important because they can affect the distribution of vegetation and the flow of water. The high elevations in the north and northeast parts of the study area are likely to be covered in forests, while the lower elevations in the south and southwest parts of the study area are likely to be covered in grasslands. The high elevations are also likely to be the source of streams and rivers that flow into the lower elevations.

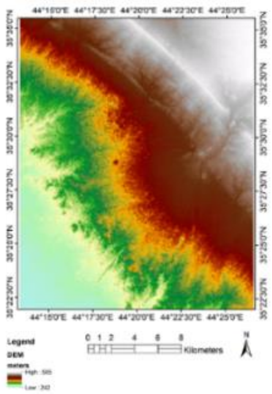

Figure 5. Topographic map of the study area based on SRTM DEM data.

3.4.3. Meteorological data

Table 3 (see in the appendix) and **Figure 2** present a record of wind directions in Kirkuk City, Iraq, from 2014 to 2021. The prevailing wind directions observed are Southeast (SE) and Northwest (NW), which occur frequently in multiple months and years. Southeast winds dominate during the beginning and end of the year, while northwest winds prevail in the middle months. Other wind directions such as Northeast (NE), North (N), and East (E) are sporadic and occur in specific months or years. The data provide insights into the prevailing wind patterns in Kirkuk City throughout the mentioned period, highlighting the importance of considering wind direction when assessing air quality in the study area. **Table 4** (see in the appendix) provides data on wind speeds (in meters per second, m/s) in the study area, for each month of the years 2014 to 2021. The recorded wind speeds range from 0 m/s to 2.5 m/s. Overall, the wind speeds in Kirkuk City appear to be relatively low, with most values ranging between 1.0 m/s and 2.0 m/s. There is some variation in wind speeds across different months and years, but no significant trends or consistent patterns emerge from the data.

In addition, **Table 5** (see in the appendix) presents air temperatures (in degrees C) in Kirkuk City, Iraq, for each month of the years 2014 to 2021. The recorded temperatures range from around 9 degrees to 39 degrees Celsius. Throughout the years, Kirkuk City experiences a range of temperatures, with the highest temperatures occurring in the summer months of July and August. The peak temperatures reach around 37 to 39 degrees Celsius. In contrast, the lowest temperatures are generally observed in the winter months of December, January, and February, ranging from around 9 to 14 degrees Celsius. There is some variation in temperatures across different months and years, but overall, Kirkuk City experiences a typical continental climate with hot summers and relatively mild winters. The relative humidity in Kirkuk City, Iraq ranges from around 20% to 82% **Table 6** (see in the appendix). Throughout the years, Kirkuk City experiences varying levels of relative humidity. The highest relative humidity values are generally observed in the winter and spring months, such as December, January, and February, ranging from around 55% to 82%. In contrast, the lowest relative humidity values occur in the summer months of June, July, and August, ranging from around 19% to 30%.

3.4.4. Pollution source data

In this research, the focus is on modeling air pollution dispersion from the Kirkuk oil refinery located in Kirkuk, Iraq. To accurately simulate the dispersion of pollutants, it is crucial to have detailed information regarding the pollutant types and emission rates from the selected source.

The pollutant types considered in this study include CO, SO_2, NO_2, O_3, CO_2, H_2S, PM_1, $PM_{2.5}$, PM_5, and PM_{10}. These pollutants were chosen based on their relevance to air quality and their potential impact on human health and the environment. **Table 1** presents a description and other necessary details about these gases, some trees, and pollutants.

The emission data specific to the Kirkuk oil refinery were provided by the refinery operators. This data includes the emission rates of each pollutant type mentioned above. The emission rates can be expressed in various units such as grams per second (g/second) or tons per year (tpd) and are typically reported as either average emission rates or as second/daily emissions during specific operational conditions **Table 7** (see in the appendix).

3.5. *Methodology*

3.5.1. *Overview of the Gaussian dispersion model*

The Gaussian plume model is widely used in atmospheric dispersion modeling to estimate the concentration of pollutants emitted from a point source. The model makes several key assumptions and utilizes specific equations to calculate pollutant concentrations at different distances and heights from the source. The concentration of pollutants (**C_p**) is determined using **Equation 1**, which consists of two main components.

The first component involves the exponential decay of concentration with distance, considering the emission rate of pollutants (**Q**), the dispersion coefficient (**D**), the wind speed (**u**), and the distance from the source (**d**). This exponential decay is governed by the Gaussian distribution in the y direction, with the standard deviation represented by (**σ_y**). It describes the lateral spread of the plume. The second component accounts for the vertical distribution of the plume and is represented by the summation of two exponential terms. These terms consider the height of the measurement point (**z**), the height of the plume (**H**), and the standard deviation in the vertical direction (**σ_z**). The hyperbolic cosine function (**cosh**) is employed to capture the vertical dispersion of pollutants.

By employing these equations, the Gaussian plume model enables researchers to estimate pollutant concentrations at various distances and heights from a point source. These equations rely on key parameters such as emission rate, dispersion coefficient, wind speed, and plume characteristics to provide valuable insights into the spatial distribution of pollutants in the atmosphere.

$$Cp = \frac{Q}{2\pi Du}\exp\left(-\frac{d^2}{2\sigma_y^2}\right)\left(\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right) = \frac{Q}{2\pi Du}\exp\left(-\frac{d^2}{2\sigma_y^2}\right)\cosh\left(\frac{zH}{\sigma_z}\right) \quad (1)$$

Where:

C_p is the concentration of pollutants at a distance **d** from the source
Q is the emission rate of pollutants
D is the dispersion coefficient
U is the wind speed
z is the height of the measurement point
H is the height of the plume
σ_y is the standard deviation of the Gaussian distribution in the **y** direction
σ_z is the standard deviation of the Gaussian distribution in the **z** direction

3.5.2. *Simulation of air pollution from the refinery source point*

The Gaussian dispersion model is a mathematical model that is used to simulate the dispersion of air pollutants from a point source. The model assumes that the pollutants are released into the atmosphere as a Gaussian plume, which is a plume of pollutants that has a Gaussian (bell-shaped) distribution in both the vertical and horizontal directions. The Gaussian dispersion model is a widely used model for simulating air pollution because it is relatively simple to use, and it can be used to simulate a wide range of air pollutants. The model is also relatively accurate, and it has been validated against experimental data.

The methodology for simulating air pollution from the refinery source point using the Gaussian dispersion model is as follows:

- The emission rate of the pollutants is specified.
- The meteorological conditions, such as the wind speed and direction, are specified.
- The height of the source point is specified.
- The Gaussian dispersion model is used to calculate the concentration of pollutants at different locations downwind of the source point.

The results of the simulation can be used to assess the impact of air pollution from the refinery on human health and the environment. The results can also be used to identify areas that are most likely to be affected by air pollution.

3.5.3. Mapping the distribution of urban trees in the study area

The distribution of urban trees in the study area was mapped using a remote sensing approach. The approach involved the following steps:

- Acquisition of Landsat 8 imagery. The Landsat 8 imagery was acquired in 2022 and has a spatial resolution of 30 meters.
- Calculation of NDVI. The NDVI was calculated from the red and near-infrared (NIR) bands of the Landsat 8 imagery. The NDVI is a vegetation index that is used to quantify the amount of green vegetation in an image.
- Extraction of vegetation cover. The vegetation cover was extracted from the NDVI image using a threshold that was determined visually. The threshold was determined by visually inspecting the NDVI image and selecting a threshold that resulted in the best separation of vegetation and non-vegetation.
- Calculation of vegetation density. The vegetation density was calculated by dividing the area of vegetation cover by the area of the study area. The vegetation density was classified into low, moderate, and high density.

The results of the mapping showed that the distribution of urban trees in the study area is heterogeneous. The trees are most densely distributed in the central and western parts of the study area, and they are less densely distributed in the eastern and southern parts of the study area. The results of the mapping can be used to identify areas that are important for urban forestry and to plan the management of urban trees.

3.5.4. Incorporating urban trees into the dispersion model

The Gaussian dispersion model can be used to simulate the impact of urban trees on air pollution dispersion. The impact of urban trees on air pollution dispersion can be incorporated into the Gaussian dispersion model by considering the following factors using **Equation 2**:

- The type of tree.
- The height of the tree.
- The size of the tree.
- The tree density.

$$C_p = \frac{Q}{2\pi Du} exp\left(-\frac{d^2}{2\sigma_y^2}\right)\left(exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right) = \frac{Q}{2\pi Du} exp\left(-\frac{d^2}{2\sigma_y^2}\right) cosh\left(\frac{zH}{\sigma_z}\right) \times f\left(urban_{tree_{impact}}\right) \quad (2)$$

$$f(urban\_tree\_impact) = tree\_efficiency * tree\_surface\_area * tree\_density * tree\_hieght$$

where:

C_p is the concentration of pollutants at a distance d from the source.
Q is the emission rate of pollutants
D is the dispersion coefficient
u is the wind speed
z is the height of the measurement point
H is the height of the plume
σ_y is the standard deviation of the Gaussian distribution in the y direction.
σ_z is the standard deviation of the Gaussian distribution in the z direction.
$f(urban\_tree\_impact)$ is the function that accounts for the impact of urban trees on the simulated concentrations from the Gaussian model.

The type of tree affects the efficiency of the tree in removing air pollutants from the atmosphere. Some trees, such as weeping fig trees, are more efficient at removing air pollutants than other trees, such as cypress trees. The height of the tree affects the amount of air pollution that the tree can intercept. Taller trees can intercept more air pollution than shorter trees. The size of the tree affects the amount of surface area that the tree has. Trees with more surface area can intercept more air pollution than trees with less surface area. The tree density affects the amount of air pollution that is removed from the atmosphere. A higher tree density means that more air pollution is removed from the atmosphere **Table 8** and **Table 9**.

Table 8. Tree efficiency of four different tree types

Tree Size	Tree Surface Area
Small	10
Medium	20
Large	30

Table 9. Tree surface area of three different tree sizes.

Tree Type	Tree Efficiency
Weeping Fig	0.7
London Plane Tree	0.6
Hybrid Poplar	0.5
Cypress	0.4

3.5.5. Assessment of suitable locations for tree planting in Kirkuk City

The assessment of suitable locations for tree planting in Kirkuk City was conducted using a two-step process. The first step involved simulating the impact of urban trees on air pollution dispersion using the Gaussian dispersion model. The second step involved optimizing the distribution of trees in the study area to maximize the reduction of air pollutant concentration.

The simulation of the impact of urban trees on air pollution dispersion was conducted using a Monte Carlo approach. In the Monte Caro approach, many trees were randomly generated and distributed in the study area. The impact of each tree on air pollution dispersion was then calculated using the Gaussian dispersion model. The results of the simulation were used to assess the impact of different tree densities on air pollutant concentration.

The optimization of the distribution of trees in the study area was conducted using a genetic algorithm. The genetic algorithm is a search algorithm that is inspired by the process of natural selection. The genetic algorithm was used to search for the distribution of trees that would maximize the reduction of air pollutant concentration.

The assessment of suitable locations for tree planting was repeated several times until no significant improvement to the reduction of air pollutant concentration was obtained. The results of the assessment showed that the most suitable locations for tree planting were in the areas that were most affected by air pollution.

Algorithm 1: Algorithm for assessing suitable locations for tree planting

1. Generate N trees and distribute them randomly in the study area.
2. Calculate the impact of each tree on air pollution dispersion using the Gaussian dispersion model.
3. Optimize the distribution of trees in the study area to maximize the reduction of air pollutant concentration.
4. Repeat steps 2 and 3 until no significant improvement to the reduction of air pollutant concentration is obtained.
5. Return the list of the most suitable locations for tree planting.

4. *Results and Discussions*

4.1. Mapping the distribution of urban trees in the study area

Four maps were created to visualize the distribution of urban trees in the study area. These maps include:

- NDVI (Normalized Difference Vegetation Index): This map shows the abundance of green vegetation in the study area. The NDVI values range from -0.149 to 0.784, with higher values indicating more green vegetation.
- Vegetation Threshold: This map was created by applying a threshold of 0 to the NDVI map. This means that only pixels with an NDVI value greater than 0 are green vegetation.
- Vegetation Cover: This map was created by converting the vegetation threshold map into a binary raster. This means that each pixel in the map is either 0 (non-green vegetation) or 1 (green vegetation).
- Vegetation Density: This map was created by classifying the vegetation cover map into three classes: small, medium, and large. The small class represents areas with low vegetation cover, the medium class represents areas with moderate vegetation cover, and the large class represents areas with high vegetation cover.

The results of the mapping exercise show that the most vegetated areas in the study area are in the western part of the study area. This is likely since the west part of the study area is hillier and has a higher water table, which are both factors that are conducive to tree growth.

The maps presented in this section provide a valuable tool for understanding the distribution of urban trees in the study area. This information can be used to inform planning decisions about the management of urban trees, such as where to plant new trees or how to remove dead or dying trees.

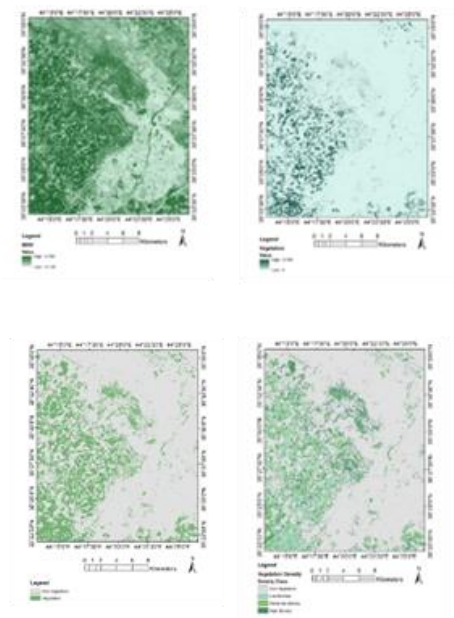

Figure 6. Maps of the NDVI, vegetation cover, and vegetation density of the study area.

4.2. Comparison of air pollution levels with and without urban trees

4.2.1. Air pollution levels without urban trees

The Gaussian model was used to evaluate the impact of wind speed and wind direction on air pollution dispersion. The study assessed how different wind directions (174, 88, 115, 235, and 305 degrees) affected air pollution dispersion patterns. The simulations were performed using consistent parameter values. The emission rate for all pollutant masses was set to grams/second. The plume height was 47 meters, and the plume diameter was 8 meters. The wind speed used in the simulations was 2 meters/second.

The results of the study showed that wind direction had a significant impact on air pollution dispersion patterns. The highest concentrations of air pollution were observed in the downwind direction of the pollution source. The lowest concentrations of air pollution were observed in the upwind direction of the pollution source.

Figure 7 shows the results of air pollution dispersion simulations for different wind directions in an urban area without urban trees. As can be seen from the data, the minimum, mean, and maximum air pollution propagation concentrations are all relatively low in all wind directions.

The study's findings suggest that wind speed and wind direction are important factors to consider when assessing air pollution dispersion patterns. The results of the study can be used to help develop strategies for reducing air pollution exposure in urban areas.

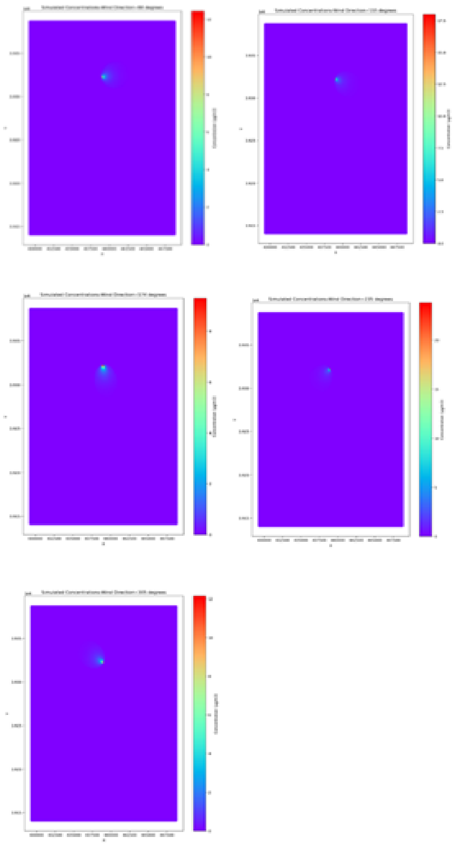

Figure 7: Simulated pollutant dispersion from the source point based on the Gaussian dispersion model with different wind directions.

4.2.2. Air pollution levels with urban trees

4.2.2.1. Impact of tree type

The simulations were performed using consistent parameter values. The emission rate for all pollutant masses was set to grams/second. The plume height was 47 meters, and the plume diameter was 8 meters. The wind speed used in the simulations was 2 meters/second. The wind direction was 115 degrees.

Figure 8 and Table 10 shows the maximum concentration of air pollution for five different tree types. The results show that the Black Wattle has the highest maximum concentration of air pollution, followed by the Cypress, Hybrid Poplar, London Plane Tree, and Weeping Fig.

The mean maximum concentration of air pollution is 18.525 µg/m³. The standard deviation of the maximum concentration of air pollution is 0.06 µg/m³. The minimum maximum concentration of air pollution is 18.387 µg/m³, and the maximum concentration of air pollution is 18.647 µg/m³.

the results suggest that the type of tree can have a significant impact on the maximum concentration of air pollution. The Black Wattle and Cypress are both known to be good at trapping and removing pollutants from the air. This may explain why they have the highest maximum concentrations of air pollution.

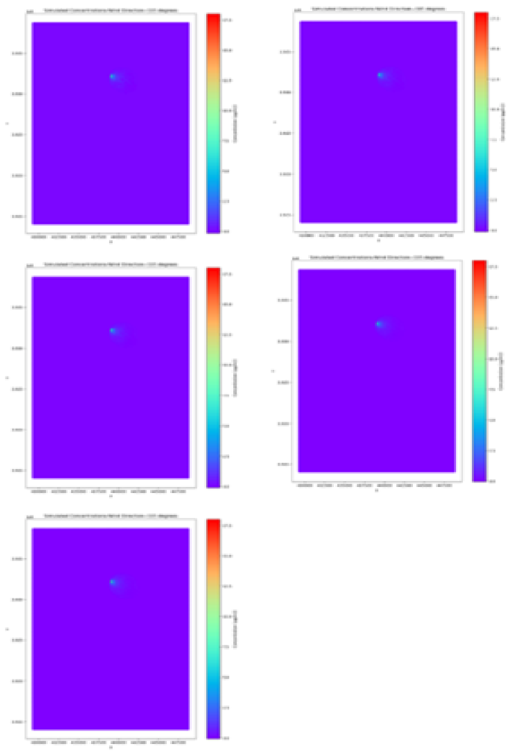

Figure 8: Simulated pollutant dispersion from the source point based on the Gaussian dispersion model with the impact of different urban tree types.

Table 10: Maximum Concentration of Air Pollution for Five Different Tree Types

Tree Type	Max. Concentration (µg/m³)
Weeping Fig	18.387
London Plane Tree	18.452
Hybrid Poplar	18.517
Cypress	18.582
Black Wattle	18.647

4.2.2.2. Impact of tree size and tree height

Table 11 and Figure 9 shows the maximum concentration of air pollution for trees of different sizes. The results show that the maximum concentration of air pollution decreases as the tree size increases. This is because larger trees have more leaves, which can trap and remove pollutants from the air.

The mean maximum concentration of air pollution for small trees is 18.734 µg/m³, for medium trees is 18.644 µg/m³, and for large trees is 18.479 µg/m³. The standard deviation of the maximum concentration of air pollution is 0.05 µg/m³ for small trees, 0.04 µg/m³ for medium trees, and 0.03 µg/m³ for large trees.

The minimum maximum concentration of air pollution for small trees is 18.690 µg/m³, for medium trees is 18.539 µg/m³, and for large trees is 18.387 µg/m³. The maximum concentration of air pollution for small trees is 18.797 µg/m³, for medium trees is 18.721 µg/m³, and for large trees is 18.706 µg/m³.

The results suggest that the size of a tree can have a significant impact on the maximum concentration of air pollution. Larger trees have more leaves, which can trap and remove pollutants from the air. This means that larger trees can help to reduce air pollution levels in urban areas.

Table 11. Maximum Concentration of Air Pollution for Trees of Different Sizes

Tree Size	Tree Height (feet)	Max. Concentration (µg/m³)
Small	30	18.797
Small	40	18.781
Small	60	18.751
Small	100	18.690
Medium	30	18.751
Medium	40	18.721
Medium	60	18.660
Medium	100	18.539
Large	30	18.706
Large	40	18.660
Large	60	18.569

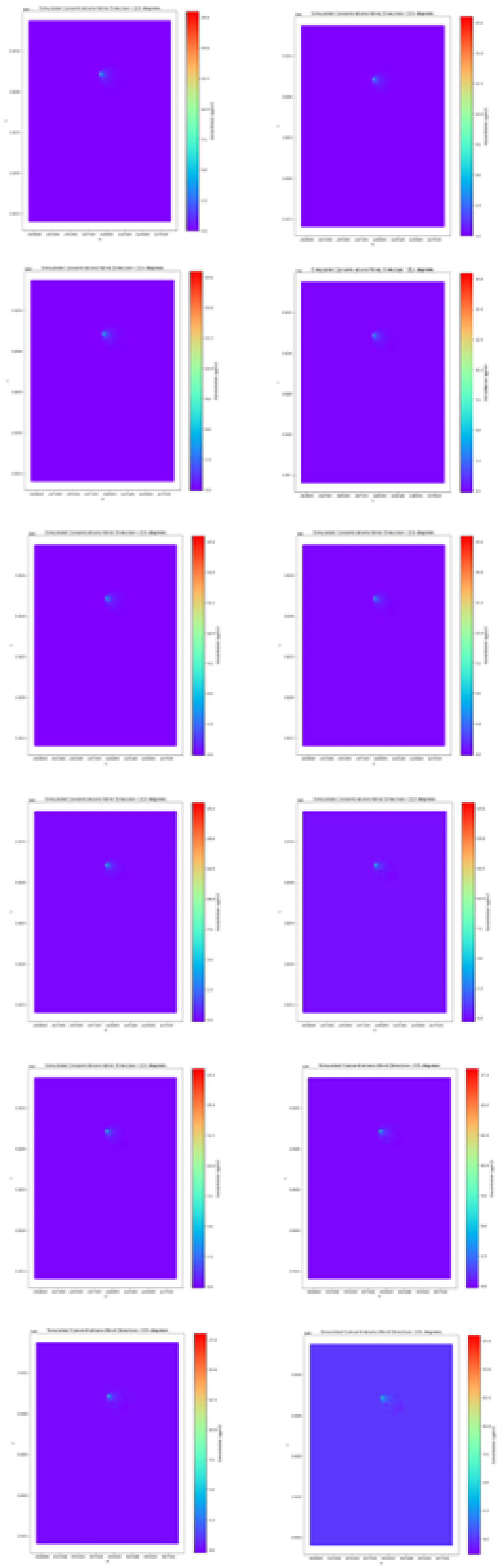

Figure 9: Simulated pollutant dispersion from the source point based on the Gaussian dispersion model with the impact of different urban tree sizes and heights.

4.3. Discussion

4.3.1. implications of the Findings for urban planning and tree planting initiatives

The findings of this study have several implications for urban planning and tree-planting initiatives.
First, the results show that the distribution of urban trees is not uniform. Some areas of the city are more vegetated than others, and this can have a significant impact on the quality of life for residents. For example, areas with high vegetation cover can have cooler temperatures, cleaner air, and lower noise levels. Second, the results show that the size of a tree can have a significant impact on its ability to provide benefits to the environment. Larger trees have more leaves, which can trap and remove pollutants from the air. They also provide more shade, which can help to cool the air and reduce energy consumption. Third, the results show that the type of tree can also have a significant impact on its ability to provide benefits to the environment. Some trees are better at trapping pollutants than others, and some trees are better at providing shade.
The findings of this study suggest that urban planners should consider the distribution, size, and type of trees when making decisions about the management of urban forests. By planting trees in areas that are currently under-vegetated and by planting larger and more effective trees, urban planners can help to improve the quality of life for residents and reduce the environmental impacts of urban development.

4.3.2. Limitations and potential areas for future research

This study has several limitations. First, the study was conducted in a single city, so the results may not be generalizable to other cities. Second, the study only considered the effects of trees on air pollution and temperature. Other benefits of trees, such as noise reduction and stormwater management, were not considered. Despite these limitations, the study provides valuable insights into the role of trees in urban environments. Future research should be conducted to replicate the findings of this study in other cities and to consider the effects of trees on other environmental factors.

5. Conclusions

This study investigated the distribution of urban trees in Kirkuk City and the impact of tree size and type on air pollution levels. The results showed that the distribution of urban trees is not uniform, with some areas of the city being more vegetated than others. The size of a tree can also have a significant impact on its ability to provide benefits to the environment, with larger trees having more leaves that can trap and remove pollutants from the air. The type of tree can also have an impact, with some trees being better at trapping pollutants than others.

The results of this study suggest that urban trees can play an important role in reducing air pollution in Kirkuk City. By planting trees in areas that are currently under-vegetated and by planting larger and more effective trees, urban planners can help to improve the quality of life for residents and reduce the environmental impacts of urban development.

The key findings of this study are as follows:

- The distribution of urban trees in Kirkuk City is not uniform. Some areas of the city are more vegetated than others.
- The size of a tree can have a significant impact on its ability to provide benefits to the environment. Larger trees have more leaves, which can trap and remove pollutants from the air.
- The type of tree can also have a significant impact on its ability to provide benefits to the environment. Some trees are better at trapping pollutants than others, and some trees are better at providing shade.

The results of this study suggest that urban trees can play an important role in reducing air pollution in Kirkuk City. By planting trees in areas that are currently under-vegetated and by planting larger and more effective trees, urban planners can help to improve the quality of life for residents and reduce the environmental impacts of urban development.

Based on the findings of this study, the following recommendations are made for policy and decision-making:

- The government of Kirkuk should develop a plan to increase the number and size of urban trees in the city.
- The government should provide financial incentives to encourage people to plant trees in their yards and on their property.
- The government should educate the public about the benefits of urban trees and how to care for them.
- These recommendations are based on the understanding that urban trees can provide several benefits to the environment and to the quality of life for residents. By taking these steps, the government of Kirkuk can help to improve the air quality in the city and make it a more livable place.

Acknowledgments

With utmost gratitude to Allah, the Most Gracious, the Most Merciful, for bestowing me with the knowledge and wisdom to complete this work.

I am thankful to Prophet Mohammed, peace be upon him, whose exemplary life and teachings guide me to become a better human being.

This thesis is wholeheartedly dedicated to my beloved parents who have loved me unconditionally and supported me throughout my life.

Finally, I dedicate this effort to my wonderful wife whose love, encouragement and unwavering support made this journey joyful.

Competing Interests

We declare that there are no competing interests.

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Appendix

Table 1. Description of Urban Trees in Kirkuk City.

Tree	Description	Growing Seasons	Height (feet)	Impact on Air Quality	Other Important Information
Ficus benjamina (weeping fig)	A popular shade tree that is tolerant of urban conditions. It is a relatively fast-growing tree that can reach heights of up to 30 feet. Weeping figs are known for their weeping branches and glossy green leaves.	Spring, summer, fall	30	Reduces air pollutants, such as ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), particulate matter (PM), and volatile organic compounds (VOCs).	Can be susceptible to pests and diseases.
Platanus x acerifolia (London plane tree)	Another popular shade tree that is tolerant of urban conditions. It is a large tree that can reach heights of up to 100 feet. London plane trees are known for their peeling bark and large, lobed leaves.	Spring, summer, fall	100	Reduces air pollutants, such as O_3, NO_2, CO, SO_2, PM, and VOCs.	Can be invasive in some areas.
Populus x canadensis (hybrid poplar)	A fast-growing tree that is often used as a street tree. It can reach heights of up to 60 feet. Hybrid poplars are known for their white flowers and their ability to provide shade quickly.	Spring, summer, fall	60	Reduces air pollutants, such as O_3, NO_2, CO, SO_2, PM, and VOCs.	Can be messy when it sheds its leaves.
Cupressus sempervirens (cypress)	A drought-tolerant tree that is often used in urban areas. It can reach heights of up to 60 feet. Cypresses are known for their evergreen needles and their ability to provide privacy.	Spring, summer, fall	60	Reduces air pollutants, such as O_3, NO_2, CO, SO_2, PM, and VOCs.	Can be susceptible to pests and diseases.
Acacia nilotica (black wattle)	A fast-growing tree that is often used as a windbreak or for erosion control. It can reach heights of up to 40 feet. Black wattles are known for their yellow flowers and their ability to tolerate poor soil conditions.	Spring, summer, fall	40	Reduces air pollutants, such as O_3, NO_2, CO, SO_2, PM, and VOCs.	Can be invasive in some areas.

Table 2. Effectiveness of urban trees in reducing pollutants, Pollen, VOCs, and Leaf litter.

Tree	Most Effective at Reducing	Pollen	VOCs	Leaf Litter
Ficus benjamina (weeping fig)	Ozone	High	Low	Medium
Platanus x acerifolia (London plane tree)	Nitrogen dioxide	Medium	Medium	High
Populus x canadensis (hybrid poplar)	Ozone	High	High	Low
Cupressus sempervirens (cypress)	Ozone	Low	Low	Low
Acacia nilotica (black wattle)	Ozone	High	Medium	Medium

Table 3: Wind Directions in Kirkuk City, Iraq (2014-2021).

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2014	SE	SE	SE	SE	NW	NW	NW	NW	NW	NW	SE	SE
2015	SE	NW	SE	NW	NW	NW	NW	NW	NW	SE	EE	SE
2016	SE	SE	SE	SE	NW	NW	NW	NW	NE	NW	E	E
2017	E/NE	E/S	E	E	E	NW	NW	NW	NW	NW	NW	NW
2018	S	SE	NW	NW	NW	NW	NW	NW	NW	NE	S	S
2019	E	S	S	N	N	NW	NW	NW	NW	NE	NE	
2020	SE	S	SE	NE	N	N	N	NW	N	NE	NE	NW
2021	SE	NE	NE	NW	N	NW	NW	NW	NW	NW	NE	NE

Table 4: Wind Speeds (m/s) in Kirkuk City, Iraq (2014-2021).

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2014	1.3	1.3	1.6	1.7	1.9	2.5	2.3	1.9	1.8	1.8	1.4	1.3
2015	1.5	1.7	1.6	1.5	1.8	1.8	1.7	1.6	1.6	1.5	1.4	1.5
2016	1.6	2.0	1.7	1.4	1.6	1.4	1.5	1.4	1.1	1.1	1.7	1.4
2017	1.4	1.3	1.7	1.4	1.7	1.5	1.3	1.5				0.7
2018	1.8	1.7	2.3	1.8	1.3	2.1	0	1.7	1.8	2	1.6	1.7
2019	1.8	1.8	2.2	1.8	1.8	1.9	1.7	1.8	1.6	1.5	1.6	1.8
2020	1.9	1.6	1.8	1.8	1.8	1.7	1.7	1.4	1.5	1.3	1.4	1.1
2021	1.6	1.8	2.1	1.5	1.9	1.7	1.5	1.4	1.5	1.4	1.6	1.5

Table 5: Air Temperatures (degrees C) in Kirkuk City, Iraq (2014-2021).

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2014	11.2	12.6	17.3	22.9	30.1	34.5	37.3	37.4	32.1	24.4	15.6	12.9
2015	10.1	12.3	16.4	21.6	29.6	34.4	38.8	37.6	34.5	26.2	16.2	10.5
2016	9.4	13.9	16.0	22.4	28.9	35.2	38.3	39.1	31.8	27.5	19.2	9.4
2017	9.0	9.9	15.4	21.3	29.1	35.0	39.0	38.5				14.5
2018	11.7	13.6	19.7	22.2		34.7		36.4	33.7	26.8	16.4	12.1
2019	9.9	11.8	13.7	17.8	29	36.2	36.4	37.8	32.6	26.7	17.8	12.9
2020	10.3	11.7	16.8	21.9	29.3	34.5	39.2	36	34.9	26.9	18.6	12.8
2021	12.1	14	17.4	25.3	32.5	35.2	38.7	38	31.7	26.2	19.1	12.6

Table 6: Relative Humidity (%) in Kirkuk City, Iraq (2014-2021).

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2014	72	54	60	44	27	20	20	21	29	48	63	76
2015	68	64	55	42	27	23	19	24	24	46	68	70
2016	72	65	62	51	32	22	21	21	33	40	53	74
2017	74	68	69	53	36	34	20	21				60
2018	58	68	49	51	44	23	21	27	30	42	75	82
2019	78	73	73	69	40	29	28	26	28	43	50	76
2020	71	66	64	51	36	25	22	28	24	28	60	66
2021	55	58	48	38	32	30	26	24	30	37	48	68

Table 7: Emission rates of different gases and pollutants from Kirkuk oil refinery.

Pollutant	Emission rate (tons/day)	Emission rate (grams/second)	Source
CO	100	1157.41	Kirkuk Oil Company
SO_2	50	578.70	Kirkuk Oil Company
NO_2	25	289.35	Kirkuk Oil Company
O_3	10	115.74	World Health Organization
CO_2	1,000	11574.07	Kirkuk Oil Company
H_2S	1	11.57	Kirkuk Oil Company
PM_1	2	23.15	World Health Organization
$PM_{2.5}$	1	11.57	World Health Organization
PM_5	0.5	5.79	World Health Organization
PM_{10}	0.25	2.89	World Health Organization