ASSESSMENT OF AMBIENT AIR QUALITY IN HARAR CITY, ETHIOPIA

M.Sc THESIS

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We hereby certify that we have read and evaluated this Thesis entitled "Assessment of Ambient Air Quality in Harar City, Ethiopia" prepared under our guidance by Mubeshir Kedir. We recommend that it be submitted as fulfilling the thesis requirement.

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Final approval and acceptance of the thesis is contingent upon the submission of its final copy to the council of graduate studies (CGS) through the candidate's school graduate committee (SGC).

DEDICATION

I hereby dedicate this thesis to the memory of my beloved father, Haji Kedir Ahmed, who passed away during my thesis preparation, before seeing the fruits of his lifelong efforts. His absence has been deeply felt. I also dedicate this work to my dear grandfather, Haji Nesro Mosa, and my uncle, Haji Mohammed Ahmed, who left us in recent months, both of whom I miss profoundly.

STATEMENT OF THE AUTHOR

By my signature below, I declare and affirm that this Thesis is my work. I have followed all ethical and technical principles of scholarship in the preparation, data collection, data analysis, and compilation of this Thesis. Any scholarly matter that is included in the Thesis has been given recognition through citation.

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BIOGRAPHCAL SKETCH

The author, Mr. Mubeshir Kedir Ahmed, was born on July 13, 1997, from his Father Kedir Ahmed and mother Fesu Nesro in Hulbareg District, Silte Zone of Central Ethiopia Region (the then SNNPR), Ethiopia. He attended elementary school at Demeke Elementary School from 2004 to 2011. Then, he joined Hulbareg Secondary and Preparatory School in 2012 and attended there from grade 9 to 12.

After passing the Ethiopian Higher Education Entrance Certificate Examination (EHEECE) in 2016, he joined Wollega University in 2017 and graduated with Bachelor of Science (BSc) degree in Environmental Sciences on June 24, 2019. After graduation, the author was employed by Haramaya University as a Graduate Assistant since October 23, 2020 and has been serving in the School of Natural Resource Management and Environmental Sciences to date. He joined the Postgraduate Programs Directorate in November 2022 to pursue his study leading to Master of Science degree in the field of Environmental Sciences and Management.

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ABBREVIATIONS AND ACRONYM

AQI	Air quality Index
CO	Carbon monoxide
EPA	Environmental Protection Authority
HPNRS	Harari Peoples National Regional State
LMICs	Low and Medium Income Countries
PM	Particulate Matters
PM_{10}	Particulate matter with aerodynamic diameter of < 10 microns
$PM_{2.5}$	Particulate matter with aerodynamic diameter of < 2.5 microns
VOCs	Volatile Organic Compounds
WHO	World Health Organization

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ABSTRACT

Air pollution is responsible for an estimated 7 million deaths across the globe due to fossil fuel burning, vehicular emissions, factories, industries and other activities. Despite vulnerability of communities living in close proximity to major roadways and factories, no scientific studies explored the ambient air quality of Harar city. The objective of this study was to assess the concentration levels of particulate matters ($PM_{2.5}$ and PM_{10}) Carbon monoxide (CO), Sulphur dioxide (SO_2), and Nitrogen dioxide (NO_2), and compare them against both Ethiopian and World Health Organization (WHO) guidelines to determine exceedance levels and spatial distribution of the pollutants in the Harar city. Measurements were taken across various sample points within the city, providing a comprehensive overview of spatial distribution and pollutant concentrations. A total of 21 air samples at each of 16 junctions for each parameter for 7 days using Aeroqual's Series 500 handheld portable device. Moreover, maps of the selected criteria air pollutants were created and visualized to represent the spatial distributions of the pollutants in Harar City. Data analysis revealed that the average concentrations of $PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2 were 79.77µg/m³, 185.33 µg/m³, 2586.51 µg/m³, 47.42 µg/m³, and 216.49 µg/m³, respectively. Among these values, $PM_{2.5}$, PM_{10} and NO_2 significantly exceeded both WHO and Ethiopian air quality guidelines. Carbon monoxide and SO_2 also showed high exceedance levels from WHO guidelines indicating a critical issue with air quality in Harar City even though they were within the national guidelines. This study indicates the urgent need for effective mitigation strategies to improve air quality and protect public health in Harar. Thus, better urban planning, promoting the use of cleaner energy sources, and implementing stringent emissions regulations for both industrial and vehicular sources could improve ambient air quality of the city.

Keywords: *Air pollutant, Concentration, Exceedance, Harar city, spatial distribution*

1. INTRODUCTION

Economic development and globalization have led in migration of fast changing energy intensive lifestyles, mechanization, and automation as a result of scientific advancements and evolution of newer branches of research (Balashanmugam *et al*., 2012). Polluted air, polluted space, contaminated land, and polluted water are the unintended consequences; awareness of air contamination and efforts to monitor and manage air quality are inadequate given the rapidity with which pollution levels are increasing (Balashanmugam *et al*., 2012)

Air pollution is one of the most serious environmental health issues challenging humanity. Indeed, a number of epidemiological and pathophysiological data suggest the relationship between air pollution and all-cause mortality and morbidity, primarily but not entirely from respiratory and cardiovascular disorders (Mannucci *et al*., 2015). Ambient air pollution is perceived as a major concern due to elevated concentrations of some contaminants such as PMs and CO, which result in negative health and environmental effects (Hands, 2022). Urban air pollution, with its long- and short-term effects on human health, well-being, and the environment, has become a generally acknowledged issue during the last 50 years (Özden *et al*., 2008). Pollution has major detrimental consequences not just on human health, but also on ecosystems, materials, and visibility (Özden *et al*., 2008). The world health organization (WHO, 2014) reported that seven (7) million people died worldwide as a result of air pollution in 2012 (Okoro, 2019).

Air pollution is a silent killer and foremost cause of some of the most common human health challenges. Air pollution is responsible for 36% of lung cancer fatalities, 35% of Chronic Obstructive Pulmonary Disease (COPD) and lung disease deaths, 34% of stroke deaths, and 27% of heart disease deaths (Kasim *et al*., 2018). Globally, about 1.4 billion urban inhabitants breathe air that does not satisfy WHO air quality criteria (Kasim *et al*., 2018). The global mortality rate from outdoor air pollution is estimated to be between 200,000 and 570,000 (Kasim *et al*., 2018). According to World Health Organization (WHO) data, 9 out of 10 people breathe polluted air, with low- and middle-income countries (LMICs) bearing the burden of poor air quality (Xie *et al*., 2021). Air pollution is the most significant environmental risk factor for early death (Xie *et al*., 2021). Urban air pollution episodes are primarily due to increased concentrations of pollutants from traffic and industries (Ganguly and Thapa, 2016). Motor vehicles release a wide range of pollutants, including nitrogen oxides (NOx), carbon monoxide (CO), volatile organic compounds (VOC), which are hydrocarbons, and particle matter (PM) (Ganguly and Thapa, 2016). Exposure to traffic-related air pollution has negative health consequences such as asthma and birth complications (Ganguly and Thapa, 2016). In view of the harmful human health impacts, monitoring stations have been established in several nations to check air quality on a continuous basis, measuring concentrations from both roadside and urban areas (Ganguly and Thapa, 2016).

Pollution prevention and control approaches in developing nations are also acquiring greater importance under stronger regulations, especially in recent years, however, air pollution remains a severe environmental issue in many developing countries' urban centers, and many cities throughout the world are subjected to high levels of air pollution (Özden *et al*., 2008).

One of the main issues facing developing nations' is the rising population and associated demand for transportation services and challenges of the prevailing poverty. According to Kume *et al*., (2010), more than 50% of cities with increased level of ambient urban air pollution are found in developing countries. Urban air pollutants such as particulate matter (PM_{10}) and volatile organics were found to surpass international standards in developing-country cities (Kume *et al*., 2010). The existence of poorly maintained old cars on the one hand, and restricted and gradually expanding urban road networks on the other side, are issues that may not sustain clean urban air surrounding traffic zones in many developing countries (Kume *et al*., 2010).

Ambient air pollution, or pollution in the natural outdoor environment, is an increasing concern in Ethiopia, caused mostly by rapid urbanization, industrial growth, and transportation emissions. (Redi, 2024). According to the Ministry of Health, air pollution was the third greatest cause of premature death in 2017, accounting for roughly 8% of all deaths, or approximately 41,000. By 2021, air pollution was responsible for about 10% of deaths in the country, with outdoor particle matter (PM) ranking as the seventh largest risk factor for deaths, and household air pollution (HAP) ranked first (Redi, 2024). Particulate matter (PM_{10}) and carbon monoxide (CO) concentrations along the roadsides in developing countries commonly exceeded the local and international guidelines (Kume *et al*., 2010).

Ambient air pollution is a complicated problem that involves emissions from numerous sources and stakeholders. Cooking and heating are common sources of ambient air pollution in cities and the areas around them, as are thermal power plants, construction sites, unpaved roads, bare earth open spaces, agricultural activities (especially the burning of agricultural residuals), and solid waste management, which includes open trash burning. Studies conducted in other African cities show that the transportation industry accounts for the majority of air pollution emissions. For example, a study in Nairobi, Kenya, shows traffic is responsible for 39% of ambient $PM_{2.5}$ concentrations (Gaita *et al*., 2014). Outdoor and indoor air pollution remain a major concern in South Africa, with emissions of sulphur dioxide, particulate matter, nitrogen dioxide, nitrogen oxides, ozone, benzene, and VOCs, as well as their quantities, causing concern, thus, pollutants generated by a variety of sources have an impact on air quality throughout the country (Hands, 2022).

The majority of impoverished cities worldwide do not satisfy the World Health Organization's (WHO) recommendation for air quality. The expected trend of rapid urban population growth and urbanization in general is likely to result in significant increases in pollution levels because urbanization naturally necessitates growing energy-intensive service sectors, more transportation, additional industries, and energy production, all of which exacerbate air pollution.

Harar City is among rapidly growing urban centers in Ethiopia where increasing population and industrialization have increased concerns about the quality of ambient air and its potential impact on the health and well-being of its residents. Despite the magnitude of the impacts of air pollution on the environment and human health, there is a lack of comprehensive data and analysis on the current state of air quality in Harar city.

The research has effectively provided a comprehensive understanding of ambient air pollution concentrations in Harar City, aligning with the World Health Organization (WHO) standards for air pollutants. The findings present essential information regarding the levels of ambient air pollution and its associated impacts on public health. This analysis revealed critical areas of concern, which will guide targeted environmental protection measures. By deeply assessing the concentration of pollutants, the research has indicated the need for strategic interventions to mitigate air quality issues in Harar City.

Therefore, the main aim of this study was to provide a comprehensive assessment of the ambient air quality in Harar City, considering various criteria air pollutants such as CO, $PM_{2.5}$, PM_{10}, NO_2, SO_2 and their concentrations. The study was limited to the above listed parameters due to lack of equipment.

The specific objectives of the study were:

- ✓ To analyze the current status of air quality in Harar City based on selected criteria air pollutants ($PM_{2.5}$, PM_{10}, CO, NO_2 and SO_2)
- ✓ To determine the spatial distribution of air pollutants in Harar city

2. LITERATURE REVIEW

2.1. Ambient Air Quality

Ambient air quality refers to the physical and chemical measurement of pollutant levels in the surrounding atmosphere that the general population is exposed to (Hands, 2022). Over the years, rapid population growth has spurred swift industrialization, urbanization, and a rise in vehicular traffic, resulting in declining air quality (Garaga *et al.*, 2018). Air quality is a major concern throughout the world and one of the basic necessities and requirement of human existence (Okoro, 2019). In urban areas, high population density combined with concentrated economic activities leads to significant energy consumption and the release of large amounts of environmental pollutants, including air pollutants. As a result, cities face multiple environmental challenges, with air quality issues being a major concern. Urban air pollution is a critical global environmental problem (Kim and Lee, 2018).

In many developing countries, ambient air quality has significantly worsened, particularly in urban areas, exposing populations to pollutant levels that exceed recommended limits (Hands, 2022). Poor air quality, caused by high concentrations of atmospheric pollutants from sources like fossil fuel power plants and natural events such as volcanic eruptions, poses significant threats to public health, the environment, and development. These pollutants contribute to increased respiratory problems (Okoro, 2019). Ambient air pollution has posed a serious threat to the sustainable growth of society and the economy, raising broad concerns about public health (Guo *et al.*, 2020). Not only will this deteriorate outdoor air quality, but it will also impair the inside air environment through (natural and mechanical) ventilation or infiltration (Guo *et al.*, 2020).

Analyzing current air quality is crucial for evaluating public health and progress towards sustainable development goals in affected regions, as air pollution indirectly impacts the economy by raising medical expenses and the cost of environmental preservation (Okoro, 2019). Good air quality lowers healthcare costs related to air pollution diseases, boosts worker productivity, increases life expectancy, and reduces mortality rates (Okoro, 2019).

2.2. Air Pollution

Air pollution refers to a state in which pollutants like sulfur dioxide, inhalable particulate matter, nitrogen oxides, and ozone exceed levels that could negatively affect human health and the environment (Kara *et al*., 2013). Extreme amounts of air pollutants (CO, CO_2, SOx, NOx, VOC, PM, NH_3, O_3) present in the air cause contamination of the atmosphere, which is known as air pollution. The issue of air quality is shown by a number of variables, including mobility, electric city generation, land use forestry, business and residential buildings, industry smoke and greenhouse gas emissions. It is a primary cause of lung cancer, heart disease, stroke, and respiratory infections that are linked to pollution (European Environment Agency, 2017). The term "air pollution" also refers to the presence of harmful substances for human health in the atmosphere. These substances are linked to an increased risk of premature mortality from heart disease, stroke, chronic obstructive pulmonary disease, asthma, lower respiratory infections, and lung cancer (Tiotiu *et al*. 2020). Outdoor and indoor air quality are important to human health. The average 70 kg adult inhales about 20 m^3 of air per day (Curtis *et al*., 2006). The issue of air pollution has been difficult and pervasive in both non-LMIC and Low and Middle Income Countries (LMIC) contexts, with notable differences in the sources and levels of pollution between the two (Tefera, 2017).

Both industrialized and developing nations struggle with the grave issue of air pollution. Since industrial emissions are poorly controlled and vehicle maintenance is inadequate, the majority of developing country cities have severe outdoor air pollution (Centers and Uttarakhand, 2021). Worldwide air pollution levels have risen due to the onset of the industrial revolution and the growing demand for automobiles. Due to industrialization and urbanization—which are necessary to meet the rising demands of an expanding population—air pollutants are directly released into the atmosphere (Centers and Uttarakhand, 2021). It is impossible to discontinue these kinds of activities because they are essential to society's advancement. SPM (suspended particulate matter) and SO_2 (sulfur dioxide) are two undesirable air pollutants that come with urbanization and industrialization (Centers and Uttarakhand, 2021).

Globally, poor atmospheric quality caused by rising air pollution has a negative impact on human health and poses numerous problems to biodiversity, ecosystems, and regional climate (Khan *et al*. 2023). According to the World Health Organization (WHO, Geneva, Switzerland), metropolitan regions are more vulnerable to air pollution, and as a result, respiratory problems account for 80% of all chronic diseases. Developing countries are at a higher risk because of their rapid industrial and urban growth, lack of health awareness, rapid industrialization, vehicular pollution, insufficient air quality standards, outdated technology, and high-density population regions (Khan *et al*. 2023).

2.2.1. Sources of air pollutants

Identifying emission sources and quantifying their contribution to the ambient concentration of pollutants has been a primary focus in urban air quality research (Chan *et al*., 2011). Numerous emission sources, both natural and man-made, are the source of air pollution; with the start of industrialization, the latter has become the primary source worldwide. The process of burning, particularly when using biomass and fossil fuels to produce electricity, is the main source of air pollution (Geneva: World Health Organization, 2021). Anthropogenic sources are what we focus on because we may be able to effect some control of these sources (Karl *et al*., 2016). Both gaseous and particle emissions are problematic. The source of air pollutants varies greatly depending on land use and the extent of pollution controls in place. Existing studies, particularly in Addis Abeba, have identified air pollution sources as light and heavy-duty vehicles, industry, household heating and cooking, as well as fugitive sources such as biogenic emissions and dust (Kasim *et al*., 2018). Pollutant emission sources are either limited to a small area (such as traffic along highways, industrial chimneys) or localized (such as biomass burning associated with deforestation in tropical regions, an industrialized urban environment). The principal "hotspots" for air pollution are the densely populated areas. Pollution levels are regulated at the local, regional, and global levels by the interaction between emissions and transportation (Saxena and Sonwani 2019). In terms of emissions, criteria pollutants come from a variety of sources, including both natural and artificial. Natural sources include volcanic eruptions, forest fires, lightning strikes, and biological emissions. Anthropogenic sources include emissions from industries, cars, biomass burning, cooking activities, and the re-suspension of soil/road dust. These pollutants either originate directly from primary emission sources or from their precursors via chemical transformation events in the atmosphere (Saxena and Sonwani, 2019). Air pollution in the ambient is made up of thousands of different components. The most significant elements in terms of health are airborne particulate matter (PM) and gaseous pollutants such as sulphur dioxide (SO_2), nitrogen dioxide (NO_2), benzene, ozone, and volatile organic compounds (VOCs).

When fossil fuels burn, primary pollutants such soot particles and sulphur and nitrogen oxides are released into the atmosphere. Motorized road traffic, electricity production, industrial sources, and home heating are the main sources of NO_2. Other elements in the atmosphere can produce secondary pollutants, such ozone, which is created by photochemical interactions between nitrogen oxides and volatile organic compounds (Mannucci *et al*., 2015). There are two major categories among the air pollution sources, viz. anthropogenic and natural.

2.2.1.1. Anthropogenic sources

It has been evident that in modern times numerous anthropogenic activities impose adverse impacts on the urban quality of air and make it injurious for human health and living creatures (Tabinda*etal*.2020).

Anthropogenic sources are the end products of a wide range of human activities, including the bu rning of fossil fuels, the emissions from industries (such as cement factories, oil refineries, and el ectroplating), the burning of crops and plowing in agriculture, the transportation of light and hea vy-duty vehicles, mining, cooking, and burning of refuse, among other human activities (Saxena and Sonwani, 2019). The major anthropogenic sources of air pollutants are industrial emissions, domestic fuel burning, emissions from power plants and transportation activities (Centers and Uttarakhand, 2021). Fossil fuel burning in motor vehicles and stationary sources (heating, power generation) is the main human-caused source of nitrogen oxide emissions into the atmosphere (Brunekreef and Holgate, 2002). In cities, motor vehicles are the primary cause of pollution. Traffic emits toxic pollutants like nitrogen oxides (NOx), volatile organic compounds (VOC), and particulate matter (PM), which through photochemical reactions help create secondary pollutants like ozone (Parra *et al*., 2010).

Depending on the kind of industry, the fuels and solvents utilized, and the degree of pollution controls in place, industrial source emissions can vary significantly. For instance, PM, SO_2, NOx, and organic compound emissions are produced during the combustion of coal for electricity generation and metal smelting (Etyemezian *et al*., 2005). Toxic substances like lead, mercury, arsenic, and aromatics can also be released in large amounts, depending on the kind of coal utilized or the metal that is treated. Chemical plants can release volatile organic chemicals, which can be precursors of ozone (O_3) or carcinogens. O_3 precursors, odor-causing chemicals, and primary and secondary PM are produced by processes involving food and cattle (Etyemezian *et al*., 2005). Because hydroelectric power is so readily available, coal-fired power facilities only supply a small portion of Ethiopia's electricity needs (Etyemezian *et al*., 2005). Combustion of fossil fuels for transportation, power generation, and other human activities produces a complex mixture of pollutants comprising literally thousands of chemical constituents (Part *et al*., 2004).

2.2.1.2. Natural sources

Natural sources such as volcanic eruptions, dust storms, and forest fires are connected to the processes of the planet and release large amounts of pollutants into the atmosphere quickly (Saxena and Sonwani, 2019). Pollutants were also released in substantial quantities by a few other natural sources and activities, such as lightning and grazing animals. Biogenic emissions, which include chemical and gas emissions from vegetation and soil microbiological activity, are also a component of natural sources (Saxena and Sonwani, 2019).

Natural occurrences like volcanic activity, vegetation breakdown, and forest fires continuously emit gases into the atmosphere, including sulfur dioxide (SO_2), hydrogen sulfide (H_2S), and carbon monoxide (CO). In addition, winds, forest fires, volcanic eruptions, and other such natural occurrences disperse fine particles throughout the atmosphere (Baklanov *et al.,* 2016).

2.3. Major Air Pollutants

According to the World Health Organization (WHO), six major air pollutants are reported including particle pollution, ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead (Manisalidis *et al*., 2020). The primary gaseous pollutants are volatile organic compounds (VOCs), such as polycyclic aromatic hydrocarbons (PAHs), as well as inorganic substances like lead or chromium (Pb or Cr), ozone (O_3), carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon dioxide (CO_2) (Tiotiu *et al*., 2020).

The standard classification of pollutants can be of two types: Primary Pollutant: Such type of air pollutants which are emitted directly from a source, for example, oxides of nitrogen (NOx), oxides of sulfur (SOx), volatile organic compounds (VOCs), Particulate Matter (PM) and oxides of carbon (CO_2 + CO). Secondary Pollutant: Those pollutants that are derived from various reactions between different primary pollutants or with natural constituents in the atmosphere Examples are ozone (O_3) and PAN (Sonwani and Saxena, 2016).

2.3.1. Particulate matters (PM)

Particulate matter (PM) refers to a suspension of solid, liquid or a combination of solid and liquid particles in the air (Saxena and Sonwani, 2019) . Particulate matter (PM) is made up of solid and liquid particles that are discharged directly into the air as a result of diesel use, road and agricultural dust, and industrial activity (Thangavel *et al.*, 2022). Depending on where they come from, particulate matter from both natural and man-made sources can be divided into primary and secondary pollutants. Emission sources directly emit primary particulate matter, which is frequently linked to combustion sources. Primary pollutants such as NOx, SOx, and VOCs undergo a variety of photochemical reactions to produce secondary particulate matter in the atmosphere (Saxena and Sonwani, 2019).

The primary determinant of the location of particle deposition in the lung is particle size. Fine particles have a greater ability to travel farther and stay suspended in the atmosphere for longer than huge particles do (Daxini *et al*., 2020). The size of PM is of vital importance since it determines, to a great extent, its impact on respiratory health and the penetration degree in the human respiratory system (Tiotiu *et al.*, 2020).

PM can be classified by its aerodynamic diameter size as PM_{10} (particles $\leq$ 10 μm in diameter); $PM_{2.5}$ (particles $\leq$ 2.5 μm in diameter), also called fine particles; and $PM_{0.1}$ (particles $\leq$ 0.1 μm in diameter), called ultrafine particles, which have different health effects, as the particles are strongly linked to particle size, which can deposit in the lung and can navigate through bronchioles and escape lung defense mechanisms (Thangavel *et al*., 2022). PM consists of particles that, on the basis of their size are classified in coarse (diameter\10 lm; PM_{10}), fine (diameter\2.5 lm; $PM_{2.5}$) and ultrafine (\0.1 lm; PM0.1). $PM_{2.5}$ are contained within, and track with, the coarse particle fraction, broadly representing approximately 50 % of the total mass of PM_{10}. Re-suspension of soil and road dust by wind or moving vehicles, as well as construction work and industrial emissions, generate coarse particles (PM_{10}) (Mannucci *et al*., 2015). A number of researches have proved that long-term exposure to $PM_{2.5}$ pollution is largely related to premature death of cardiovascular, respiratory, and cerebrovascular diseases (S. Yang *et al*., 2019). Important sources of primary particles include road traffic, power plants and industrial and residential heating based upon the use of oil, coal or wood (Mannucci *et al*., 2015).

PM_{10} comes primarily from motor vehicles, dust and construction and $PM_{2.5}$ comes from many types of combustion, including vehicles, power plants, industry, waste burning, agricultural burning and cooking (Daxini *et al*., 2020). The characteristics of PM, such as size, content, origin, solubility, and reactive oxygen production, all influence how pathogenic they are. Based on research, smog is typically brought on by high concentrations of aerosols or fine particles (also known as $PM_{2.5}$, or particles with a size of less than or equal to 2.5 btm) (Xing *et al*., 2016). Epidemiologic research have found consistent and substantial links between ambient PM_{10} (fine particulate matter with aerodynamic dimensions less than or equal to 10 pm) concentrations and higher daily death and morbidity rates. To put it simply, inhalable particulate matter is divided into two size fractions: those with aerodynamic diameters (da) less than or equal to 2.5 pm ($PM_{2.5}$), or small particles, and those with aerodynamic diameters between 2.5 and 10 pm, or coarse particles. The two size fractions have distinct origins and makeup. Fine particles are typically produced by combustion sources (such as automobiles, power plants, and wood stoves), either by the condensation of volatilized materials (primary particulate matter) or from precursor gases reacting in the environment to form secondary particles (Suh *et al*., 2000). Coarse particles, on the other hand, are created by mechanical crushing, grinding, or abrasion of surfaces, and are suspended and spread by wind and anthropogenic activity such as traffic and agriculture (Suh *et al*., 2000).

Particulate matter of 10 micrometers or less in diameter is considered as PM_{10}. They are capable of penetrating deep into the lungs which causes severe respiratory problems (Dockery, 2009). Short and long-term exposure to PM_{10} can cause lung irritation, immunological reactions, lung constriction, shortness of breath, cell damage, worsened coughing, aggravated asthma, increased hospital admissions, chronic bronchitis, cancer, and mortality (Geravandi *et al.*, 2015). The fine particulates (aerodynamic diameters lesser than 2.5μm) are the most harmful among air pollutants. $PM_{2.5}$ particles can easily enter the alveoli and consequently be stuck to the lung parenchyma (Dockery, 2009). $PM_{2.5}$ can cause various adverse health effects and cause cardiovascular problems, respiratory diseases and lung cancer (Saxena and Sonwani, 2019).

Although all forms of air pollution are detrimental to human health, ambient particulate matter (PM) has been found to have the most severe consequences. PM contains and transports a wide variety of hazardous compounds into the respiratory system, and its ability to cause harm is inversely correlated with its aerodynamic diameter (Mannucci *et al*., 2015). Some research' findings strongly suggest that long-term exposure to particulate matter reduces life expectancy. The key discovery is that when the air becomes polluted with dust, the rate of cardiac and pulmonary disorders increases 12% and 14%, respectively (Geravandi *et al.,* 2015). On inhalation, coarse PM stays around in the nasal cavities and upper airways, while fine and ultrafine PM may permeate deeper into the lung alveoli and perhaps flow into the bloodstream (Mannucci *et al*., 2015). The effects of particulate matter (PM) pollution on human health are often enormous. The World Health Organization (WHO) has conducted studies which indicate that every year, PM pollution causes around 3.2 million premature deaths and 7.4 million disability-adjusted life years (Wang *et al*., 2015).

2.3.2. Carbon monoxide (CO)

Carbon monoxide (CO) is a colorless, odorless, flammable and tasteless gas. It is very toxic for several organisms including human being (Saxena and Sonwani, 2019). The toxic gas known as carbon monoxide (CO) is released from the exhaust system of a combustible engine in a car that runs on gasoline or diesel. It has no taste, smell, or irritation (Chamberlain, 2016). It has an impact on the atmosphere's capacity to purge itself of dangerous gases. The most prevalent and extensively distributed air contaminant is carbon monoxide (CO). It is present in very low concentration regions of the atmosphere (the troposphere typically has a CO concentration of about 100 ppb), however it can drop as low as 50 ppb in pure air. CO has a few months to an average lifetime in the atmosphere. In the end, the gas and oxygen (O_2) react to produce carbon dioxide (CO_2) (Saxena and Sonwani, 2019).

Approximately 90% of CO emissions in metropolitan areas come from motor traffic. CO is a main contaminant, therefore ambient concentrations closely track emissions (EPA and UNIDO, 2003). In metropolitan places, concentrations are thus highest at the kerbside and rapidly fall as distance from the road increases. Automatic analyzers are mostly utilized for the direct measurement of ambient levels against guidelines (EPA and UNIDO, 2003).

The incomplete combustion process that occurs in an engine causes the release of carbon monoxide (CO) as a waste product from the exhaust system of a vehicle. Environmental carbon monoxide is created by the incomplete combustion process of any carbon-containing fuel (Chamberlain 2016). Numerous anthropogenic and natural processes, including the burning of biomass and volcanoes, emit carbon monoxide into the atmosphere. Up to 2600 MT of CO_2 are predicted to be released annually globally, with roughly 60% coming from anthropogenic activities and 40% from natural processes (Saxena and Sonwani, 2019). Carbon monoxide (CO) is a silent killer since it is colorless and odorless. Inhaling exhaust fume has caused a high fatality rate in the USA, estimated that more than 10,000 persons each year in the USA require medical attention, miss at least one day of work in the early 1970s because of exposure to carbon monoxide (Chamberlain, 2016).

2.3.3. Nitrogen dioxide (NO_2)

Nitrogen dioxide is a reddish brown trace gas found in the urban atmosphere. It is primarily created by combustion techniques. As a result, the environmental concentration depends on traffic, notably car traffic, which accounts for up to 50% of total nitrogen oxide emissions in industrialized countries (Koehler *et al*., 2010). Nitrogen dioxide is a reddish-brown gas that emits an unpleasant and irritating odor. This is the principal gas that is discharged into the atmosphere as a result of fuel combustion. NO_2 is a strong oxidizing agent that is transformed into gaseous nitric acid, poisonous organic nitrates, and tropospheric ozone (a significant component of smog). Because of its participation in the creation of photochemical smog, it is designated as one of the key air pollutants with considerable implications on human health (Saxena and Sonwani, 2019). Among all nitrogen oxides, nitrogen dioxide (NO_2) is the most toxic one. It is supposed to have a considerable health impact particularly in workplaces, as, e.g., professional drivers or welders can be exposed to high concentrations of NO_2 (Brand *et al*., 2016). Animal toxicology tests show that acute exposure to NO_2 concentrations below 1880 $\mu g/m^3$ (1 ppm) has few consequences. Exposure to concentrations above 4700 $\mu g/m^3$ (2.5 ppm) at rest or with modest exercise for less than two hours results in significant losses in pulmonary function. Concentrations below 1880 $\mu g/m^3$ (1.0 ppm) have no effect on normal persons (EPA and UNIDO, 2003).

The high concentration of NO_2 causes health concerns, including both short-term (cardiovascular and respiratory) and long-term (cancer and mental development in children). The most major natural mechanisms that contribute to the creation of NO_2 are atmospheric ammonia oxidation, microbiological activities in soil, and lightning (Saxena and Sonwani, 2019). Anthropogenic sources are more significant than natural sources in terms of NO_2 and O_3 air pollution because they are concentrated in more populated areas (Saxena and Sonwani, 2019).

The primary human-caused source of NO_2 emissions is high-temperature fuel burning in cars, as well as industrial and utility boilers. Other large sources of nitrogen dioxide in the atmosphere include emissions from power plants, automobiles, and off-road equipment (Saxena and Sonwani, 2019). It has been established that nitrogen dioxides in combination with other gases (CO) are toxic to small animals such as rats in concentrations of 104 ppm and higher. With increasing NO_2 exposure, the health effects result in the perception of odor, mucosal irritation of the nose and eyes, pulmonary congestion and lung edema (Koehler *et al*., 2010). More recent research has focused on NO_2 as a potential independent contributor to negative health outcomes. An increasing amount of research has indicated links between NO_2 and mortality due to respiratory and cardiovascular diseases. For instance, Jerrett *et al*. (2009b), reported that long term exposure to NO_2 is positively associated with cardiovascular (RR = 1.45, 95%CI: 1.11–1.91) and respiratory mortality (RR = 1.06, 95%CI: 0.79–1.43) (Huang *et al*., 2021). The recent review of the health effects of air pollution by a WHO working group (Review of Evidence on Health Aspects of Air Pollution (REVIHAAP)) evaluated the most recent studies on long-term exposure to NO_2 and both natural (non-accidental)/total and cause-specific mortality (Faustini *et al*., 2014). A number of studies have found that NO2 may not directly alter pulmonary function but does increase the nonspecific sensitivity of the airways to agonists such as meth choline, histamine, and carbachol. This appears to occur predominantly in asthmatics and not in healthy persons (Brand *et al*., 2016).

2.3.4. Ozone (O_3)

Ozone (O_3) is a gas formed from oxygen under high voltage electric discharge. It is a strong oxidant, 52% stronger than chlorine. It arises in the stratosphere, but it could also arise following chain reactions of photochemical smog in the troposphere (Manisalidis *et al*., 2020). Ozone can travel to distant areas from its initial source moving with air masses. It is surprising that ozone levels over cities are low in contrast to the higher amounts in urban areas being a risk for cultures, forests and vegetation as it is reducing carbon assimilation (Manisalidis *et al*., 2020). Ozone's antibacterial properties diminish growth and yield while also affecting plant microflora. To this extent, ozone has an impact on other natural habitats, microflora, and animal species, altering species composition. Ozone damages DNA in epidermal keratinocytes, resulting in decreased cellular function. Ground level ozone (GLO) is produced by a chemical interaction between nitrogen oxides and volatile organic compounds (VOCs) emitted by natural sources and/or anthropogenic activities. Ozone is mainly absorbed through inhalation. Ozone damages the upper layers of skin and the tear ducts (Manisalidis *et al*., 2020).

In the troposphere, O_3 is a secondary pollutant produced by a chemical interaction between nitrogen oxides and Volatile Organic Compounds (VOCs) released by natural or manmade sources in the presence of sunlight. Other relevant components are CO and methane (Tiotiu *et al*., 2020).

2.3.5. Sulfur dioxide (SO_2)

Sulfur dioxide, SO_2, is a poisonous and pungent-smelling gas that is found in the Earth's atmosphere at one part per billion by volume (1 ppbv) (Deeming *et al*. 2014). Sulfur dioxide is a colourless gas with a suffocating, pungent odor and possesses unusual biological properties (Bisseret and Blanchard, 2013). Sulfur dioxide (SO_2) in the atmosphere is emitted from both anthropogenic and natural sources (Lu *et al*., 2010). Sulphur dioxide (SO_2) is released primarily from the combustion of sulfur-containing coal and oil (Tiotiu *et al*., 2020). It is naturally produced by volcanoes that result from the aerobic combustion of sulfur-containing ores, but its presence in the atmosphere is predominantly ‘man-made' due to industrial activities such as fossil fuel combustion at power plants; sulfur impurities present in coal, for example, release SO_2 upon combustion in air (Deeming *et al*., 2014). The widespread use of fossil fuels has significantly boosted sulfur emissions into the atmosphere, with the anthropogenic component becoming substantially bigger than natural emissions on a global scale (Smith *et al.*, 2005). Anthropogenic emissions have resulted in increased sulfur deposition and atmospheric sulfate loadings in many areas (Smith *et al.*, 2005). Sulphur dioxide (SO_2) comprises a major portion of the pollutant load in many cities (Geravandi *et al*. 2015). Sulfur dioxide emissions have substantial impacts on human health, terrestrial and aquatic ecosystems and have come under increasing regulation world-wide (Klimont *et al.*, 2013).

It can cause irritation, reduction of visibility and some respiratory diseases. Sulfur dioxide can be dangerous to the respiratory system and the function of the lungs and can also lead to irritation of eyes (Geravandi *et al.*, 2015).

People with allergies, particularly allergic asthma, may be exceptionally susceptible to breathed SO_2. Bronchitis, mucus production, and bronchospasm are the most common health issues connected with SO_2. It is an irritant that penetrates deep into the lung and is transformed into bisulfite, which interacts with sensory receptors and causes bronchoconstriction (Tiotiu *et al*., 2020).

Information on the effects of exposure averaged over a 24-hour period is derived mainly from epidemiological studies in which the effects of SO_2, SPM and other associated pollutants are considered. Exacerbation of symptoms among panels of selected sensitive patients seems to arise in a consistent manner when the concentration of SO_2 exceeds 250 $\mu g/m^3$ in the presence of SPM (EPA and UNIDO, 2003). Sulfur dioxide (SO_2) is a heavy, penetrating gas that is colorless, stifling, and has a stench. It reacts with water to generate acid. SO_2 quickly oxidizes to sulfate when transition metals catalyze the reaction. During the smelting of metals and the combustion of fossil fuels, sulfuric acid can adsorb to metal oxide particles; hence, in some coals, more than 9% of the resident sulfur may be sulfuric acid (W. Yang and Omaye, 2009). In addition to adverse effects on human health, SO_2 and its atmospheric products (e.g., sulfate, sulfuric acid) can affect the atmospheric environment from local to regional and global scales (e.g., acid deposition, direct and indirect radiative forcing) (Lu *et al*., 2010).

Sulphur is discharged into the environment during various stages of oxidation. Despite its widespread presence on the planet, the most identifiable form of sulfur in the atmosphere is SO_2, which serves as a precursor for sulphate aerosol, a significant component of PM. SO_2 in the atmosphere comes from both natural and manmade sources, but the anthropogenic component has grown significantly over time. The primary source of SO_2 is the combustion of coal and oil (which contain 1-2% sulfur by weight), with minor contributions from other industrial activities such as metal smelting and H_2SO_4 production, as well as industrial activity with sulfur-containing material processing, such as the generation of electricity from coal, oil, or gas (Saxena and Sonwani, 2019). Motor vehicles also contribute significantly to the atmospheric concentration of sulfur dioxide. SO_2 can be oxidized to sulfur trioxide, which can then be converted into sulfuric acid mist in the presence of water vapor. SO_2 is a precursor of sulphates, which are a major constituent of respirable particles in the environment. It simply combines with other molecules to produce hazardous substances, such as sulfuric acid (H_2SO_3) and sulphate particles (Saxena and Sonwani, 2019).

2.4. Impacts of Air Pollution

Air pollution is acknowledged as a serious health hazard, affecting millions of lives around the world (Aggarwal and Jain, 2021). It also adversely affects local ecological systems, regional atmospheric chemistry as well as global climate (Aggarwal and Jain, 2021). The World Health Organization (WHO) classified ambient air pollution as one of the ten primary risk factors contributing to the global health burden, causing around 16% of premature deaths in 2009 and around 3.7 million deaths in 2012 (Aggarwal and Jain, 2021). Several studies have proven the negative effects of long-term and short-term exposure to various types of air pollutants on human health and the relationship of air pollution with a range of diseases, mainly cardiovascular and respiratory ailments (Bai *et al*., 2021). Respiratory, and cardio- and cerebrovascular diseases are generally considered associated with air pollution (Zhong *et al*., 2019). According to several research, short-term exposures are the main risks that aggravate symptoms or create acute forms of diseases, while long-term exposures are most likely the main hazards that cause this sort of diseases (Zhong *et al*., 2019) . Studies show that the increase in air particulate matter, SO_2, NO_2, CO, O_3, and other pollutants can worsen respiratory, and cardio- and cerebrovascular diseases (Zhong *et al*., 2019).

Ambient air pollution is a significant risk factor for human health, causing a variety of illnesses. Air pollution is linked to a wide range of acute and chronic ailments, including lung cancer, chronic obstructive pulmonary disease (COPD), and heart disease. An increase in CO_2 concentration can have a variety of physiological consequences, including hypercapnia (an increase in bloodstream CO_2). Prolonged exposure to low CO_2 concentrations can cause cardiac failure, cerebral bleeding, immunological abnormalities, miscarriages, and behavioral issues (Taghizadeh-Hesary and Taghizadeh-Hesary, 2020). Air pollution has numerous health impacts. Even on days with low pollution levels, vulnerable and sensitive individuals can experience adverse health effects. Short-term exposure to air pollutants is strongly linked to conditions such as COPD (Chronic Obstructive Pulmonary Disease), coughing, shortness of breath, wheezing, asthma, respiratory diseases, and increased hospitalization rates (an indicator of morbidity). Long-term exposure to air pollution is associated with chronic asthma, pulmonary insufficiency, cardiovascular diseases, and increased cardiovascular mortality (Manisalidis *et al*., 2020). A Swedish cohort study suggests that prolonged exposure to air pollution may also contribute to the development of diabetes. Additionally, air pollution can have various severe health effects in early human life, including respiratory, cardiovascular, mental, and perinatal disorders, which may lead to infant mortality or chronic diseases in adulthood (Manisalidis *et al*., 2020).

Carbon monoxide leads to dizziness, headaches, fatigue, and impaired judgment, affecting brain and heart function. At higher concentrations, it can be fatal. Particulate matter contributes to respiratory disorders, asthma, reduced visibility, and cancer, impacting the lungs and tissues. Nitrogen oxides cause lung irritation, bronchitis, pneumonia, asthma, respiratory infections, pulmonary edema, and emphysema. Sulfur dioxide impacts the lungs and respiratory system, leading to sulfurous smog, acid rain, and reduced visibility. The combination of particulate matter with sulfur oxides is more harmful than either pollutant alone. Ground-level ozone, a key component of photochemical smog (formed when CO, NOx, and hydrocarbons react in sunlight), causes chest tightness and irritation of the mucous membranes (Balashanmugam *et al*., 2012).

Outdoor air pollution is a major environmental and health problem worldwide, with the World Health Organization (WHO) referring to it as the silent killer. According to new statistics from 2018, nine out of 10 people breathe polluted air. Furthermore, ambient (outdoor) and household (indoor) air pollution cause approximately seven million fatalities globally each year (Taghizadeh-Hesary and Taghizadeh-Hesary, 2020).

Air pollution can also damage plants. Air pollution can harm plant health by affecting plant physiology, biochemistry, and morphology. Various atmospheric gases cause different sorts of observable symptoms, resulting in diminished plant growth and output. On a worldwide scale, plant-environment interactions have been examined when air pollution and plant health issues are taken into account (Sonwani and Saxena, 2016).

Ambient air pollution leads to significant economic losses, including medical expenses—estimated globally at US$21 billion in 2015—lost economic productivity due to pollution-related illnesses and premature deaths, and the cost of environmental degradation. These costs are often overlooked because they are dispersed across large populations over many years and affect natural resources that are frequently taken for granted (Landrigan, 2016).

2.5. International Air Quality Guidelines

The WHO's air quality guidelines were last provided in 2006. Air quality guidelines - worldwide update 2005. Particulate matter, ozone, nitrogen dioxide, and sulfur dioxide (hereafter referred to as the Global Update 2005). Since they were released, air pollution has been identified as the single most serious environmental danger to human health due to its significant contribution to disease burden (Geneva: World Health Organization, 2021). This is especially true for $PM_{2.5}$ (particles with an aerodynamic diameter equal to or less than 2.5μm) and PM_{10} (particles having an aerodynamic diameter equal to or less than 10μm). However, other frequently measured air pollutants, such as ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO), as well as other air pollution components, are cause for concern. The overarching goal of these guidelines is to provide quantitative health-based recommendations for air quality, expressed as long- or short-term concentrations of several major air contaminants. Exceeding the air quality guideline levels (hereinafter referred to as AQG levels) is associated with significant risks to public health (Geneva: World Health Organization, 2021).

The averaging times chosen were long term (annual mean or, for ozone, the highest six-month average) and short term (24 hours). Long-term effects were only examined for all-cause and cause-specific mortality ($PM_{2.5}$, PM_{10}, ozone, and nitrogen dioxide). For them, any pollutant-related increase in long-term mortality was considered bad. Short-term effects were examined for all non-accidental and cause-specific mortality ($PM_{2.5}$, PM_{10}, ozone, nitrogen dioxide, and sulfur dioxide), asthma hospital admissions and emergency room visits (ozone, nitrogen dioxide, and sulfur dioxide), and myocardial infarction hospital admissions and emergency room visits (carbon monoxide only) (Geneva: World Health Organization, 2021). When both long- and short-term AQG levels were assessed for a pollutant-outcome pair, the long-term AQG level was preferred, while the short-term AQG level was aligned using empirical data on frequency distributions of 24-hour concentrations. When just short-term AQG levels were assessed, a comparison with other pollutant-outcome combinations was employed (Geneva: World Health Organization, 2021).

2.5.1. Particulate matters (PMs)

PM in both urban and non-urban areas is a complex blend of chemical and physical components. This heterogeneity complicates PM studies and the interpretation of research findings on exposure and risk, as does the likelihood that the potential for injury caused by particles changes with size and other physical properties, chemical makeup, and source(s). Different aspects of PM may be important to different health outcomes (Geneva: World Health Organization, 2021).

Table 1. Standards for PMs

Compounds	Standards
$PM_{2.5}$:	10 µg/m^3 annual mean 25 µg/m^3 24-hour mean
PM_{10}:	20 µg/m^3 annual mean 50 µg/m^3 24-hour mean

(Source: WHO, 2005)

Studies on airborne particulate matter (PM) and its public health impact is consistent, demonstrating deleterious health impacts at exposure levels now encountered by urban populations in both developed and developing countries. The health impacts are wide-ranging, although they mostly affect the respiratory and cardiovascular systems. Pollution affects the entire population, however susceptibility varies depending on health and age. The risk of many outcomes has been demonstrated to grow with exposure, and there is little evidence to identify a threshold beyond which no harmful health impacts are expected (WHO, 2005).

2.5.2. Nitrogen dioxide

There are several chemical species of nitrogen oxides, but nitrogen dioxide is the most important air pollutant species for human health. Nitrogen dioxide is a reddish-brown gas with a distinctive unpleasant odor. When nitric oxide is exposed to air, it spontaneously generates dioxide. Nitrogen dioxide gas is a strong oxidant; it combines with water to create nitric acid and nitric oxide (Geneva: WHO, 2021).

Table 2. Standards for NO_2

Compound	Standards
NO_2 :	40 µg/m^3 annual mean 200 µg/m^3 1-hour mean

(Source: WHO, 2005)

The current WHO recommendation value of 40 µg/m^3 (annual mean) protects the public against the harmful impacts of gaseous NO_2. The reasoning for this was that while most abatement technologies are unique to NO_X, they are not designed to manage other co-pollutants and may actually increase their emissions. A lower yearly recommendation value should be utilized when monitoring NO_2 as a marker for complicated combustion-generated pollutant mixes (WHO, 2005).

2.5.3. Sulfur dioxide

Historically, sulfur dioxide and particulate matter from fossil fuel combustion have been the primary contributors to air pollution in many regions. The most severe issues have occurred in large urban areas where coal was used for domestic heating or in industrial facilities with poor emissions control. In these contexts, pollutants were often considered collectively, based on epidemiological studies conducted decades ago in previously heavily polluted areas. Guidelines developed from these studies focused on 24-hour averages for acute effects and one-year averages for chronic effects (Geneva: World Health Organization, 2021).

Table 3. Standards for SO_2

Compound	Standards
SO_2 :	20 µg/m^3 24-hour mean 500 µg/m^3 10-minute mean

(Source: WHO, 2005)

Controlled studies of asthmatics who exercise show that a proportion develop changes in pulmonary function and respiratory symptoms following exposure to SO_2 for as little as 10 minutes. Based on data, it is advised that a SO_2 concentration of 500 µg/m^3 should not be exceeded over a 10-minute average time. Early estimates of day-to-day changes in mortality, morbidity, or lung function in response to 24-hour average SO_2 concentrations had to be based on epidemiological studies in which people are typically exposed to a mixture of pollutants (WHO, 2005).

Table 4. The General International Recommended 2021 AQG levels and 2005 air quality guidelines

Pollutants	Averaging time	2005 air quality guideline	2021 AQG level
$PM_{2.5}$, µg/m^3	Annual	10	5
	24-hour	25	15
PM_{10}, µg/m^3	Annual	20	15
	24-hour	50	45
O_3, µg/m^3	Peak season	-	60
	8-hour	100	100
NO_2, µg/m^3	Annual	40	10
	24-hour	_	25
SO_2, µg/m^3	24-hour	20	40
CO, mg/m^3	24-hour	-	4

(Geneva: World Health Organization, 2021)

2.6. Air Pollution in Ethiopia

The World Health Organization (WHO) estimates that nine out of ten people worldwide breathe air that is detrimental to their health as a result of air pollution, and Ethiopia is no exception to this trend (Redi, 2024). Small-scale studies carried out in the country emphasize that air pollution is becoming a major public health concern (Redi, 2024). Ambient air pollution, which refers to pollution in the natural outdoor environment, is a growing concern in Ethiopia and is primarily driven by rapid urbanization, industrial growth, and transportation emissions (Redi, 2024). According to a study conducted in East African countries, the hotspot regions for $PM_{2.5}$ and PM_{10} concentrations were Kampala (Uganda), Addis Ababa (Ethiopia), and Nairobi (Kenya). Thus, the spatial distribution of ambient air pollution demonstrates varied levels of intensity in Africa, and Addis Abeba is the second most vulnerable city in Eastern Africa due to air pollution (Mulgeta *et al.*, 2024).

The burden of air pollution in Ethiopia is becoming one of the serious risks responsible for death and disability(Mulgeta *et al.*, 2024). Ambient air pollution is becoming a major public health concern. According to the Ministry of Health, air pollution was the third greatest cause of premature death in 2017, accounting for roughly 8% of all deaths, or approximately 41,000. By 2021, air pollution was responsible for about 10% of deaths in the country, with outdoor particle matter (PM) ranking as the seventh largest risk factor for deaths, and household air pollution

(HAP) positioned first (Redi, 2024). According to studies, air pollution is also becoming a serious health problem, mainly affecting humans' lives and affecting children and women at large, though its spatial distribution is varying (Mulgeta *et al*. 2024).

Industrial activities in Ethiopia, particularly in Addis Ababa, contribute significantly to ambient air pollution (Redi, 2024). Key sectors, including textile production, food and beverage processing, and construction materials, generate pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NOx), volatile organic compounds (VOCs), and particulate matter (PM) (Redi, 2024). There is evidence that says the level of pollution is increasing in Ethiopia with increasing urbanization, industrialization, and traffic (Shiferaw *et al*., 2023).

In Ethiopia, ambient $PM_{2.5}$ concentration is showing no reduction while countries like China, the EU, the US, Indonesia, Mexico, and Japan were able to enforce policies that resulted in a significant decline in the concentration of ambient $PM_{2.5}$ (Shiferaw *et al*., 2023).

Most developing countries, including Ethiopia, tend to have limited air quality monitoring systems (Shiferaw *et al*., 2023). The research on ambient air pollution in Ethiopia has various limitations and coverage concerns. Studies have primarily concentrated on major cities, leaving out rural and smaller urban areas. The data is frequently out of current, and there is insufficient research on rural areas and seasonal fluctuations. While most relevant research has concentrated on particulate matter and common pollutants, other dangerous pollutants have remained underexplored (Redi, 2024). Furthermore, there is limited study about health consequences, technological and regulatory hurdles, and public awareness. Addressing these constraints is necessary for a thorough knowledge and successful management of air pollution in Ethiopia (Redi, 2024).

2.7. Guideline Ambient Environmental Standards for Ethiopia

The guideline Air Quality standards for Ethiopia are presented below in summary form.

Table 5. Summary of Air Quality standards for Ethiopia

Compound	Guideline Value [μg/m^3]	Averaging time
Sulphur dioxide	500	10 minutes
	125	24 hours
	50	1 year
Nitrogen dioxide	200	1 hour
	40	1 year
Carbon monoxide	100 000	15 minutes
	60 000	30 minutes
	30 000	1 hour
	10 000	8 hours
Ozone	120	8 hours
Suspended Particulate Matter PM_{10}	50	1 year
	150	24 hours
$PM_{2.5}$	15	1 year
	65	24 hours
Lead	0.5	1 year

(Source, EPA and UNIDO, 2003)

2.8. Mitigation Measures of Air Pollution

To address these issues, effective long-term air pollution mitigation techniques must be designed and implemented. As a result, management must play a crucial role in improving the current situation. As a result, it is critical to develop a strategy plan that includes specific activities in accordance with applicable air quality standards. These acts rely heavily on local policies and economies, available technologies, and public opinion (Sofia *et al*. 2020).

The success of countries and towns around the world in reducing ambient air pollution demonstrates the technological, economic, and political feasibility of pollution control measures. Proven effective strategies include establishing and enforcing air standards, reducing emissions from coal-fired power plants and other stationary sources by requiring a transition to clean fuels and eventually to renewable energy sources, prohibiting the use of polluting fuels in urban areas, improving access to public transportation, mandating fuel efficiency standards for cars, trucks, and buses, and restricting access to private vehicles (Landrigan, 2016).

2.8.1. Public and active transport

Transportation is a key area studied for public health benefits resulting from reduced air pollution. Vehicular transport is known to contribute approximately 70% of environmental pollution, as exhaust emissions from vehicles release numerous pollutants, including CO, NO_2, VOCs, and PM. Therefore, initiatives aimed at altering travel habits are crucial. Individuals should prioritize using public transportation (buses, trams, subways, trains) and opt for active travel methods like walking and cycling whenever possible. Shifting away from personal car use towards active transport offers substantial benefits for both human health and the environment (Sofia *et al*., 2020). The standardization of vehicle fuel and the search for new energy sources for engines have garnered significant attention. A large portion of emissions originates from vehicle exhaust, particularly from diesel and gasoline-powered engines. There is growing interest in alternative, cleaner energy sources like compressed natural gas (CNG), liquefied natural gas (LNG), and alcohol (Ghorani *et al*., 2016).

Another technique for reducing air pollution is to standardize motor engines and manufacture engines with low fuel usage. Surely, motor vehicles will stop using fossil fuels and derivatives in the near future. Recently, certain automobile manufacturers in Japan and Western countries have created electric cars that use power from a battery storage for low speeds, which is usually enough for driving inside cities with traffic and/or limited speeds (Ghorani-Azam *et al*., 2016).

2.8.2. Household sector

Today, household air pollution is largely due to the use of solid fuels for cooking and heating, posing a significant health risk to exposed populations. Therefore, reducing energy consumption in homes and buildings is crucial due to their substantial contribution to gas emissions. Transitioning to energy generated from renewable sources like biomass is expected to improve public health by creating a cleaner environment with lower emissions compared to traditional fossil fuels (Sofia *et al*., 2020)

2.8.3. Industrial sector

Even today, fossil fuels remain the primary energy source, contributing significantly to the production of pollutants, particularly particulate matter (PM), nitrogen oxides (NOx), and sulfur oxides (SOx). Reducing power generation from fossil fuels such as coal, oil, and gas can lead to health benefits by lowering local air pollutants, especially microscopic and submicroscopic particles (Sofia *et al.,* 2020). Recently, numerous initiatives have been explored to replace fossil fuels with renewable alternatives. Among various renewable energy technologies, biomass combustion is a promising alternative to fossil fuels. Another strategy to reduce industrial air pollution involves implementing advanced technologies in industrial processes. For instance, clean coal technologies (CCT) can enable the efficient use of coal with minimal environmental impact (Sofia *et al.,* 2020).

Imposing penalties on polluting sectors while creating a low-tax strategy for clean technologies. Increasing taxes on autos, particularly those older than 20 years, to differentiate between unclean and clean vehicles. The government should develop incentive plans for automobile manufacturers and other firms who meet environmental norms. Furthermore, exhortation programs should be developed for all types of emissions. These strategies may include tax breaks or other financial incentives for both consumers and producers (Ghorani-Azam *et al*., 2016).

2.8.4. Urban planning

Rapid urbanization has posed significant challenges in cities, leading to severe impacts on air quality (Sofia *et al*. 2020). Vehicular traffic is the main source of atmospheric pollution, with emissions varying throughout the day and peaking during rush hours. To address this, policymakers must support strategies and actions that reduce urban air pollution while fostering economic growth and improving quality of life. In this context, the concept of a "smart city" has emerged as a way to meet residents' needs more efficiently and sustainably. Within urban planning, smart mobility is a critical factor, as a large portion of city pollution is traffic-related, making effective transport design essential in urban areas (Sofia *et al*., 2020).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

This study was conducted in Harar City, Eastern Ethiopia. Harar city is the capital of Harari Peoples National Regional State (HPNRS) and East Hraraghe zone of Oromia National Regional State (Figure 1). The city is located in the eastern extension of the Ethiopian Highlands, about 525 km from Addis Ababa at an elevation of 1,885 meters, 6^0 36’ to 7^0 21’ north latitude and 36^0 68’ to 37^0 52’ east longitude (Mekonen, 2017). This region has an area of 343.2 square kilometers with a perimeter of 113 kilometers and is entirely surrounded by Oromia National Regional State (Adil, 2016). The population of the city is estimated to be 240,000 (Tiruye *et al*., 2018).

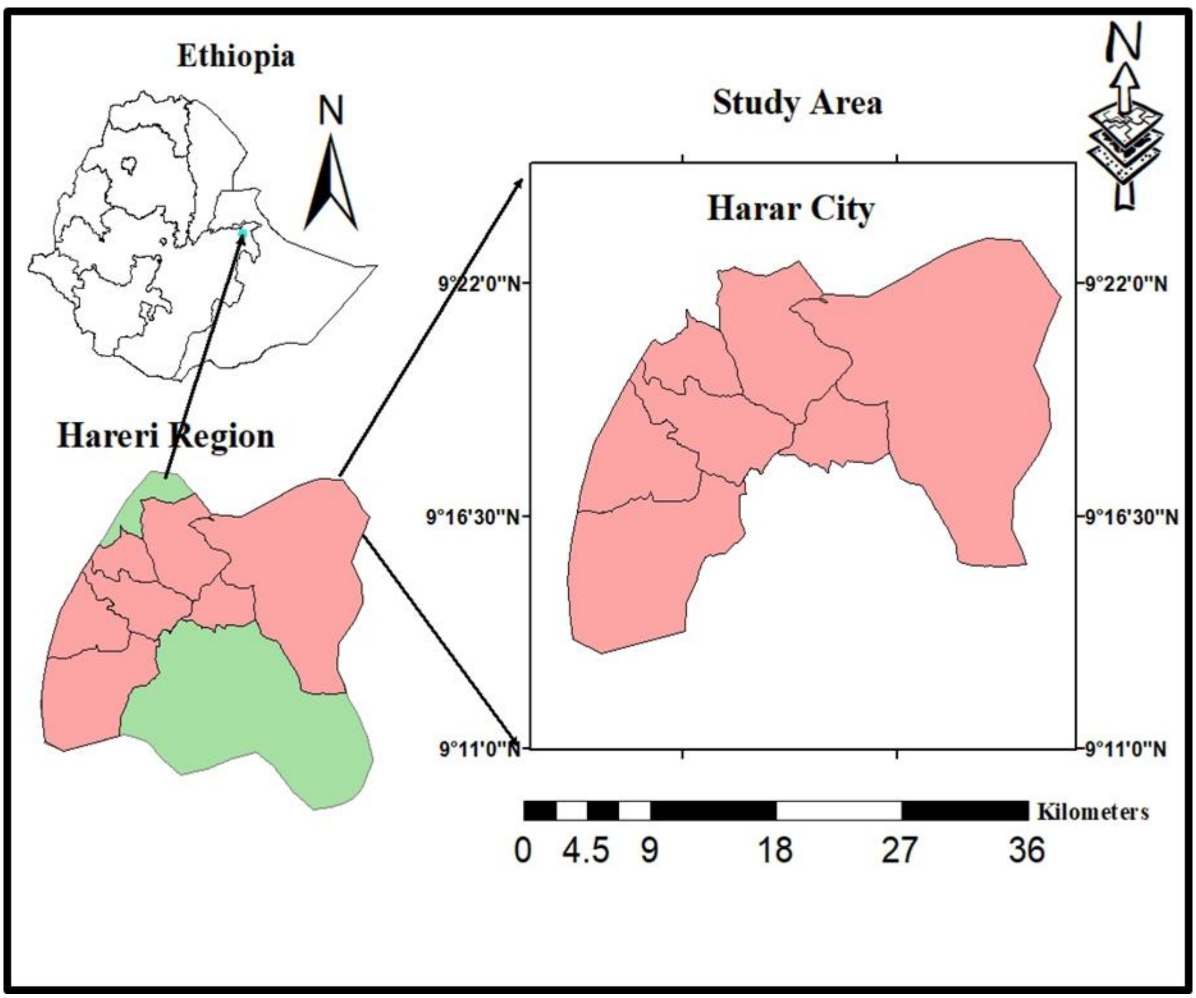

Figure 1. Map of the Study Area

3.2. Economic Activities

Tourism is another major sector in Harar City. Harar is the region's tourist and cultural center, with the majority of its revenue coming from tourism, which the municipal authorities actively promote. Harar's biggest tourist attraction is now the old Jugol wall, which was added to UNESCO's World Heritage List in 2006, as well as the House of the French artist Arthur Rimbaud, who lived in Harar for eleven years (1880-1991). Harar won the UNESCO Cities for Peace Prize for the African Continent in 2002/2003 due to its strong social cohesion, improved living circumstances in sensitive neighborhoods, and development of urban conviviality (Lxiv, 2011).

Additionally, trade and commerce thrive in Harar City. Harar is the main destination and crossroad for the trade in the eastward and particularly for the traders from Zeila or Berbera because of its geographical location (Gudeta, 2019). The bustling markets offer a variety of goods, including spices, grains, textiles, and household items. Small businesses, such as shops, restaurants, and guesthouses, provide employment opportunities and contribute to the city's economic growth.

3.3. Sampling Site and Timing Selection

3.3.1. Sample selection

The sampling sites were selected by preliminary survey data gathered from transport bureau of Harari Region that shows highly traffic crowded areas on the intersection road of the city to assess the vehicle flow and other sites like residential, commercial and industrial land uses in the city were also selected from the survey data gathered from Environmental Protection Agency (EPA) of Harar Region which is based on their crowdedness and its contribution to air pollution. Then ambient air measurement was carried out at thirty minutes (30) interval from 7:00 AM–1:30 PM and 2:30- 6:30 PM for consecutive seven (7) days to quantify the concentration of the pollutants such as CO, SO_2, NO_2, PM_{10}, $PM_{2.5}$) at each selected sites. Real time measurement of SO_2, NO_2, CO_2, $PM_{2.5}$ and PM_{10} was done using portable digital aeroqual instrument (Aeroqual series 500).

3.3.2. Description of the sample points

The sample points that were selected for sampling are basically considered all types of land uses like circulation, commercial, industrial, institutional, residential and traffic. A total of 16 sample points were selected (five traffic, three residential, three circulation, two commercial, two industrial and one institutional) as shown in Table 6. Sampled point coordinates were obtained with hand-held automated Garmin GPSMAP 64 GPS.

Table 6. Sampled Locations and Their Geographic Coordinates

	Name of the sample points	Land use type	Coordinates (X,Y)	
			X	Y
1	Hamaressa	Industrial	9°19'57.1"	42°04'49.1"
2	Arategna	Traffic	9°18'40.8"	42°06'23.8"
3	Harar Ber	Traffic	9°18'36.1"	42°07'51.8"
4	Aroge Menaheriya	Traffic	9°18'33.1"	42°07'49.3"
5	Shewa Ber	Commercial	9°18'31.1"	42°07'50.9"
6	Feres Megalla	Circulation	9°18'34.9"	42°08'08.6"
7	Felana Ber	Circulation	9°18'40.5"	42°08'10.6"
8	Gelmeshira	Residential	9°18'16.1"	42°06'07.1"
9	Kelad Amba	Residential	9°18'48.9"	42°06'49.6"
10	Buda Ber	Residential	9°18'23.7"	42°08'04"
11	Deker	Commercial	9°17'59.8"	42°08'08.5"
12	Hywet Fana	Institutional	9°18'15.2"	42°07'39.1"
13	Adisu Menaheriya	Traffic	9°18'41.8"	42°07'03"
14	Shenkor	Circulation	9°31'57.9"	42°13'13.4"
15	Harar Brewery	Industrial	9°30'22.8"	42°12'48.7"
16	Ajip	Traffic	9°31'25.9"	42°12'27.7"

3.4. Data Sources and Method of Collection

In order to gather data on pollution levels in Harar city, measurements were taken at various sampling sites. The objective was to collect information on different pollutants or parameters throughout the day when vehicular and human activities are at their peak on the intersection roads and all other types of land uses in the city. The air samples were collected between 7:00 am - 6:00 pm and 7:00 pm – 6:00 am to ensure the presence of high levels of activity.

To gather the necessary data, a gas measuring instrument called Aeroqual's series 500 was used. This instrument is designed to accurately measure various gases and pollutants, providing reliable information for the study. By utilizing this instrument and following the specified data collection procedures, a comprehensive understanding of pollution levels in Harar city can be obtained. The air quality measuring equipment (Aeroqual's series 500) used for data collection were recalibrated before each usage for quality assurance and average of the readings for each point was recorded.

3.4.1. Aeroqual’s series 500

Aeroqual's portable air quality monitors enables air quality professionals and enthusiasts alike to collect real-time information about the surrounding air. They are a flexible air quality monitoring device that can be outfitted with 27 different gas and particle sensors for a variety of applications ranging from environmental monitoring to industrial use. Aeroqual's portable air quality monitors can be used to measure: short term air quality studies, checks on pollution "hot spots", site air quality surveys, personal exposure assessments, and short term fixed monitoring.

Aeroqual's Series 500 during the air quality data collection, followed the following general steps:

1. To turn on the device, press the power button. The display will turn on, and the system will start.
2. Choose the suitable sensor for the pollutant(s) being measured, such as ozone, particulate matter, or gases like NO_2, CO, SO_2 and PMs based on the application.
3. Configure measurement parameters (e.g., sampling time, units, and data logging) from the device's menu. This can be accomplished using the screen interface or associated applications.
4. Calibrate according to manufacturer's recommendations. Calibration aligns the equipment with recognized standards, ensuring reliable measurements.
5. To begin the air quality measurement, press the "Start" or equivalent button. The device will begin collecting data from the air samples.
6. Data Logging: The Series 500 captures data continuously or at predetermined intervals. The display shows real-time readings.
7. Download Data: Once the measurement is complete, you can download it by USB or wirelessly (depending on your model). Data can be analyzed using a computer or software platform.
8. After collecting data, turn off the device to save battery life.

Ensure you follow any specific user manual instructions for calibration, maintenance, and data processing to ensure accuracy and reliability in your air quality measurements.

3.4.2. Mapping spatial distribution of pollutants

The researcher collected air pollutant measurements and their corresponding geographic coordinates from selected stations in Harar city. Inverse Distance Weighting (IDW) method was used to estimate pollutant concentrations at unmonitored locations within Harar city. The method calculates the weighted average of the pollutant concentrations at the surrounding monitored sample points, giving more weight to closer junctions. The maps were created and visualized to represent the spatial distribution of air pollutants in Harar city using the interpolation technique.

3.5. Data Analysis

The collected data was entered to Microsoft excel database for further analysis and interpretation. The graphs were drawn using Origin Pro 8 software. For summarizing all the pollutant concentrations descriptive statistics were used. Mean pollutants concentration of sample points were compared between the selected sampling points and a p-value of 0.05 were considered for the statistical significance. Then, overall mean pollutant concentrations of the city were compared with WHO and Ethiopian air quality guidelines and also among selected sampling sites. The data regarding spatial distribution of air pollutants in Harar city was mapped and visualized using Arc Map 10.8 software.

4. RESULTS AND DISCUSSION

4.1. The Selected Air Quality Parameters within all Junctions

Table 7 contains air quality data for sixteen junctions, focusing on the levels of five criteria air pollutants: $PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2. The key criteria air pollutants measured include $PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2, all of which are critical indicators of air pollution and have significant health and environmental impacts.

Table 7. Selected criteria air pollutants at selected sites in Harar city (µg/m³)

Junction names	**PM $_{2.5}$**	**P-value**	**PM $_{10}$**	**P-value**	**CO**	**P-value**	**SO_2**	**P-value**	**NO_2**	**P-value**
Arategna	95.37	0.0111	157.37	0.7645	2590.96	0.2329	0	.000	203.43	0.0251
Adisu Menaheriya	85.71	0.1959	288.81	0.0179	1906.33	0.5814	0	.000	234.29	0.0166
Deker	66.51	0.3601	243.01	0.0330	2429.2	0.3802	0	.000	199.49	0.1322
Budaber	43.84	0.3601	113.95	0.9343	0	0.000	0	.000	177.81	0.4984
Harar Ber	47.43	0.7268	67.86	0.0048	2692.57	0.0179	0	.000	209.13	0.5363
Gelmeshira	68.14	0.5680	29.71	0.0317	3091.71	0.5335	60	.003	202.14	0.0141
Felanaber	75.14	0.0168	167	0.3680	1817.71	0.3601	61	.142	196.04	0.0091
Kelad amba	61.86	0.6322	104.14	0.0030	0	0.000	0	.000	196.2	0.6017
Shenkor	51.73	0.0065	86.57	0.0405	2479.29	0.4371	0	.000	217.71	0.0079
Ajip	61.47	0.0179	113.43	0.0016	4867.34	0.1908	117.24	0.0329	207.71	0.1197
Hywet fana	275.7	0.3104	587.8	0.0271	7057.06	0.0179	126.46	0.0824	210.23	0.8765
Shewaber	73.46	0.0694	200.71	0.4177	1788.63	0.0016	151.67	0.3680	225.6	0.4432
Harar brewery	60.57	0.0179	162.33	0.7645	3904.28	0.0271	242.38	0.1420	239.64	0.0172
Hamaressa	50.91	0.1022	179.61	0.7655	2375.14	0.0306	0	0.000	234.63	0.4150
Aroge menaheriya	97.04	0.0580	350.93	0.7334	2315.71	0.0179	0	0.000	297	0.7106
Feres Magalla	61.46	0.0769	113.06	0.9150	2068.38	0.0179	0	0.000	212.86	0.4881

4.1.1. Particulate matter ($PM_{2.5}$) (µg/m³)

The $PM_{2.5}$ levels vary significantly across the junctions, with the lowest recorded at Budaber (43.84 µg/m³) and the highest at Hywet Fana (275.70 µg/m³) (Figure 2). The high $PM_{2.5}$ levels at Hywet Fana suggest a severe pollution issue, likely due to emissions from construction sites, traffic emissions, or other localized sources such as dusts, soot, dirt and smoke. In contrary, the lowest $PM_{2.5}$ was observed at Budaber, it is likely due to the land use type of the sample point as it is a residential area as there is less human and vehicular activities (Table 7). That could be the difference. Most junctions exhibit $PM_{2.5}$ levels above the World Health Organization (WHO) recommended limit of 25 µg/m³ for 24-hour exposure, indicating widespread air quality concerns. The P-value assesses the statistical significance of the variables from one sample point to the other. Lower p-values (e.g., below 0.05) confirm that the clustering is statistically significant. In this dataset $PM_{2.5}$ is significant ($P < 0.05$) at Arategna, Felanaber, Shenkor, Ajip, Harar Brewery, Aroge Menaheriya and the rest of the junctions show insignificant ($P > 0.05$).

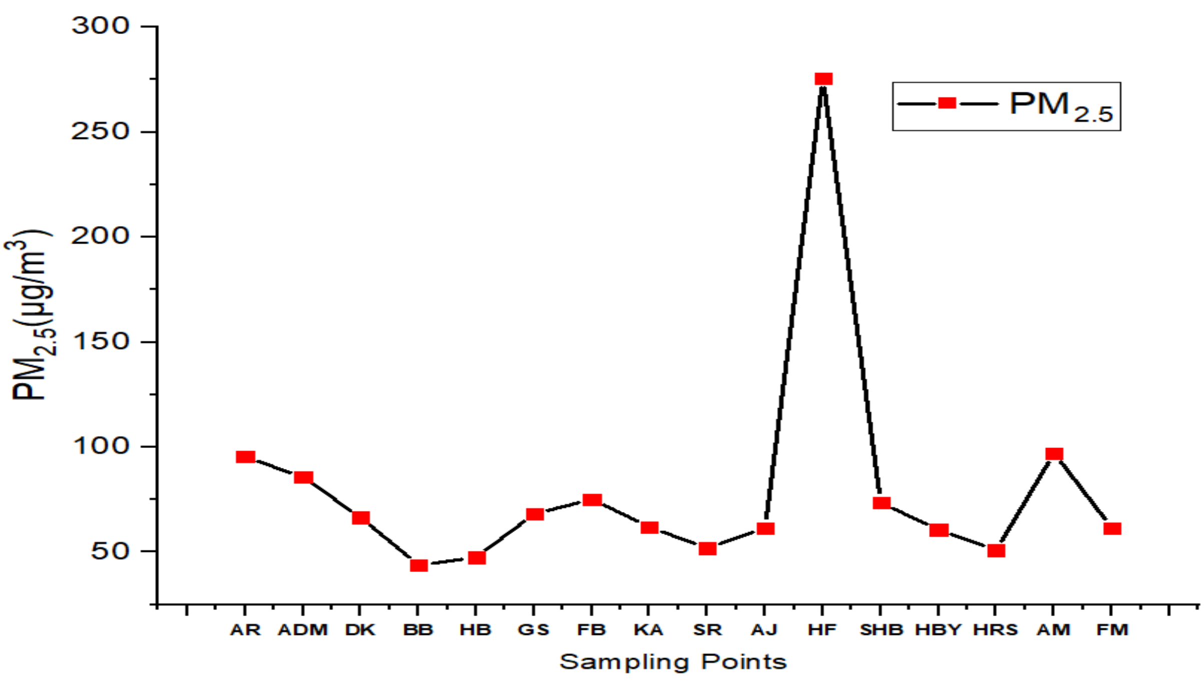

Figure 2. Concentration of $PM_{2.5}$ in Harar City

AR= Arategna; ADM= Adisu Menaheriya; DK= Deker; BB= Buda Ber; HB= Harar Ber; GS= Gelmeshira; FB= Felana Ber; KA= Kelad Amba; SR= Shekor; AJ= Ajip; HF= Hywet Fana; SHB=Shewa Ber; HBY= Harar Brewery; HRS= Hamaressa; AM= Aroge Menaheriya; FM= Feres Megalla

The average concentration of $PM_{2.5}$ across the junctions was 79.77 µg/m³ (Table 8). This level is significantly higher than the recommended by the World Health Organization (WHO) 25 µg/m³ for 24-hour mean, and Ethiopian Air quality guideline of 65 µg/m³ as well. The $PM_{2.5}$ concentration found in Harar city is slightly higher than the concentration (50-60 µg/m³) reported in Nairobi, Kenya (Kiai *et al.,* 2021). However, the concentration in the current study is much lower than the mean $PM_{2.5}$ (455.37 µg/m^3) concentration found in Jimma town (Elias *et al*., 2024). This finding corroborates the findings of several studies conducted in similar settings in Ethiopia, Ghana and India (Mulat *et al*., 2024).

Prolonged exposure to high levels of $PM_{2.5}$ can lead to severe health problems, including chronic respiratory diseases, heart disease, and lung cancer (Zheng *et al*., 2015). Children, the elderly, and individuals with pre-existing health conditions are particularly vulnerable (Anderson *et al*., 2012). Long-term exposure to $PM_{2.5}$ is associated with increased mortality from ischemic heart disease, cerebrovascular disease (stroke, CEV), chronic obstructive pulmonary disease (COPD), and lung cancer, and increased incidence of acute lower respiratory infections (ALRI) (Anderson *et al*., 2012; Zheng *et al*., 2015). According to Grzywa-celińska *et al*. (2020), $PM_{2.5}$ are much more dangerous to health because of greater ability to penetrate into the lower respiratory tract, and even deeper into the alveoli. Major sources of $PM_{2.5}$ include motor vehicle emissions, industrial processes, residential heating etc. To reduce $PM_{2.5}$ levels, strategies such as enhancing emission standards for vehicles, promoting the use of cleaner fuels, implementing industrial emission controls, and increasing green spaces in urban areas can be effective.

4.1.2. Particulate matter (PM_{10}) (µg/m³)

The PM_{10} concentrations were notably high at several junctions, particularly Hywet Fana (587.80 µg/m³) and the lowest was observed at Gelmeshira sample point (29.71 µg/m³) (Figure 3). Particulate matter (PM_{10}) at Hywet Fana sample point is this high likely due to high human and vehicular activities in the area while the lowest was observed at Gelmeshira sample point. The reduced value of PM at Gelmeshira is due to absence of industries, dusts, construction activities. The presence of such high PM_{10} levels at Hywet Fana sample point suggests significant pollution from both natural sources like dust and anthropogenic sources such as construction, vehicular emissions, and industrial activities. PM_{10} is significant ($P< 0.05$) at sample points like Adisu

Menaheriya, Deker, Harar Ber, Gelmeshira, Kelad Amba, Shenkor, Ajip, Hywet Fana and the rest of the junctions showed insignificant ($P > 0.05$).

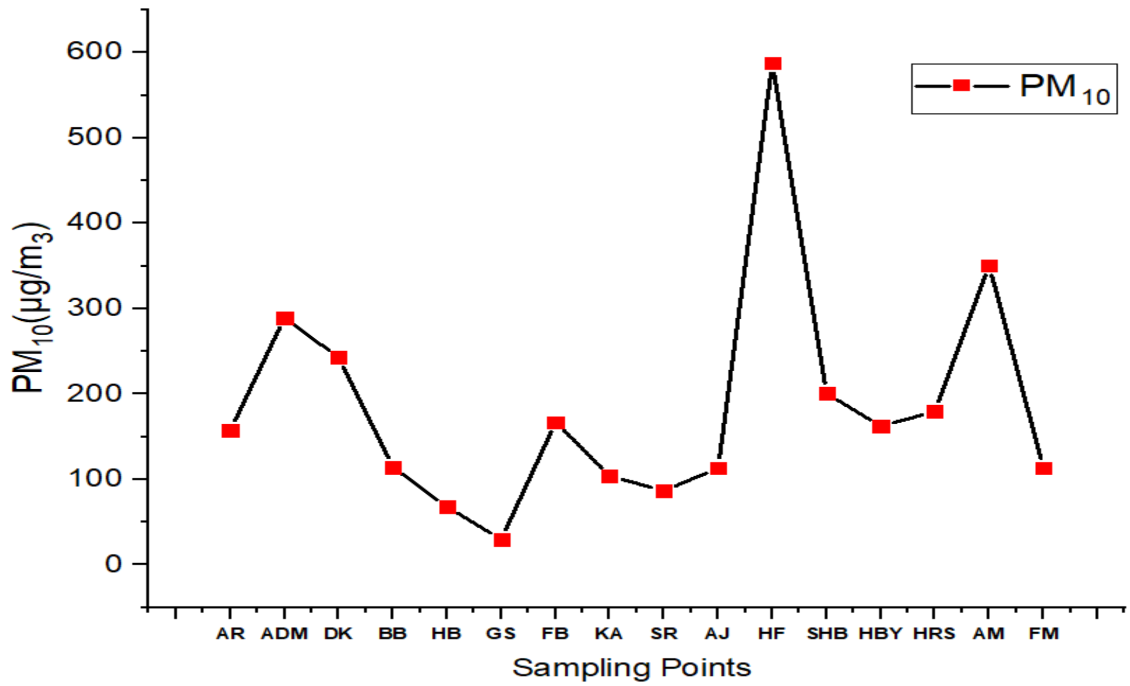

Figure 3. Concentration of PM_{10} in Harar City

AR= Arategna; ADM= Adisu Menaheriya; DK= Deker; BB= Buda Ber; HB= Harar Ber; GS= Gelmeshira; FB= Felana Ber; KA= Kelad Amba; SR= Shekor; AJ= Ajip; HF= Hywet Fana; SHB=Shewa Ber; HBY= Harar Brewery; HRS= Hamaressa; AM= Aroge Menaheriya; FM= Feres Megalla

The average PM_{10} concentration in Hararcity was 185.33 µg/m³ (Table 8), which is also significantly above the concentration in the WHO and Ethiopian guidelines. Similar concentrations of PM_{10} have been observed in Cairo, Egypt (160-180 µg/m³) (Abu-Allaban *et al*., 2002). However, a study in Jimma town showed a very high level of PM_{10} (819.06 µg/m³), which was over 18 times higher than the WHO recommended values of 45 µg/m³ (Mulat *et al*., 2024).

Similar to $PM_{2.5}$, PM_{10} can cause respiratory and cardiovascular issues. However, PM_{10} particles are less likely to penetrate as deeply into the lungs as $PM_{2.5}$, but they still pose significant health risks (Geravandi *et al.*, 2015). Common sources include construction sites, unpaved roads, fields, smokestacks, and fires. Effective dust control measures, regulation of industrial emissions, and promoting public transportation and cycling to reduce vehicular emissions can help lower PM_{10} levels (Geravandi *et al.,* 2015).

4.1.3. Carbon monoxide (CO) (μg/m³)

Carbon monoxide (CO) levels vary dramatically, with some sample points like Budaber and Kelad Amba showed no detectable CO levels as the areas are residential (Table 7), while others like Hywet Fana exhibit extremely high levels (7057.06 μg/m³) (Figure 4). These high CO concentrations suggest significant combustion-related pollution, likely from heavy traffic or industrial processes. Hywet Fana's elevated levels are particularly concerning and indicate a severe pollution hotspot. Carbonmonoxide (CO) is significant ($P < 0.05$) at junctions like Harar Ber, Hywet Fana, Shewa Ber, Harar Brewery, Hamaressa, Aroge Menaheriya, Feres Megalla and the rests showed insignificant ($P > 0.05$).

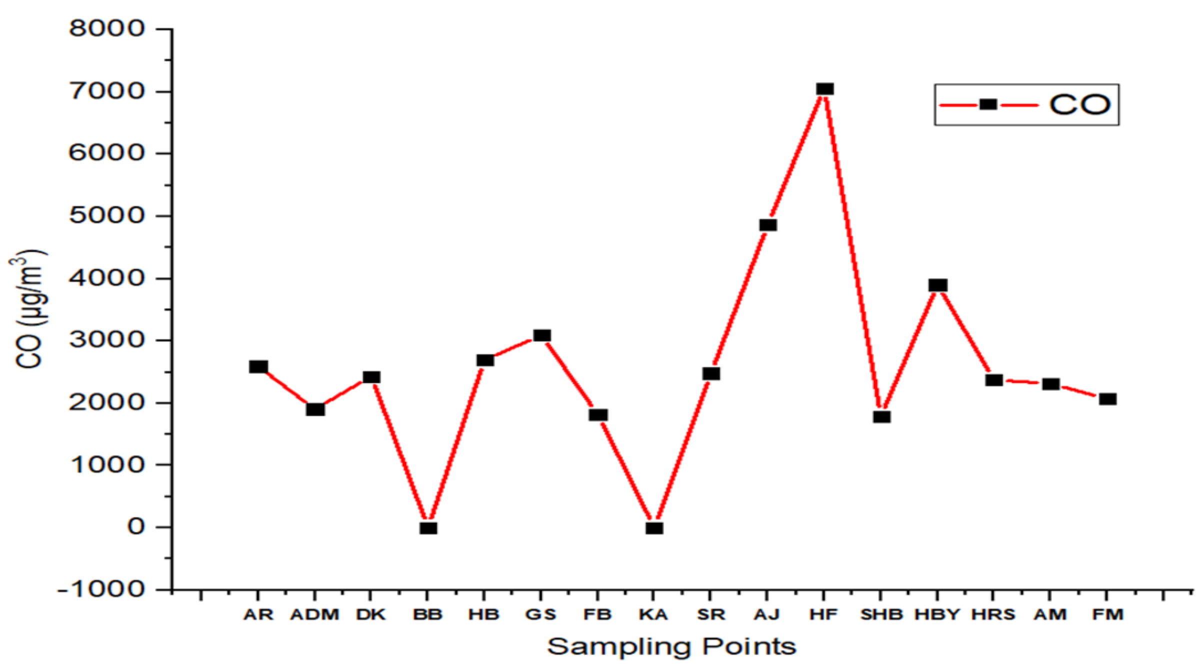

Figure 4. Cocentration of CO in Harar City

AR= Arategna; ADM= Adisu Menaheriya; DK= Deker; BB= Buda Ber; HB= Harar Ber; GS= Gelmeshira; FB= Felana Ber; KA= Kelad Amba; SR= Shekor; AJ= Ajip; HF= Hywet Fana; SHB=Shewa Ber; HBY= Harar Brewery; HRS= Hamaressa; AM= Aroge Menaheriya; FM= Feres Megalla

The average concentration of carbon monoxide (CO) of Harar city was 2586.52 µg/m³ (Table 8). These levels far exceed the WHO guideline for CO. Carbon monoxide levels in Ethiopia are typically high due to vehicular emissions, especially from older cars that lack proper emission controls. Study in Dire Dawa showed almost similar levels of CO (mention the concentration), driven by traffic and industrial activities (Kasim *et al*., 2018). Other studies have also shown CO levels exceeding 4,000 ppm in homes burning cow dung, as observed in rural Tigray (Redi, 2024).

Carbon monoxide interferes with the oxygen-carrying capacity of blood, leading to cardiovascular and neurological effects. High levels can cause dizziness, confusion, unconsciousness, and even death (Chamberlain, 2016). The WHO estimates that 99% of people lived in areas where the air quality was not up to the WHO guidelines and outdoor pollution contributed to approximately 4.2 million premature deaths worldwide (Meo *et al*., 2024). Cabonmonoxide is primarily produced from vehicle emissions, industrial processes, residential heating, and biomass burning. Reducing CO levels can be achieved through improving combustion efficiency in vehicles and industrial processes, promoting the use of electric vehicles, and enhancing ventilation in indoor spaces where combustion occurs.

4.1.4. Sulfur dioxide (SO_2) (µg/m³)

Many sample points showed no detectable SO_2 levels, while others like Harar Brewery (242.38 µg/m³) and Shewa Ber (151.67 µg/m³) have significantly high levels (Figure 5). These elevated SO_2 concentrations likely stem from industrial activities involving the combustion of sulfur-containing fuels. The presence of SO_2 at these levels poses a risk to respiratory health and indicates the need for regulatory measures to control industrial emissions.

Sulphur dioxide (SO_2) is significant ($P < 0.05$) at junctions like Gelmeshira and Ajip while the rest of the junctions showed insignificant ($P > 0.05$).

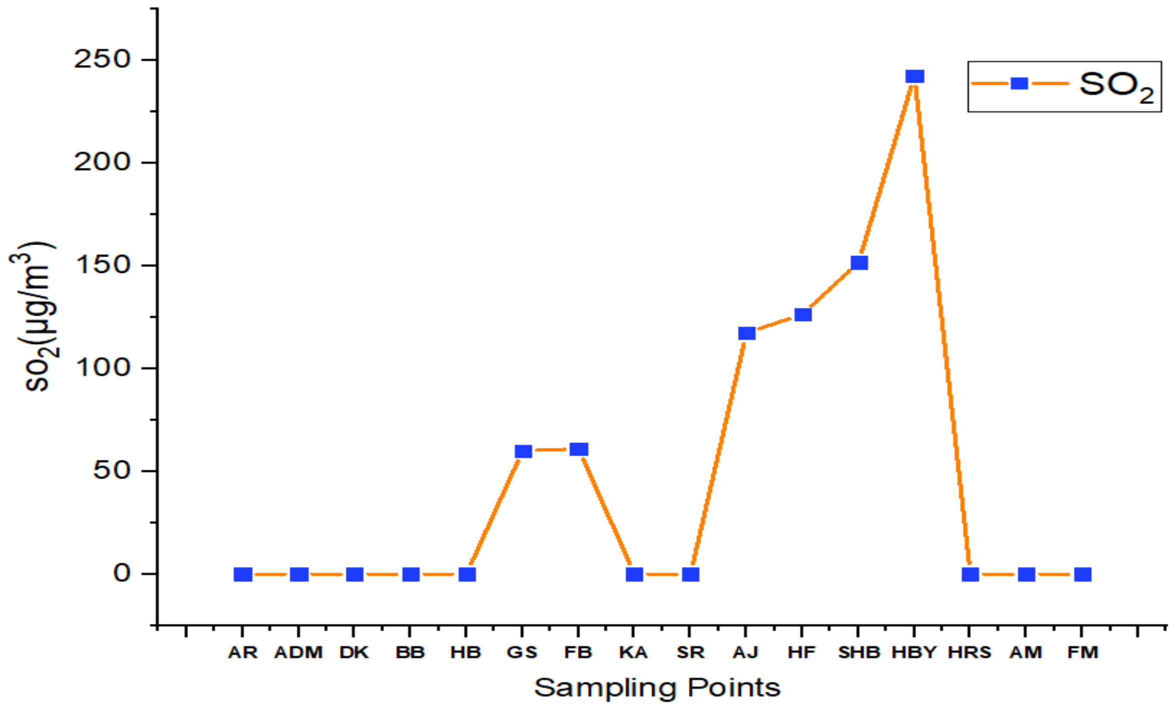

Figure 5. Concentration of SO_2 in Harar City

AR= Arategna; ADM= Adisu Menaheriya; DK= Deker; BB= Buda Ber; HB= Harar Ber; GS= Gelmeshira; FB= Felana Ber; KA= Kelad Amba; SR= Shekor; AJ= Ajip; HF= Hywet Fana; SHB=Shewa Ber; HBY= Harar Brewery; HRS= Hamaressa; AM= Aroge Menaheriya; FM= Feres Megalla

The average SO_2 concentration is 47.42 µg/m³ (Table 8), which is more than double the SO_2 concentration recommended by the WHO guideline (20 µg/m³) for 24-hour mean. Sulfur dioxide levels in Ethiopia are often driven by industrial emissions and the burning of sulfur-rich fuels like coal. Levels similar to 47 µg/m³ have been recorded near industrial zones in Addis Ababa and Dire Dawa (Kasim *et al*., 2018). Sulfur dioxide can cause respiratory symptoms, particularly in asthmatics (Nurhisanah and Hasyim, 2022). It also contributes to the formation of $PM_{2.5}$ and acid rain, which have broader environmental and health impacts (Geravandi *et al.,* 2015; Nurhisanah and Hasyim 2022). Reducing sulfur content in fuels, switching to cleaner energy sources, and implementing flue-gas desulfurization technologies in industries can help lower SO_2 levels.

4.1.5. Nitrogen dioxide (NO_2) (µg/m³)

Nitrogen dioxide (NO_2) levels are consistently high across most sample points, with the lowest recorded at Budaber (177.81 µg/m³) and the highest at Aroge Menaheriya (297.00 µg/m³) (Figure 6). This high NO_2 concentrations at Aroge Menaheriya is likely due to vehicular emissions indicating the need for improved emission control strategies. Nitrogen dioxide (NO_2) is significant ($P< 0.05$) at junctions like Arategna, Gelmeshira, Felana Ber, Shenkor, Harar Brewery, Adisu Menaheriya and the rests showed insignificant ($P> 0.05$).

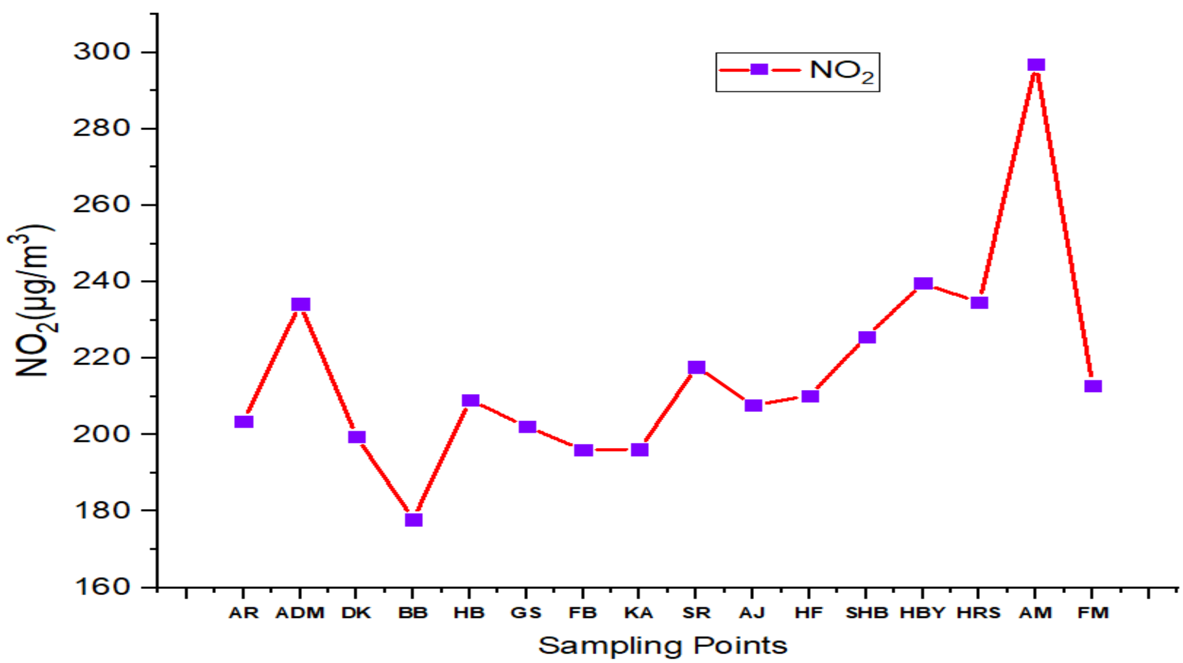

Figure 6. Concentration of NO_2 in Harar City

AR= Arategna; ADM= Adisu Menaheriya; DK= Deker; BB= Buda Ber; HB= Harar Ber; GS= Gelmeshira; FB= Felana Ber; KA= Kelad Amba; SR= Shekor; AJ= Ajip; HF= Hywet Fana; SHB=Shewa Ber; HBY= Harar Brewery; HRS= Hamaressa; AM= Aroge Menaheriya; FM= Feres Megalla

The average Nitrogen dioxide (NO_2) concentration in Harar city was 216.49 µg/m³ (Table 8). This is significantly above the WHO guideline of 40 µg/m³ for annual mean and 200 µg/m³ for 1-hour mean. Nitrogen dioxide concentrations are especially high near traffic-heavy areas in Ethiopian cities. Similar levels have been observed in major intersections in Dire Dawa, driven by vehicle exhaust and industrial activities (Kasim *et al*., 2018). Study found that in one region in Ethiopia the level of NO_2 in households that used biomass fuel for cooking was twice the WHO guideline for NO_2 concentrations (Keil *et al*., 2010).

Nitrogen dioxide can irritate airways and exacerbate respiratory diseases, such as asthma. Long-term exposure can decrease lung function and increase the risk of respiratory infections (Koehler *et al*., 2010). Exposure to NO_2 pollutants is associated with an increased risk of lung cancers and heart and respiratory diseases, so they are considered a serious risk on human health (Hesami *et al*. 2021). Implementing stricter vehicle emission standards, promoting public transportation, and using cleaner industrial technologies can reduce NO_2 levels.

Average concentrations of Air Pollutants in Harar city (μg/m³)

Table 8 contains the mean concentrations of the measured selected criteria air pollutants across all junctions and its exceedance level in Harar city.

Pollutant	Average Concentration (μg/m³)	Ethiopian Guideline (μg/m³)	WHO Guideline (μg/m³)	Exceedance (WHO)	Exceedance (Ethiopia)
$PM_{2.5}$	79.77	65	15	5.3 times	1.22 times
PM_{10}	185.33	150	45	4.12 times	1.24 times
CO	2586.52	10,000	4	646.63 times	Within Limit
SO_2	47.42	125	25	1.90 times	Within Limit
NO_2	216.49	200	40	5.41 times	1.08 times

Comparison of Average Pollutant Concentrations with Ethiopian and WHO Guidelines

The table 8 comparing the average concentrations of pollutants ($PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2) against both Ethiopian and WHO guidelines provides a comprehensive view of air quality in Harar city. As it is indicated in the table 8, $PM_{2.5}$, PM_{10} and NO_2 far exceeded both WHO and Ethiopian air quality guidelines. On the other hand, CO and SO_2 exceeded the WHO air quality guideline for daily exposure by far but they are within the limit of the national guideline. The degree of exceedance indicates significant disparities between local conditions and WHO standards, illustrating the need for targeted interventions. Air quality is an important public health and environmental concern. Various pollutants, such as $PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2, can significantly impact human health and the environment. Both the World Health Organization (WHO) and national regulatory bodies, such as the Ethiopian Environmental Protection

Authority, provide guidelines for acceptable daily concentrations of these pollutants. This discussion compared the average concentrations of these pollutants with both Ethiopian and WHO guidelines, examining the implications of these measurements.

4.2. Spatial Distribution of Air Pollutants in Harar City

4.2.1. Carbon monoxide

Figure 7 shows the Carbon Dioxide map of Harar city reflecting the spatial distribution of CO and its variation in the city. The statistics table 9 for CO (Carbon Monoxide) concentrations in Harar city provides insight into the distribution of CO levels across the area. The majority of the city (66.25%) has CO concentrations up to 2380 µg/m³, indicating that most regions experience relatively high CO pollution levels. A notable portion of the area, 16.23%, has concentrations up to 2271 µg/m³, while 6.93% of the city has levels up to 2335 µg/m³.

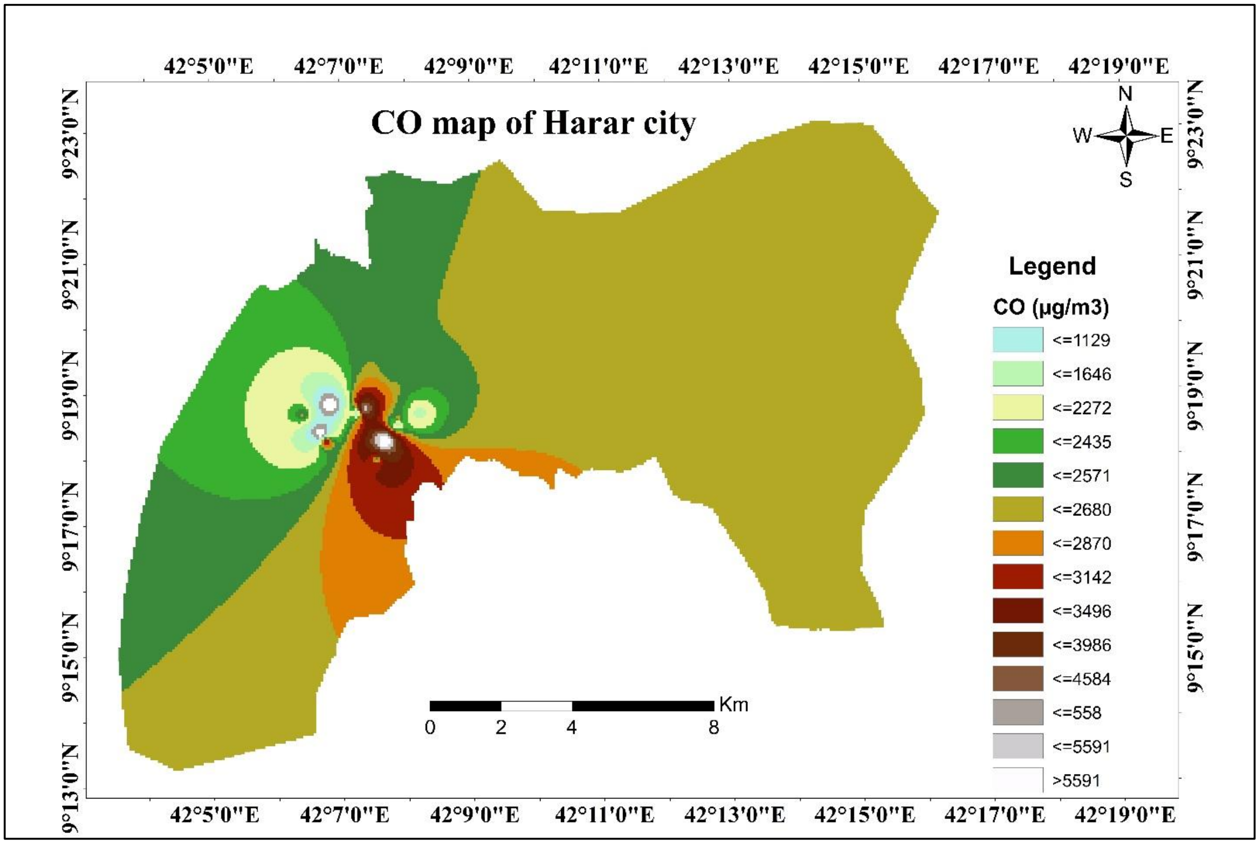

Figure 7. CO map of Harar city

Table 9 .Carbon monoxide concentrations and proportion at different areas of the city.

CO (µg/m^3)	Area (Km^2)	Area (%)
<=1129	0.1372	0.064201
<=558	0.2744	0.128402
<=1129	0.5684	0.265976
<=1646	1.127	0.527366
<=2272	5.439	2.545113
<=2435	14.8127	6.931419
<=2571	34.6871	16.2314
<=2680	141.5855	66.25318
<=2870	9.2071	4.308348
<=3142	3.7681	1.763236
<=3496	1.2691	0.59386
<=3986	0.4459	0.208653
<=4584	0.2058	0.096302
<=5591	0.1078	0.050444
>5591	0.0686	0.032101
Total	213.7037	100

Smaller portions of the city are exposed to very higher concentrations: 4.31% of the area has CO levels up to 2570 µg/m^3, and 1.76% of the city has concentrations up to 3042 µg/m^3. As the concentration levels increase further, the areas affected decrease markedly. For instance, only 0.59% of the city has CO levels up to 3496 µg/m^3, 0.21% up to 3986 µg/m^3, 0.10% up to 4584 µg/m^3, and just 0.05% up to 5591 µg/m^3. The smallest area, accounting for 0.03% of the city, experiences CO concentrations exceeding 5591 µg/m^3. This distribution suggests that while there are small pockets within Harar city with highly elevated CO concentrations, the majority of the area maintains medium concentration levels, implying that overall, the city's air quality is predominantly within moderate CO pollution ranges according to national Air quality guidelines however, it is significantly higher than the WHO air quality guidelines.

4.2.2. Nitrogen dioxide

Figure 8 shows the Nitrogen Dioxide map of Harar city reflecting the spatial distribution of NO_2 and its variation in the city.

The table 10 detailing Nitrogen Dioxide (NO_2) concentrations in Harar city provides a comprehensive look at the distribution of NO_2 levels across different areas. Each range is presented with the corresponding area in square meters and as a percentage of the total area. The data shows how NO_2 concentrations vary within the city. A very small portion of the city (0.04%) has NO_2 concentrations up to 186 µg/m³. Slightly larger areas fall within the next ranges: 0.11% of the city has concentrations up to 195 µg/m³, and 0.39% has levels up to 201 µg/m³. About 0.89% of the city experiences NO_2 concentrations up to 204 µg/m³, and 1.46% has levels up to 208 µg/m³. The portion of the city with NO_2 concentrations up to 211 µg/m³ is 2.72%, and 6.75% of the city has concentrations up to 213 µg/m³.

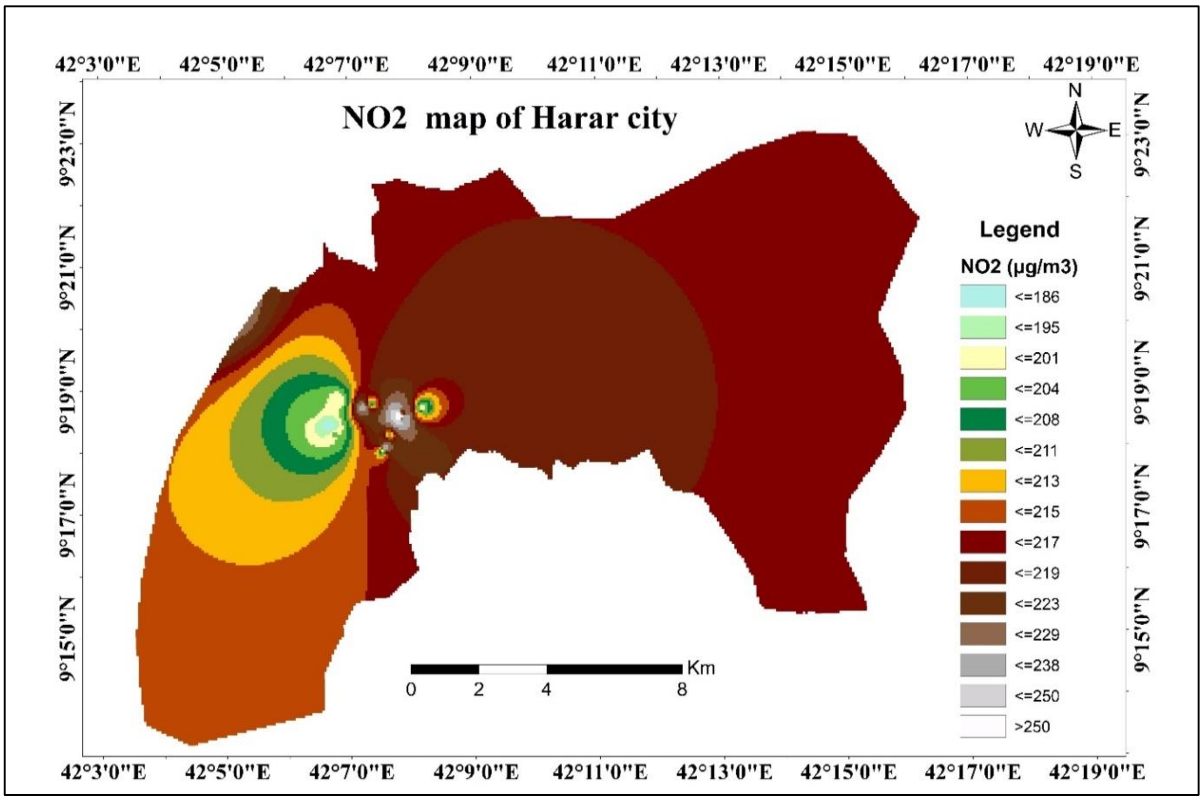

Figure 8. NO_2 map of Harar city

Table 10. Nitrogen Dioxide concentrations and proportion at different areas of the city.

NO_2 (µg/m^3)	Area (Km^2)	Area (%)
<=186	0.0784	0.036686
<=195	0.2352	0.110059
<=201	0.8281	0.387499
<=204	1.9012	0.889643
<=208	3.1164	1.458281
<=211	5.8114	2.719373
<=213	14.4354	6.754867
<=215	36.946	17.28842
<=217	89.8072	42.02417
<=219	55.7032	26.06562
<=223	3.4496	1.614198
<=229	0.9702	0.453993
<=238	0.3087	0.144452
<=250	0.0784	0.036686
>250	0.0343	0.01605
Total	213.7037	100

The largest areas are found within the mid-range concentrations: 17.29% of the city has NO_2 levels up to 215 µg/m³, and the majority of the city (42.02%) falls within the concentration range of up to 217 µg/m³. Another important portion, 26.07%, experiences NO_2 concentrations up to 219 µg/m³. Smaller areas are associated with higher concentrations: 1.61% of the city has NO_2 levels up to 223 µg/m³, 0.45% up to 229 µg/m³, and 0.14% up to 238 µg/m³. The least amount of area (0.04%) has concentrations up to 250 µg/m³, and an even smaller portion (0.02%) experiences NO_2 concentrations above 250 µg/m³. As a whole, the majority of Harar city has NO_2 concentrations up to 217 µg/m³, covering 42.02% of the total area. The data indicates that a largest portion of the city has higher NO_2 levels against both national and international air quality guidelines.

4.2.3. Particulate matter ($PM_{2.5}$)

Figure 9 shows the Particulate Matter ($PM_{2.5}$) map of Harar city reflecting the spatial distribution of $PM_{2.5}$ and it's variation from in the city.

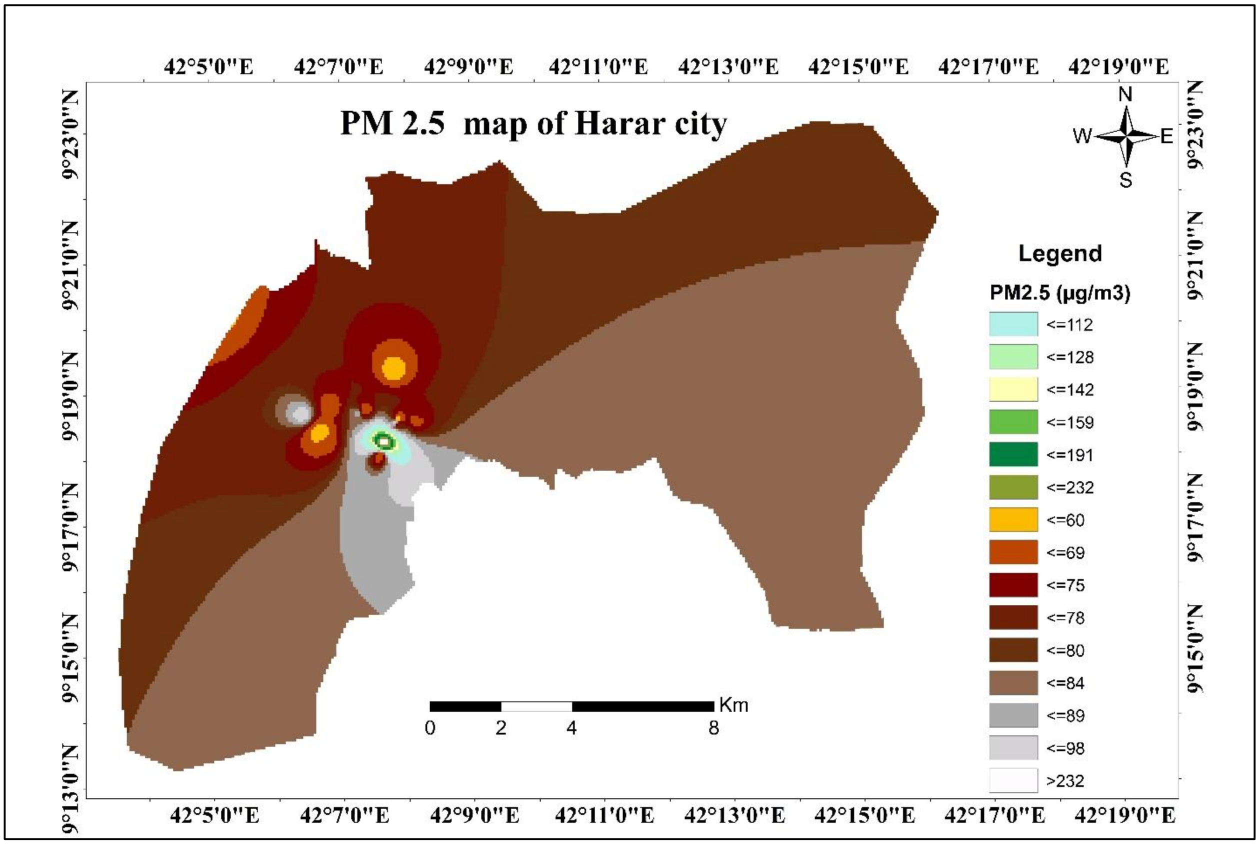

Figure 9. $PM_{2.5}$ map of Harar city

The table 11 for $PM_{2.5}$ (fine particulate matter) concentrations in Harar city provides a detailed breakdown of how different concentration ranges are distributed across the area in both square meters and percentage terms. This data helps to understand the extent of air pollution related to $PM_{2.5}$ in the city. A small fraction of the city (0.25%) has $PM_{2.5}$ concentrations up to 60 µg/m³. As the concentration levels increase, the areas covered also increase. For instance, 1.61% of the city experiences $PM_{2.5}$ levels up to 69 µg/m³, and 4.95% has concentrations up to 75 µg/m³. The most significant portions of the city fall within mid-range concentrations: 15.85% of the city has $PM_{2.5}$ levels up to 78 µg/m³, and 25.34% has concentrations up to 80 µg/m³. The largest area, 47.30%, has $PM_{2.5}$ concentrations up to 84 µg/m³, indicating that nearly half of the city experiences higher $PM_{2.5}$ pollution levels.

Table 11. Particulate matter ($PM_{2.5}$) concentrations and proportion at different areas of the city.

$PM_{2.5}$ (µg/m^3)	Area (Km^2)	Area (%)
<=60	0.5439	0.254511
<=69	3.43	1.605026
<=75	10.584	4.952652
<=78	33.8786	15.85307
<=80	54.1597	25.34336
<=84	101.0821	47.30012
<=89	7.3745	3.450806
<=98	1.7395	0.813978
<=112	0.4312	0.201775
<=128	0.1862	0.08713
<=142	0.0686	0.032101
<=159	0.0637	0.029808
<=191	0.0784	0.036686
<=232	0.0539	0.025222
>232	0.0294	0.013757
Total	213.7037	100

For higher concentrations, the covered areas decrease significantly: 3.45% of the city has $PM_{2.5}$ levels up to 89 µg/m^3, and 0.81% experiences levels up to 98 µg/m^3. Smaller areas correspond to even higher concentrations: 0.20% of the city has $PM_{2.5}$ levels up to 112 µg/m^3, and 0.09% up to 128 µg/m^3. The smallest portions of the city are exposed to the highest concentrations: 0.03% of the area has $PM_{2.5}$ levels up to 142 µg/m^3, 0.03% up to 159 µg/m^3, and 0.04% up to 191 µg/m^3. Very minimal areas, 0.03%, experience levels up to 232 µg/m^3, and the smallest area, 0.01%, has $PM_{2.5}$ concentrations exceeding 232 µg/m^3. Overall, almost all areas within the city experiences higher level of $PM_{2.5}$ when compared with both national and international air quality guidelines.

4.2.4. Particulate matter (PM_{10})

Figure 10 shows the Particulate Matter (PM_{10}) map of Harar city reflecting the spatial distribution of PM_{10} and its variation in the city.

The table 12 for PM_{10} concentrations in Harar city shows the distribution of different concentration ranges across the city in both square meters and percentage terms. This data provides a clear picture of the extent and variability of PM_{10} pollution in the city. A small portion of the city (0.08%) has PM_{10} concentrations up to 85 µg/m^3.

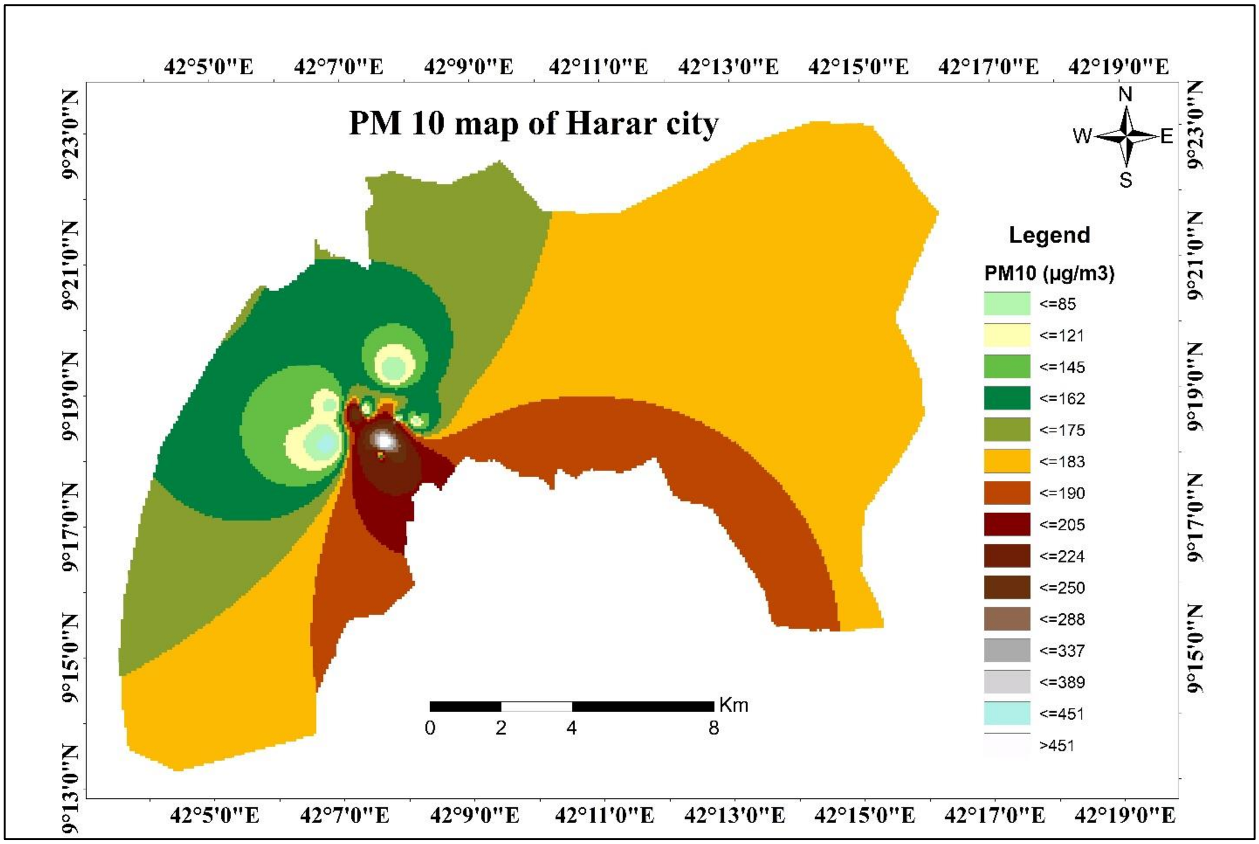

Figure 10. PM_{10} map of Harar city

As the concentration levels increase, the areas covered also grow. For example, 0.48% of the city experiences PM_{10} levels up to 121 µg/m³, and 1.03% has concentrations up to 145 µg/m³. Significant portions of the city fall within mid-range concentrations: 3.28% of the city has PM_{10} levels up to 162 µg/m³, and 11.71% has concentrations up to 175 µg/m³. Another substantial portion, 15.71%, has PM_{10} levels up to 183 µg/m³. The majority of the city is covered by areas with moderate PM_{10} pollution: 50.33% of the city experiences PM_{10} concentrations up to 190 µg/m³. This indicates that half of the city has high levels of PM_{10} pollution.

For higher concentrations, the covered areas decrease: 14.40% of the city has PM_{10} levels up to 205 µg/m³, and 1.65% experiences levels up to 224 µg/m³. Smaller areas correspond to even very higher concentrations: 0.91% of the city has PM_{10} levels up to 250 µg/m³, and 0.23% up to 288 µg/m³. The smallest portions of the city are exposed to the highest concentrations: 0.08% of the area has PM_{10} levels up to 337 µg/m³, 0.04% up to 389 µg/m³, and 0.02% up to 451 µg/m³. The smallest area, 0.03%, has PM_{10} concentrations exceeding 451 µg/m³. In general, almost all areas within the city experiences higher level of PM_{10} in comparison with both national and international air quality guidelines.

Table 12. Particulate matter (PM_{10}) concentrations and proportion at different areas of the city.

PM_{10} (µg/m^3)	Area (Km^2)	Area (%)
<=85	0.1764	0.082544
<=121	1.029	0.481508
<=145	2.2001	1.02951
<=162	7.0021	3.276546
<=175	25.0341	11.7144
<=183	33.5797	15.71321
<=190	107.5648	50.33361
<=205	30.7769	14.40167
<=224	3.5329	1.653177
<=250	1.9355	0.905693
<=288	0.4851	0.226996
<=337	0.1764	0.082544
<=389	0.0931	0.043565
<=451	0.049	0.022929
>451	0.0686	0.032101
Total	213.7037	100

4.2.5. Sulfur dioxide

Figure 11 shows the Sulfur Dioxide map of Harar city reflecting the spatial distribution of SO_2 and its variation in the city. As the concentration levels increase, the areas covered also grow. For example, 1.51% of the city experiences SO_2 levels up to 25 µg/m³, and 3.86% has concentrations up to 33 µg/m³. Significant portions of the city fall within mid-range concentrations: 6.52% of the city has SO_2 levels up to 40 µg/m³, and 10.41% has concentrations up to 45 µg/m³. Another substantial portion, 26.03%, has SO_2 levels up to 49 µg/m³.

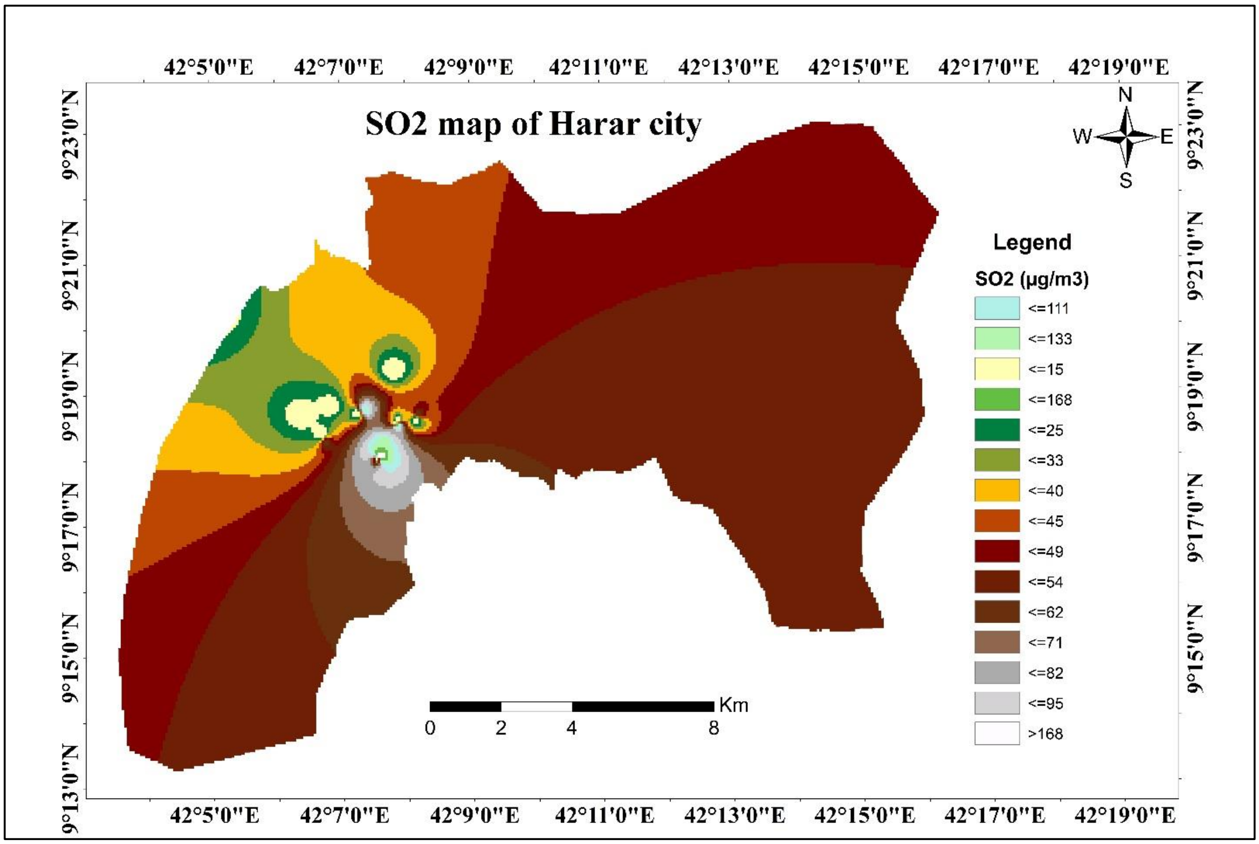

Figure 11. SO_2 map of Harar city

The majority of the city is covered by areas with moderate SO_2 pollution: 43.37% of the city experiences SO_2 concentrations up to 54 µg/m³. This indicates that nearly half of the city has moderate levels of SO_2 pollution. For higher concentrations, the covered areas decrease: 4.24% of the city has SO_2 levels up to 62 µg/m³, and 1.72% experiences levels up to 71 µg/m³. Smaller areas correspond to even higher concentrations: 0.96% of the city has SO_2 levels up to 82 µg/m³, and 0.38% up to 95 µg/m³. The smallest portions of the city are exposed to the highest concentrations: 0.18% of the area has SO_2 levels up to 111 μg/m³, 0.09% up to 133 μg/m³, and 0.03% up to 168 μg/m³. The smallest area, 0.01%, has SO_2 concentrations exceeding 168 μg/m³.

Table 13. Sulfur Dioxide concentrations and proportion at different areas of the city.

SO_2 (μg/m^3)	Area (Km^2)	Area (%)
<=25	3.2193	1.506432
<=33	8.2418	3.856648
<=40	13.9307	6.518699
<=45	22.2411	10.40745
<=49	55.6346	26.03352
<=54	92.6884	43.37239
<=62	9.0601	4.239562
<=71	3.6701	1.717378
<=82	2.0482	0.95843
<=95	0.8134	0.38062
<=111	0.3773	0.176553
<=133	0.196	0.091716
<=168	0.0735	0.034393
>168	0.0294	0.013757
Total	213.7037	100

5. SUMMARY, CONCLUSION AND RECOMMENDATIONS

Air quality is crucial and one of the basic necessities for human survival and a global concern. Ambient air pollution is a significant intercontinental health crises affecting millions of people leading to several critical health conditions. According to World Health Organization (WHO), nine out of ten people worldwide breathe air that is unhealthy due to pollution, Ethiopia is no exception to this trend. Despite the severity of the issue, no scientific studies explored the ambient air quality status of Harar city. The overall objective of the study was to evaluate the current air quality status with WHO and Ethiopian air quality guidelines, understand the spatial distribution of pollutants, and analysis of ambient air quality in the city.

The methodology involved sampling air pollutants at various sample points across the city using an Aeroqual Series 500 portable handheld device. Data was collected for pollutant concentrations, which were then compared against Ethiopian and WHO air quality standards. And also using Arc Map 10.8, mapping of spatial distribution and proportion analysis of the pollutants concentration in the city is discussed. The key findings are as follows:

Particulate Matters ($PM_{2.5}$ and PM_{10}): The average concentrations of $PM_{2.5}$ and PM_{10} were found to exceed both Ethiopian and WHO guidelines significantly. $PM_{2.5}$ averaged 79.77 µg/m³, which is over 5.3 times the WHO guideline of 15 µg/m³ and Ethiopian guideline of 65 µg/m³ for daily exposure. Similarly, PM_{10} averaged 185.33 µg/m³, far exceeding both WHO and Ethiopian guideline of 45 and 150 µg/m³ respectively.

Carbon Monoxide (CO): The average concentration of CO was 2586.52 µg/m³. While this is within the Ethiopian guideline of 10,000 µg/m³, it is important to note that this value is 646.63 times the WHO guideline of 4 µg/m³. This shows significant exceedance of WHO guidelines for carbon monoxide. Nitrogen Dioxide (NO_2): The average NO_2 concentration was 216.49 µg/m³, which is 5.4 and 1.08 times the WHO and Ethiopian guideline of 40 and 200 µg/m³ respectively. Sulfur Dioxide (SO_2): The average concentration of SO_2 was 47.42 µg/m³, which is within the Ethiopian guideline but exceeds the WHO guideline of 25 µg/m³ for 24-hour exposure. The study also mapped the spatial distribution of these pollutants, revealing higher concentrations in traffic-heavy and industrial areas, indicating the significant impact of vehicular emissions and industrial activities on air quality.

Conclusion

In conclusion, the assessment of ambient air quality reveals a concerning trend, with some key criteria air pollutants, such as particulate matters ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2) far exceed both Ethiopian and WHO guidelines. And also pollutants such as carbon monoxide, and sulfur dioxide (SO_2), consistently exceeding international air quality guidelines but within the limit of the national air quality. This emphasizes the critical need for improved monitoring, stricter enforcement of air quality standards, and the implementation of comprehensive mitigation techniques to reduce pollution levels. The negative health and environmental consequences of prolonged exposure to this high pollution levels cannot be stressed. As a result, immediate action is required to protect public health and maintain long-term environmental sustainability. Addressing air quality issues is critical to creating a better, more sustainable future for everyone.

Recommendations

Based on the findings of the study, the following effective strategies are recommended to address air pollution problems in Harar City. Enhancement of public transport; improving public and active transport such as using public Buses, Cycling and also walking whenever possible can significantly reduce emissions from vehicles, which could be considered a major source of pollutants in Harar City. Industrial emission controls; these are also very important in tackling air pollution. Implementing stricter emission standards for industries and promoting cleaner production technologies can help reduce industrial emissions.

Urban planning and green Spaces; although things that are in a process regarding greeneries in the city are a good start, but they are not adequate. Enhancing urban planning to include more green spaces can help absorb pollutants and improve air quality. Public awareness and participation; this is the other most important and necessary action. Raising public awareness about the sources and effects of air pollution and encouraging community participation in air quality management can drive collective action towards cleaner air.

This study indicates the urgent need for targeted interventions to safeguard public health and align with both national and international air quality standards. To sum up, improving Harar City's air quality needs a multi-faceted approach involving policy enforcement, technological advancements, and public engagement.

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7. APPENDIX

7.1 The following table contains the Ambient Air Quality Measurement data collection sheet that were used during the data collection.

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Arategna							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in μg/m^3	Limit standard Values by Ethiopian in μg/m^3	Remark	Limit standard Values by WHO in μg/m^3	Remark
1	PM	$PM_{2.5}$	95.37	65	Above the limit	15	Above the limit
		PM_{10}	157.37	150	Above the limit	45	Above the limit
2	CO	CO	2590.96	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	203.43	200	Above the limit	25	Above the limit
4	SO_2	SO_2	0.00	125	Within the limit	40	Within the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Adisu Menaheriya							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in μg/m^3	Limit standard Values by Ethiopian in μg/m^3	Remark	Limit standard Values by WHO in μg/m^3	Remark
1	PM	$PM_{2.5}$	85.71	65	Above the limit	15	Above the limit
		PM_{10}	288.81	150	Above the limit	45	Above the limit
2	CO	CO	1906.33	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	234.29	200	Above the limit	25	Above the limit
4	SO_2	SO_2	0.00	125	Within the limit	40	Within the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Deker							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	66.51	65	Above the limit	15	Above the limit
		PM_{10}	243.01	150	Above the limit	45	Above the limit
2	CO	CO	2429.2	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	199.49	200	Within the limit	25	Above the limit
4	SO_2	SO_2	0.00	125	Within the limit	40	Within the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Budaber							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	43.84	65	Within the limit	15	Above the limit
		PM_{10}	113.95	150	Within the limit	45	Above the limit
2	CO	CO	0.00	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	177.81	200	Within the limit	25	Above the limit
4	SO_2	SO_2	0.00	125	Within the limit	40	Within the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Harar Ber							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	47.43	65	Within the limit	15	Above the limit
		PM_{10}	67.86	150	Within the limit	45	Above the limit
2	CO	CO	2692.57	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	209.13	200	Above the limit	25	Above the limit
4	SO_2	SO_2	0.00	125	Within the limit	40	Within the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Gelmeshira							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	68.14	65	Above the limit	15	Above the limit
		PM_{10}	29.71	150	Within the limit	45	Above the limit
2	CO	CO	3091.71	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	202.14	200	Above the limit	25	Above the limit
4	SO_2	SO_2	60	125	Within the limit	40	Above the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Felanaber							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	75.14	65	Above the limit	15	Above the limit
		PM_{10}	167	150	Above the limit	45	Above the limit
2	CO	CO	1817.71	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	196.04	200	Within the limit	25	Above the limit
4	SO_2	SO_2	61	125	Within the limit	40	Above the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Keladamba							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	61.86	65	Within the limit	15	Above the limit
		PM_{10}	104.14	150	Within the limit	45	Above the limit
2	CO	CO	0.00	10000	Within the limit	4	Within the limit
3	NO_2	NO_2	196.2	200	Within the limit	25	Above the limit
4	SO_2	SO_2	0.00	125	Within the limit	40	Within the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Shenkor							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	51.73	65	Within the limit	15	Above the limit
		PM_{10}	86.57	150	Within the limit	45	Above the limit
2	CO	CO	2479.29	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	217.71	200	Above the limit	25	Above the limit
4	SO_2	SO_2	0.00	125	Within the limit	40	Within the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Ajip							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	61.47	65	Within the limit	15	Above the limit
		PM_{10}	113.43	150	Within the limit	45	Above the limit
2	CO	CO	4867.34	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	207.71	200	Above the limit	25	Above the limit
4	SO_2	SO_2	117.24	125	Within the limit	40	Above the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Hiywet Fana							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	275.7	65	Above the limit	15	Above the limit
		PM_{10}	587.8	150	Above the limit	45	Above the limit
2	CO	CO	7057.06	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	210.23	200	Above the limit	25	Above the limit
4	SO_2	SO_2	126.46	125	Above the limit	40	Above the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Shewaber							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	73.46	65	Above the limit	15	Above the limit
		PM_{10}	200.71	150	Above the limit	45	Above the limit
2	CO	CO	1788.63	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	225.6	200	Above the limit	25	Above the limit
4	SO_2	SO_2	151.67	125	Above the limit	40	Above the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Harar Brewery							
Name of inspector:- Mubeshir				**Signature of inspector:-**			
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	60.57	65	Within the limit	15	Above the limit
		PM_{10}	162.33	150	Above the limit	45	Above the limit
2	CO	CO	3904.28	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	239.64	200	Above the limit	25	Above the limit
4	SO_2	SO_2	242.38	125	Above the limit	40	Above the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Hamaressa							
Name of inspector:- Mubeshir				**Signature of inspector:-**			
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	50.91	65	Within the limit	15	Above the limit
		PM_{10}	179.61	150	Above the limit	45	Above the limit
2	CO	CO	2375.14	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	234.63	200	Above the limit	25	Above the limit
4	SO_2	SO_2	0.00	125	Within the limit	40	Within the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Aroge Menaheriya							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	97.04	65	Above the limit	15	Above the limit
		PM_{10}	350.93	150	Above the limit	45	Above the limit
2	CO	CO	2315.71	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	297	200	Above the limit	25	Above the limit
4	SO_2	SO_2	0.00	125	Within the limit	40	Within the limit

Ambient Air Quality Measurement Data Collection Sheet							
Date of data collection:-							
Name of place:- Feres Megalla							
Name of inspector:- Mubeshir					**Signature of inspector:-**		
No	Pollutant sampled		Measured Values in $\mu g/m^3$	Limit standard Values by Ethiopian in $\mu g/m^3$	Remark	Limit standard Values by WHO in $\mu g/m^3$	Remark
1	PM	$PM_{2.5}$	61.46	65	Within the limit	15	Above the limit
		PM_{10}	113.06	150	Within the limit	45	Above the limit
2	CO	CO	2068.38	10000	Within the limit	4	Above the limit
3	NO_2	NO_2	212.86	200	Above the limit	25	Above the limit
4	SO_2	SO_2	0.00	125	Within the limit	40	Within the limit

Some of the pictures during data collection