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Assessment of Particulate Matter (PM) Levels in Urban Centers in Kenya: A Case Study of Meru Town, Kisumu, and Nairobi

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ABSTRACT

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Particulate matter (PM) pollution presents a major public health challenge in urban environments globally, with rapid urbanization, industrial expansion, and weak environmental regulations intensifying the problem. In Kenya, air quality concerns have become increasingly critical, necessitating a comprehensive assessment of PM pollution in major urban centers. This study examines PM concentrations in Nairobi, Kisumu, and Meru Town to evaluate air quality and associated health risks. Real-time PM data were collected across multiple locations within each city using Internet of Things (IoT)-enabled Optical Particle Counters (OPCs), which offer high temporal resolution. Analysis incorporating historical data from 2020 onward revealed persistently elevated PM levels, surpassing the air quality thresholds recommended by the World Health Organization (WHO). These findings underscore the severity of air pollution across the study sites and the urgent need for systematic monitoring and mitigation measures. A robust air quality management framework is essential to address the escalating pollution burden in urban Kenya. Strengthening environmental policies, enforcing stricter emission controls, and promoting sustainable urban planning are imperative to curb PM emissions. Targeted interventions can significantly reduce exposure, improve air quality, and protect public health, ensuring safer living conditions for urban populations.

Introduction

Air pollution has emerged as a critical public health concern in urban environments worldwide, exerting profound adverse effects on residents' well-being. A significant contributor to this issue is particulate matter (PM), a heterogeneous mixture of microscopic solid and liquid droplets suspended in the atmosphere. These particles exhibit considerable variability in size and composition, originating from diverse sources such as industrial emissions, vehicular exhaust, dust, and combustion processes. Exposure to elevated PM concentrations has been linked to a rising incidence of respiratory and cardiovascular diseases, including lung cancer, chronic obstructive pulmonary disease (COPD), asthma, and ischemic heart conditions (*Chen & Hoek*, 2020; Elbarbary et al., 2020; *Peng et al.*, 2022). The classification of PM is primarily based on particle size, with three categories—PM10,

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PM2.5, and PM1.0—drawing significant research and policy attention (Miller & Newby, 2019). PM10 encompasses particles with diameters of 10 micrometers or less, roughly equivalent to the width of a human hair. These particles, upon inhalation, can become lodged in the upper respiratory tract, causing irritation and persistent coughing. PM2.5, often referred to as fine particulate matter, comprises particles measuring 2.5 micrometers or less. Due to their smaller size, these particles can penetrate deep into the pulmonary system, enter the bloodstream, and contribute to severe respiratory disorders, cardiovascular complications, and carcinogenesis. The smallest and least studied fraction, PM1.0, consists of ultrafine particles with diameters below 1 micrometer. Their diminutive size allows them to bypass the body's natural defense mechanisms, raising significant concerns regarding their potential health impacts (Miller & Newby, 2019). To mitigate the health risks associated with PM exposure, the World Health Organization (WHO) has established stringent air quality guidelines. The recommended annual mean concentration for PM2.5 is set at 5 μg/m³, while the 24-hour mean should not exceed 15 μg/m³ ("*Recommendations on Classical Air Pollutants*," 2021). Similarly, PM10 concentrations are advised to remain below 15 μg/m³ annually and 45 μg/m³ over a 24-hour period. Although PM1.0 is increasingly recognized as a potential health hazard, its inclusion in WHO guidelines remains pending. Given its ultrafine nature and capacity to infiltrate biological systems more efficiently than larger particulates, analyzing PM1.0 alongside PM2.5 and PM10 is essential for a comprehensive assessment of air quality. The following section provides a brief review of studies examining the detrimental effects of ultrafine PM on human health.

Toxic effects of Ultra-fine PM

Ultrafine particulate matter (UFPs) has emerged as a significant focus within nanotoxicology due to its potential health hazards (*Jain et al*., 2011; Oberdörster et al., 2005). The ability of these nanoscale particles to bypass the body's natural defense mechanisms and penetrate deep into the pulmonary system raises critical concerns. Once inhaled, their minute size facilitates direct translocation into the bloodstream, allowing systemic distribution to various organs. This unique characteristic amplifies the risk of widespread physiological effects, yet the long-term consequences of such exposure remain insufficiently understood. Addressing these uncertainties necessitates extensive research to elucidate toxicity mechanisms and their broader implications for human health. Conventional toxicological assessments may not adequately capture the intricate biological interactions of UFPs, underscoring the urgency for novel investigative methodologies.

Distinct physicochemical properties of nanoscale materials further contribute to their heightened biological reactivity (*Ray et al*., 2009; Sahu & Hayes, 2017). A significantly high surface area-to-volume ratio, coupled with quantum effects, enhances their potential to induce oxidative stress, inflammatory responses, and cellular damage. These adverse effects are particularly concerning given the widespread integration of nanomaterials in sectors such as medicine, electronics, and cosmetics. The growing utilization of these materials underscores the necessity for standardized toxicity testing protocols and robust regulatory frameworks to mitigate potential health risks. Developing such guidelines requires an interdisciplinary approach, leveraging expertise from chemistry, biology, and environmental science to achieve a comprehensive understanding of nanoparticle interactions within biological systems. Inhalation of ambient particulate matter, including ultrafine particles, has also been linked to detrimental cardiovascular effects (*Donaldson et al*., 2001; *Palacio et al*., 2023; *Polichetti et al*., 2009). Systemic inflammation, oxidative stress, and direct vascular interactions represent key mechanisms through which these particles contribute to cardiovascular morbidity. The translocation of fine and ultrafine particulates from the lungs into the circulatory system enables their interaction with vascular tissues and circulating cells, thereby exacerbating the risk of conditions such as heart attacks and strokes. Strengthening air quality regulations and implementing stringent emission control measures could play a crucial role in mitigating these risks. Further research remains imperative to delineate the precise biological pathways underlying these associations and to develop targeted public health interventions. Beyond immediate physiological effects, chronic exposure to UFPs presents additional long-term health concerns, particularly for vulnerable populations such as children, the elderly, and individuals with pre-existing conditions. The cumulative impact of sustained nanoparticle exposure necessitates ongoing epidemiological surveillance to track potential health outcomes over extended periods. Additionally, the propensity of UFPs to serve as carriers for toxic substances, including heavy metals and organic pollutants, raises further concerns regarding their environmental and human health implications. Addressing these challenges demands a multifaceted strategy, integrating advances in nanotechnology, toxicology, environmental science, and public health policy to safeguard both individual and ecological well-being.

A Review of Reported PM studies in Kenya

A growing body of research has examined particulate matter (PM) pollution in Kenya, highlighting its significant impact on air quality and public health. A comprehensive study on air pollution in Nairobi (*Kinney et al.*, 2011) revealed that PM2.5 concentrations frequently exceeded the World Health Organization (WHO) guidelines, particularly in densely populated and high-traffic areas. The study identified vehicular emissions as a dominant source of PM pollution, alongside industrial activities and domestic biomass burning. Similar findings were reported in an analysis of PM10 levels in Nairobi (Meltus & Karanja, 2024), which emphasized the substantial contribution of road dust and vehicle emissions. This study further established a seasonal variation, with PM10 concentrations peaking during the dry season due to increased dust resuspension and reduced atmospheric cleansing by rainfall.

Beyond Nairobi, research in Mombasa has demonstrated the influence of industrial activities on air quality. A study on PM2.5 exposure among residents near industrial zones (*Westervelt et al.*, 2021) found that PM2.5 levels were significantly higher in these areas compared to residential zones. The findings attributed the elevated pollution levels to emissions from factories and industrial operations, reinforcing the need for stringent regulatory measures to control industrial emissions. In addition to environmental concerns, the health impacts of PM exposure have been widely investigated. A study on PM2.5 exposure among children in Nairobi (*Oguge et al.*, 2024) established a strong correlation between high PM2.5 levels and an increased incidence of respiratory diseases, such as asthma and bronchitis. These findings underscored the vulnerability of children to air pollution and emphasized the necessity for targeted public health interventions. Similarly, an assessment of PM10 exposure and cardiovascular health risks in urban Kenya (*Pope et al.*, 2018) identified a significant association between elevated PM10 levels and increased cases of hypertension and heart disease. The study advocated for enhanced air quality monitoring and public awareness campaigns to mitigate these health risks.

Efforts to manage PM pollution in Kenya have also been examined through policy analysis. A review of air quality management policies (deSouza, 2020) found that while regulatory frameworks exist, enforcement remains weak due to resource constraints and limited public awareness. The study recommended the adoption of stricter emission standards, improved air quality monitoring networks, and greater public engagement in pollution control efforts. In the context of mitigation strategies, the role of green infrastructure in air quality improvement has been explored. An investigation into the impact of urban greenery on PM reduction (Mwangi, 2019) demonstrated that tree-lined streets and parks significantly lower PM concentrations by acting as natural air filters. The study advocated for the integration of green infrastructure into urban planning as a cost-effective solution to improve air quality.

The literature on PM pollution in Kenya presents a clear pattern of recurring challenges, including excessive PM concentrations, inadequate regulatory enforcement, and significant health implications, particularly for vulnerable populations. Despite existing studies, gaps remain in understanding the real-time spatial and temporal variations of PM levels in different urban centers. Addressing this gap, the present study investigates PM pollution in three major urban centers—Nairobi, Kisumu, and Meru—by utilizing low-cost IoT PM particle counters with a high temporal resolution of five seconds. Data collected from multiple locations within each city reveal that PM levels consistently exceed WHO recommended thresholds, indicating a widespread air quality crisis. The findings emphasize the urgency of implementing effective interventions to mitigate the adverse health effects associated with PM exposure.

A more detailed analysis of spatial variations within urban centers further reveals that PM concentrations are markedly higher in areas situated near industrial zones and major road networks compared to residential neighborhoods with lower traffic density.

This spatial pattern aligns with previous studies (*Kinney et al*., 2011; Omanga et al., 2014) and reinforces the need for targeted interventions in high-risk areas. Additionally, real-time monitoring has provided valuable insights into diurnal PM fluctuations, with pollution levels peaking during morning and evening rush hours. Such temporal trends offer critical information for designing effective air quality management strategies, including optimizing traffic flow and implementing temporary vehicle restrictions during peak pollution periods. Furthermore, high-resolution data facilitate the assessment of immediate pollution sources, such as construction activities and traffic congestion, allowing for rapid regulatory responses.

Findings from the present study support a multidisciplinary approach to tackling urban air pollution. Strengthening emission standards for vehicles and industries, expanding public transportation infrastructure, promoting non-motorized travel, and enhancing urban green spaces represent essential strategies for mitigating PM pollution. The evidence underscores the necessity of robust policy frameworks guided by continuous air quality monitoring. The pervasive nature of PM pollution in urban Kenya necessitates sustained intervention, and the innovative use of low-cost IoT sensors provides a comprehensive understanding of spatial and temporal pollution dynamics. These insights contribute to the formulation of evidence-based policies aimed at reducing air pollution, protecting public health, and improving overall urban environmental quality.

Materials and Methods

Data collection

PM 10, PM 2.5 and PM 1.0 sensor data from Nairobi, Kisumu and Meru were accessed using the following Unified Resource Locator (URL): https://open.africa/dataset/.

Areas of studies

Sabaki, Nairobi - In Sabaki, Nairobi, situated amidst industrial zones such as Kenbro Industrial Park and Royal Mabati Factory, and adjacent to the bustling Mombasa road, lies a dynamic nexus of economic activity. This strategic location, marked by GPS coordinates 1°25’15.6”S 36°57’10.8”E, places Sabaki at the crossroads of industrial development and urban infrastructure. With its proximity to key industrial facilities and major transportation routes, Sabaki serves as a vital node in Nairobi’s economic landscape.

Riruta Dagoretti Nairobi - This strategic location, marked by GPS coordinates 1°17 4 S 36°44 1 E, enhances the significance of Riruta, also known as Riruta Satellite, a vibrant settlement nestled within Nairobi’s Dagoretti area, approximately 9.4 kilometers west of Nairobi’s central business district. Despite the exact population remaining elusive, the density is likely high, showcasing a diverse mix of housing options ranging from established estates with apartments and family homes to informal settlements. This bustling urban center exudes energy, indicative of a community in growth. Despite its urban nature, Riruta offers a vibrant social scene and potential access to green spaces, enriching the quality of life for its residents.

Kisumu - This strategic location, marked by GPS coordinates 0°06’28.8”S 34°44’56.4”E, is situated in Kisumu Town along Lolwe Drive, adjacent to prominent landmarks such as the Rehema Communication Center and the Nyanza Provincial Headquarters. Kisumu Town, nestled on the shores of Lake Victoria in Kenya, is renowned for its cultural heritage and economic vitality. This location serves as a pivotal point for various research endeavors, offering insights into environmental dynamics, urban infrastructure and administrative influence.

Meru town - The sensors were strategically positioned across Meru Town, each offering unique insights into the environmental dynamics of the area. The first sensor was situated near the Meru-Nairobi highway, precisely at Njuri Ncheke Street, marked by GPS coordinates 0°02’49.2”N 37°39’10.8”E. The second sensor stood at the bustling Gakoromone Market, pinpointed at GPS coordinates 0°02’49.2”N 37°39’36.0”E, capturing data amidst commercial activities and urban traffic. The third sensor was positioned near the Jamia Mosque Meru and King’s Electronics, contributing to a comprehensive understanding of environmental conditions at this central location, with GPS coordinates 0°02’49.2”N 37°39’21.6”E. By deploying sensors at these diverse sites within Meru Town, researchers gain invaluable insights into variations in air quality, temperature, and urban dynamics, facilitating informed decision-making for sustainable urban development.

Data Preprocessing

•The dataset was cleaned and refined to eliminate outliers and missing data instances

•A detailed examination of monthly concentrations of PM2.5, and PM10 across the years 2020-2024, facilitating insightful comparisons.

•Advanced graphical techniques were applied to create visually intuitive representations of concentration trends, aiding in the interpretation of complex data patterns.

•The statistical analysis conducted involved robust tests to discern significant differences in concentration levels across different years. This analysis was performed both on a monthly and annual basis.

Results and Discussion

Annual Mean PM2.5 and PM10 Concentrations Based on Temperature and Humidity in Nairobi, Sabaki

The analysis of annual mean PM2.5 and PM10 concentrations in Nairobi, Sabaki, indicates a significant variation in particulate matter levels, influenced by temperature and humidity. The results, depicted in Figure 1, show clear patterns in PM2.5 and PM10 concentrations over the year, with noticeable peaks and troughs aligning with changes in climatic conditions.

Figure 1. Annual Mean PM2.5 and PM10 Concentrations Based on Temperature and Humidity in Nairobi, Sabaki. (The analysis of annual mean PM2.5 and PM10 concentrations in Nairobi, Sabaki, indicates a significant variation in particulate matter levels, influenced by temperature and humidity. Both PM2.5 and PM10 levels frequently exceed WHO recommended limits, highlighting potential health risks).

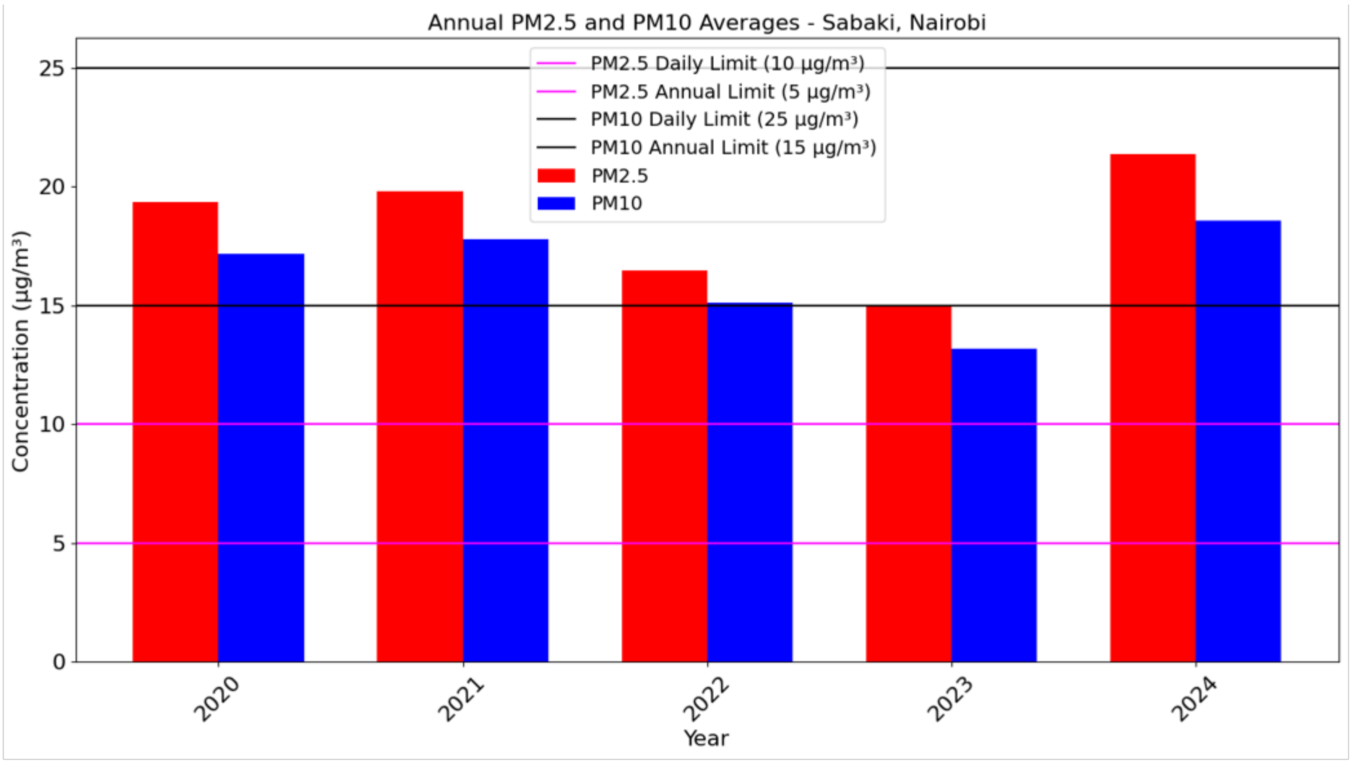
Figure 1(a) reveals substantial fluctuations in PM2.5 and PM10 concentrations in Nairobi, ranging from approximately 8.8 to 56.3 μg/m³ and 7.9 to 46.6 μg/m³, respectively. Notably, annual averages for both pollutants exceeded WHO guidelines, underscoring a significant air quality challenge with potential severe health implications for the population. These findings align with previous studies indicating elevated PM levels in urban African settings (Petkova et al., 2013). The interplay between meteorological conditions and particulate matter is evident in Figure 1(b). Temperatures varied between 10°C and 28°C, while humidity fluctuated from 45% to 75%. A clear correlation emerges between higher temperatures, especially during periods of low humidity (typically dry seasons), and increased PM2.5 and PM10 concentrations. This pattern suggests that meteorological factors, particularly temperature and humidity, significantly influence particulate matter levels in Nairobi, as observed in other studies (deSouza et al., 2017; Mutai, 2013). The consistent exceedance of WHO air quality standards for both PM2.5 and PM10 highlights a critical public health concern. Prolonged exposure to such elevated levels is associated with a range of adverse health effects, including respiratory and cardiovascular diseases ("Recommendations on Classical Air Pollutants," 2021). Given the substantial impact of meteorological factors on air quality, targeted interventions addressing both emissions reduction and climate change adaptation are essential to mitigate health risks in Nairobi.

Monthly Mean PM2.5 and PM10 Concentrations in Nairobi, Sabaki

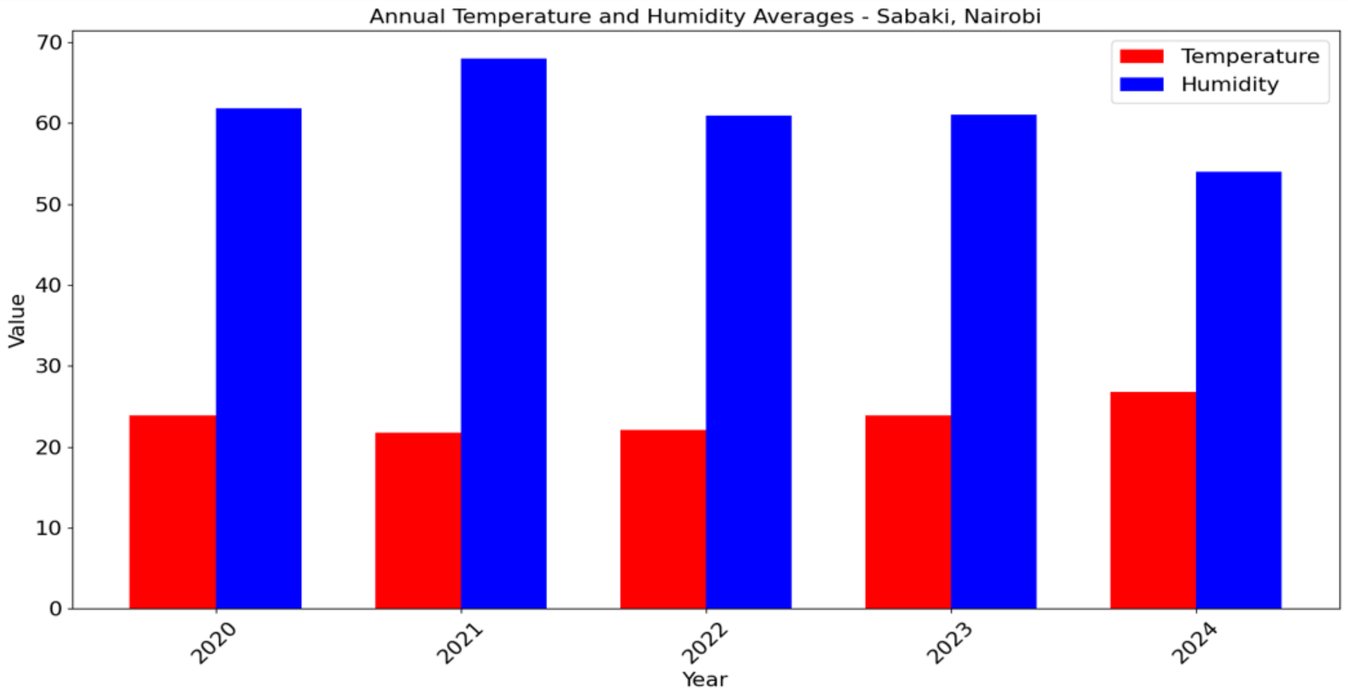
The monthly mean PM2.5 and PM10 concentrations in Nairobi, Sabaki, have been analyzed to understand the influence of temperature and humidity on these particulate matter levels. As depicted in **Figure 2**, the results show distinct monthly variations in PM concentrations, reflecting the impact of seasonal changes and environmental conditions.

Figure 2. Monthly Mean PM2.5 and PM10 Concentrations Based on Temperature and Humidity in Nairobi, Sabaki. (The results illustrates the variations in PM2.5 and PM10 levels throughout the year, influenced by changes in temperature and humidity. The data highlight significant peaks in particulate matter concentrations during warmer and drier months, emphasizing the impact of climatic conditions on air quality).

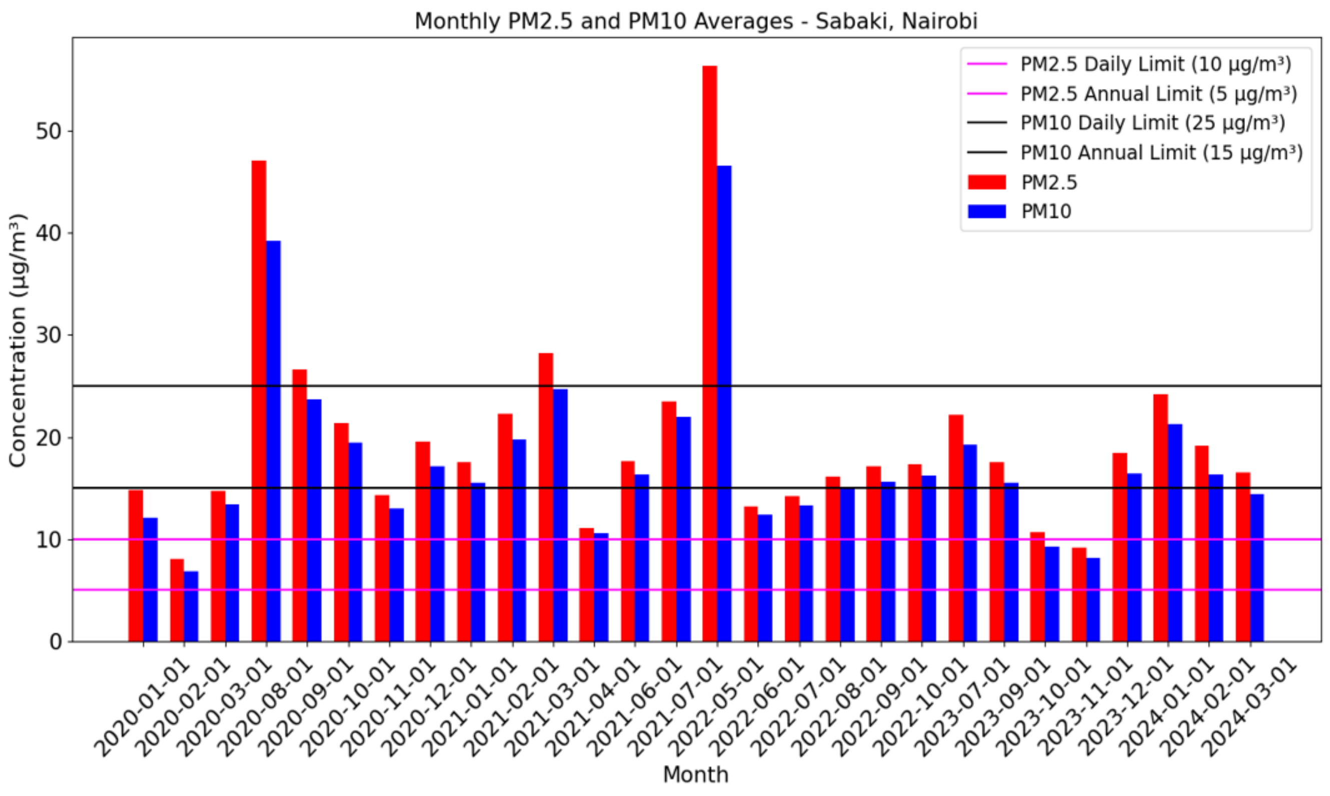
Figure 2(a) presents a clear seasonal pattern in PM2.5 and PM10 concentrations in Nairobi-Sabaki. Peak levels occurred in August 2020, with PM2.5 reaching 47.04 μg/m³ and PM10 at 39.21 μg/m³, significantly exceeding the WHO annual limit of 10 μg/m³ for PM2.5. Conversely, February 2020 exhibited the lowest concentrations. These findings align with previous studies demonstrating seasonal variations in PM levels in urban African environments (Mutai, 2013; *Petkova et al.*, 2013). **Figure 2(b)** reveals a strong correlation between temperature, humidity, and PM concentrations. Higher temperatures and lower humidity, typically associated with the dry season, correspond to elevated PM levels, suggesting


Annual PM2.5 and PM10 Averages - Sabaki, Nairobi
PM2.5 Daily Limit (10 µg/m³)
PM2.5 Annual Limit (5 µg/m³)
PM10 Daily Limit (25 µg/m³)
PM10 Annual Limit (15 µg/m³)
PM2.5
PM10
Concentration (µg/m³)
Year
2020
2021
2022
2023
2024

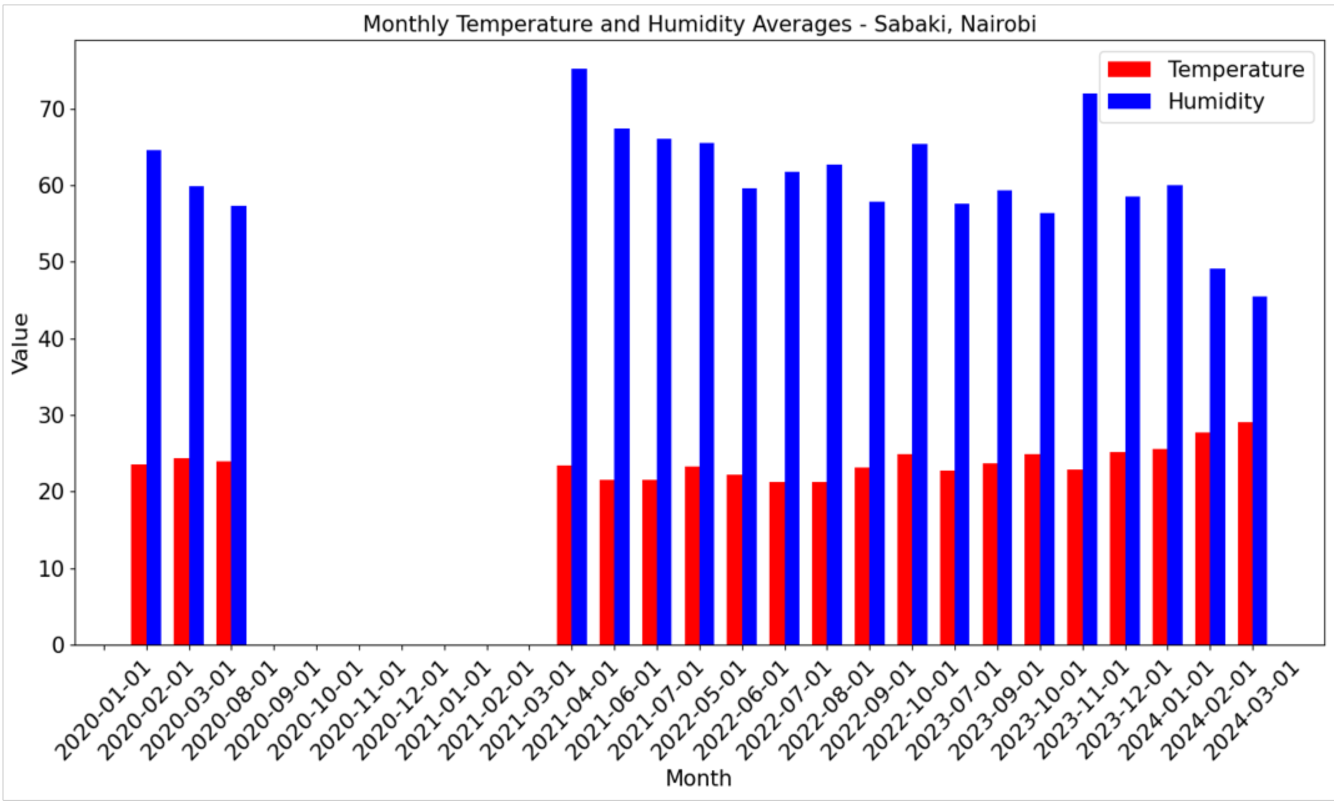
(a)


Annual Temperature and Humidity Averages - Sabaki, Nairobi
Temperature
Humidity
Value
Year
2020
2021
2022
2023
2024

(b)


Monthly PM2.5 and PM10 Averages - Sabaki, Nairobi
PM2.5 Daily Limit (10 µg/m³)
PM2.5 Annual Limit (5 µg/m³)
PM10 Daily Limit (25 µg/m³)
PM10 Annual Limit (15 µg/m³)
PM2.5
PM10
Concentration (µg/m³)
0
10
20
30
40
50
2020-01-01
2020-02-01
2020-03-01
2020-08-01
2020-09-01
2020-10-01
2020-11-01
2020-12-01
2021-01-01
2021-02-01
2021-03-01
2021-04-01
2021-06-01
2021-07-01
2022-05-01
2022-06-01
2022-07-01
2022-08-01
2022-09-01
2022-10-01
2023-07-01
2023-09-01
2023-10-01
2023-11-01
2023-12-01
2024-01-01
2024-02-01
2024-03-01
Month

(a)


Monthly Temperature and Humidity Averages - Sabaki, Nairobi
Temperature
Humidity
Value
0
10
20
30
40
50
60
70
2020-01-01
2020-02-01
2020-03-01
2020-08-01
2020-09-01
2020-10-01
2020-11-01
2020-12-01
2021-01-01
2021-02-01
2021-03-01
2021-04-01
2021-06-01
2021-07-01
2022-05-01
2022-06-01
2022-07-01
2022-08-01
2022-09-01
2022-10-01
2023-07-01
2023-09-01
2023-10-01
2023-11-01
2023-12-01
2024-01-01
2024-02-01
2024-03-01
Month

(b)

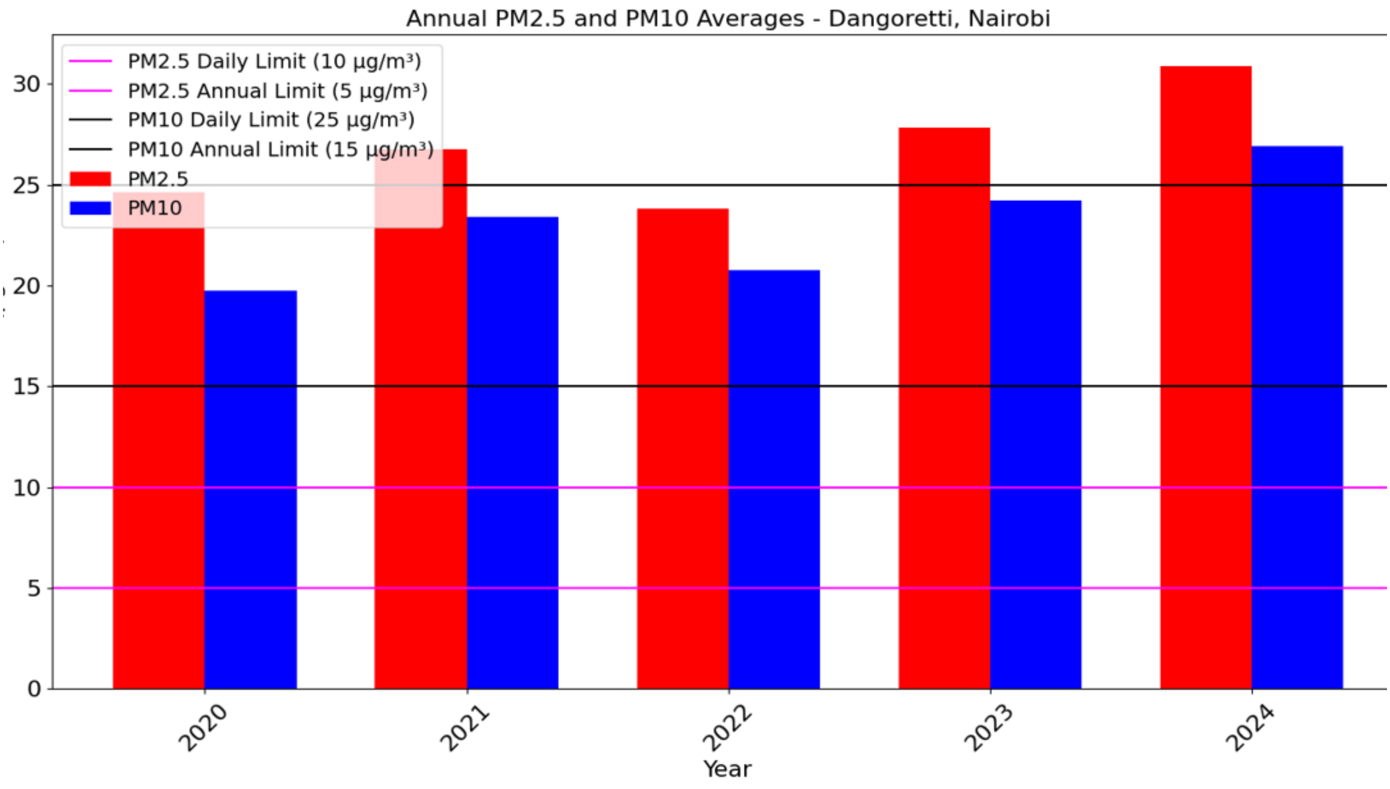
increased resuspension of particles and potentially higher emissions. This relationship is consistent with findings from other studies in similar climatic regions (*Hernandez et al.*, 2017; Oji & Adamu, 2020). The data indicate that several months experienced PM2.5 concentrations exceeding the WHO annual limit, with August 2020 displaying a particularly alarming level. These exceedances underscore the significant public health risk posed by air pollution in the region. While the analysis suggests a strong correlation between meteorological factors and PM levels, it is essential to consider other factors such as emission sources and land use changes to fully understand the complex dynamics of air pollution in Nairobi-Sabaki. To effectively address the air quality challenges, continuous monitoring of PM concentrations and meteorological parameters is crucial. Furthermore, implementing targeted interventions during peak pollution periods, such as public awareness campaigns, traffic management, and emission controls, can help mitigate health risks. Long-term strategies focusing on sustainable urban development, transportation planning, and clean energy adoption are essential for achieving sustained improvements in air quality.

Annual Mean PM2.5 and PM10 Concentrations Based on Temperature and Humidity in Riruta Dagoretti Nairobi

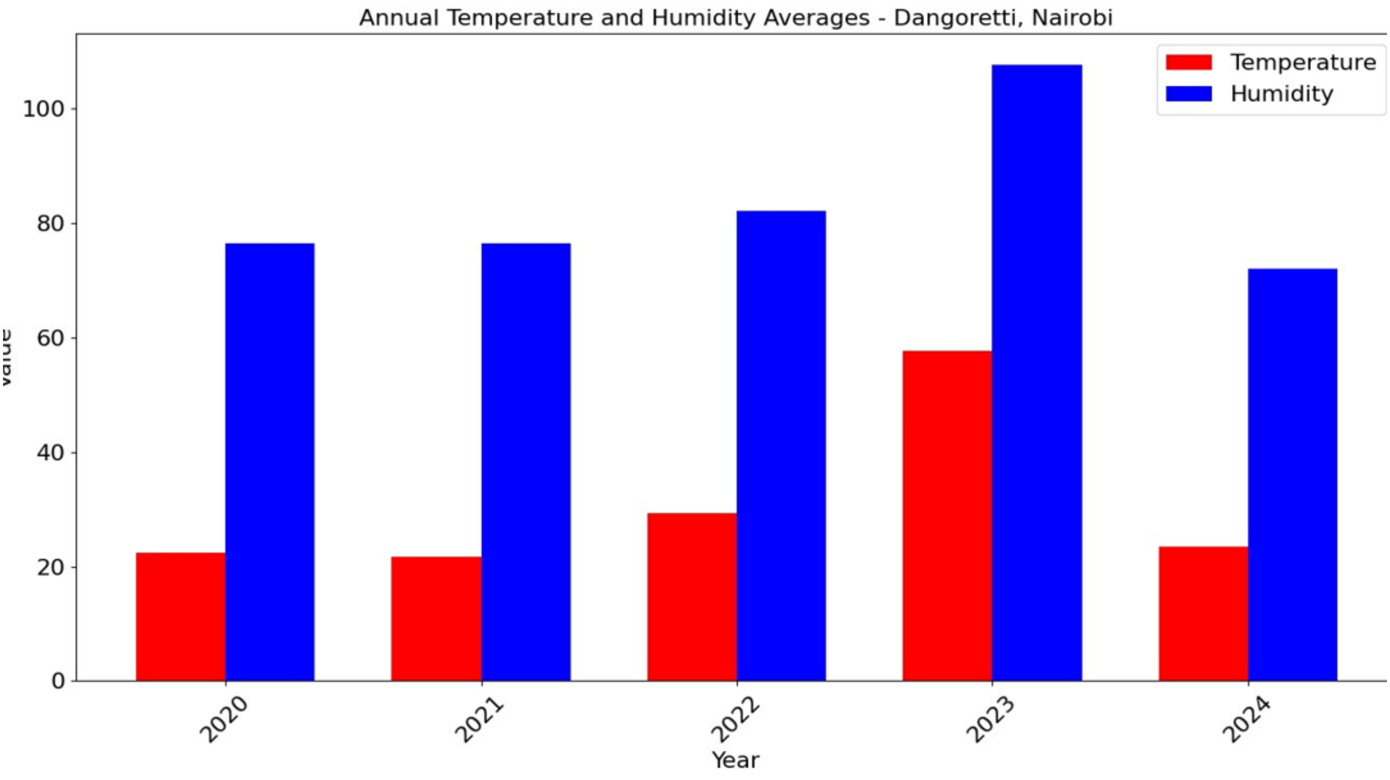
The analysis of annual mean PM2.5 and PM10 concentrations for Riruta Dagoretti, Nairobi, reveals significant insights into air quality trends and their relationship with temperature and humidity. As illustrated in Figure 3, the annual mean concentrations of PM2.5 and PM10 for the year 2020 indicate substantial variations.

Figure 3. Annual Mean PM2.5 and PM10 Concentrations Based on Temperature and Humidity in Riruta Dagoretti, Nairobi. (The results highlights the significant variation in particulate matter concentrations throughout the year 2020, influenced by temperature and humidity. The analysis shows PM2.5 levels averaging around 27.4 μg/m³ and PM10 levels at approximately 36.9 μg/m³, both exceeding WHO annual air quality guidelines. The relationship between particulate matter and meteorological conditions underscores the impact of higher temperatures and humidity on air quality).

Figure 3(a) reveals persistent and concerning levels of PM2.5 and PM10 in Riruta Dagoretti, with average concentrations of 27.4 μg/m³ and 36.9 μg/m³, respectively. These values consistently surpass the stringent WHO annual air quality guidelines of 10 μg/m³ for PM2.5 and 20 μg/m³, indicating a substantial public health risk. Figure 3(b) provides a meteorological context, showing mean annual temperature and humidity values of 22.0°C and 76%, respectively. These climatic conditions play a crucial role in influencing particulate matter levels. Previous research has established that higher temperatures can accelerate particle formation and reduce dispersion, while increased humidity can trap pollutants, leading to elevated concentrations (Hernandez et al., 2017). A detailed analysis of monthly data reveals a complex interplay between PM levels and meteorological factors. Periods of higher temperature and humidity coincide with increased PM2.5 and PM10 concentrations, emphasizing the synergistic effect of these variables on air quality. The hygroscopic nature of PM2.5, particularly during high humidity periods, contributes to its growth and detectability, exacerbating the pollution problem. The consistent exceedance of WHO air quality standards across multiple years underscores the severity of the air pollution issue in Riruta Dagoretti. The data from 2020 to 2024 highlights the persistent challenge of managing air quality in the face of fluctuating meteorological conditions. The spatial variability in PM concentrations across different sensor locations in 2022 emphasizes the need for a localized approach to air quality management. Identifying hotspots of pollution and understanding the underlying factors contributing to these variations are crucial for developing effective mitigation strategies. The long-term monitoring data provide a valuable foundation for assessing the effectiveness of air quality interventions. While the data indicate persistent challenges, it is essential to track trends over time to evaluate the impact of mitigation measures and identify emerging issues. The sustained exceedance of WHO air quality standards for PM2.5 and PM10 in Riruta Dagoretti, coupled with the influence of meteorological factors, underscores the urgent need for comprehensive air quality management strategies. These strategies should focus on reducing emissions, improving air dispersion, and protecting public health. Continued monitoring and research are essential to inform effective decision-making and to ensure the well-being of the community.


Annual PM2.5 and PM10 Averages - Dangoretti, Nairobi
PM2.5 Daily Limit (10 µg/m³)
PM2.5 Annual Limit (5 µg/m³)
PM10 Daily Limit (25 µg/m³)
PM10 Annual Limit (15 µg/m³)
PM2.5
PM10
0
5
10
15
20
25
30
2020
2021
2022
2023
2024
Year

(a)


Annual Temperature and Humidity Averages - Dangoretti, Nairobi
Temperature
Humidity
0
20
40
60
80
100
2020
2021
2022
2023
2024
Year

(b)

Seasonal Analysis of PM2.5 and PM10 Concentrations in Riruta Dagoretti, Nairobi

The analysis of monthly mean PM2.5 and PM10 concentrations in relation to temperature and humidity for Riruta Dagoretti, Nairobi, reveals significant insights into the impact of these weather variables on air quality. The results, depicted in Figure 4, show a clear variation in PM2.5 and PM10 levels across different months, reflecting the influence of seasonal changes and local environmental factors.

Figure 4. Monthly Mean PM2.5 and PM10 Concentrations and Weather Variations in Riruta Dagoretti, Nairobi. (The results illustrates the relationship between particulate matter levels and climatic factors such as temperature and humidity over the months. High humidity and moderate temperatures often correlate with elevated PM2.5 and PM10 concentrations, emphasizing the significant impact of weather conditions on air quality).

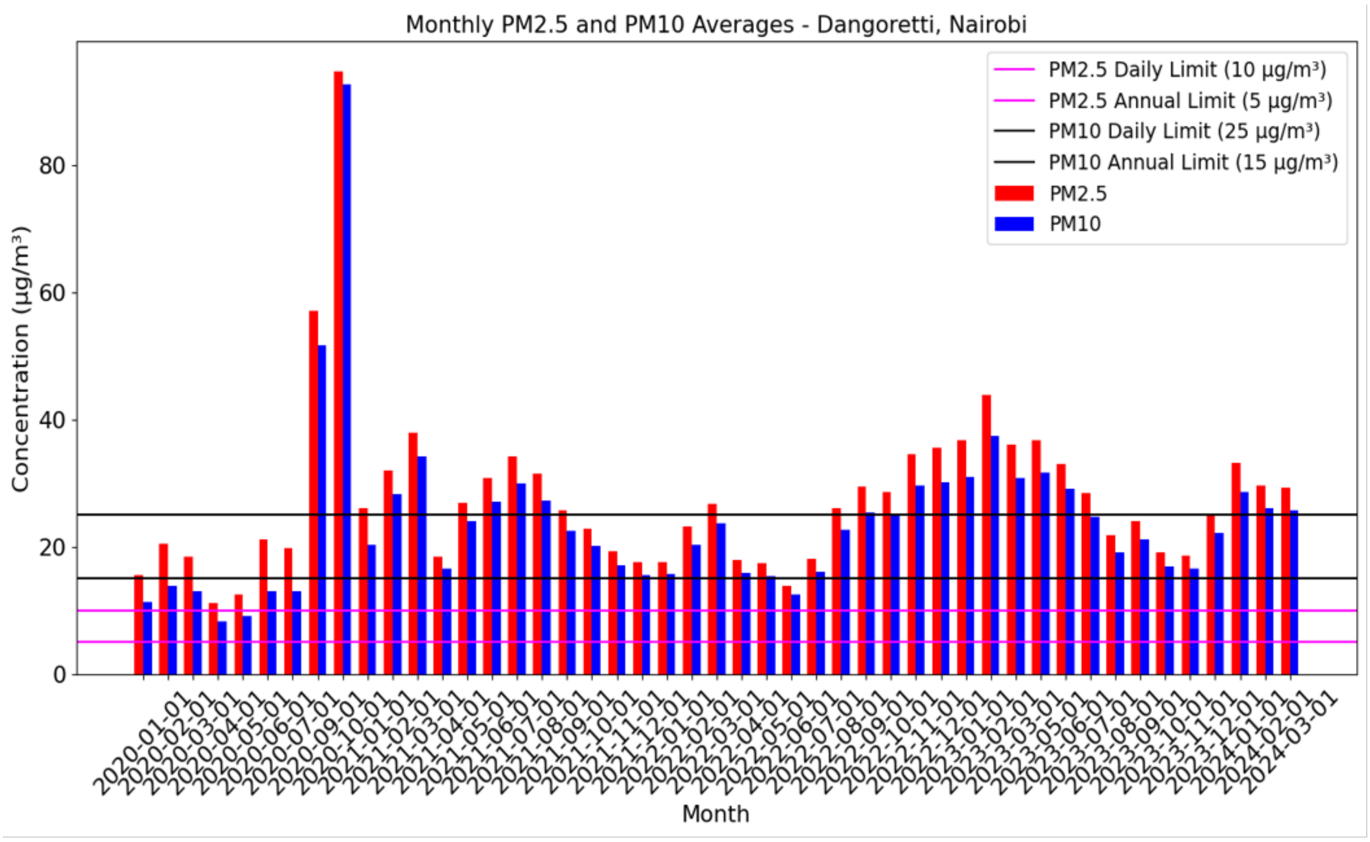
Figure 4(a) reveals pronounced seasonal fluctuations in PM2.5 and PM10 concentrations in Nairobi, with consistent exceedances of WHO annual mean limits. Peak concentrations occurred in January, February, and March 2020, and March 2021, suggesting a complex interplay of factors influencing particulate matter accumulation. These periods coincide with the region's dry season, characterized by reduced precipitation and potentially increased resuspension of dust and other particles (Mutai, 2013). The influence of meteorological conditions on PM levels is further evident in Figure 4(b). High humidity, particularly during January, February, and March, correlates with elevated PM concentrations. This suggests that hygroscopic growth of particles, facilitated by humid conditions, contributes significantly to the observed PM levels (*Amnuaylojaroen et al*., 2023; Vaishali et al., 2023). Conversely, lower humidity and higher temperatures, as observed in September, tend to disperse pollutants more effectively, resulting in lower PM concentrations. These findings align with previous studies highlighting the role of meteorological factors in modulating air quality (Vaishali et al., 2023). While the data indicate a clear correlation between humidity and PM levels, it is important to note that other factors, such as emission sources and atmospheric stability, also influence particulate matter concentrations. For instance, the significant increase in PM levels during May 2022 might be attributed to a combination of meteorological conditions and increased anthropogenic activities. The persistent exceedance of WHO air quality guidelines for PM2.5 and PM10 underscores the critical public health implications of air pollution in Nairobi. Chronic exposure to high levels of particulate matter is associated with a range of adverse health effects, including respiratory and cardiovascular diseases (*Wan Mahiyuddin et al*., 2023). To mitigate these risks, comprehensive air quality management strategies are essential, focusing on both emission reduction and adaptation to meteorological conditions.

Annual Analysis of PM2.5 and PM10 Concentrations in Kisumu

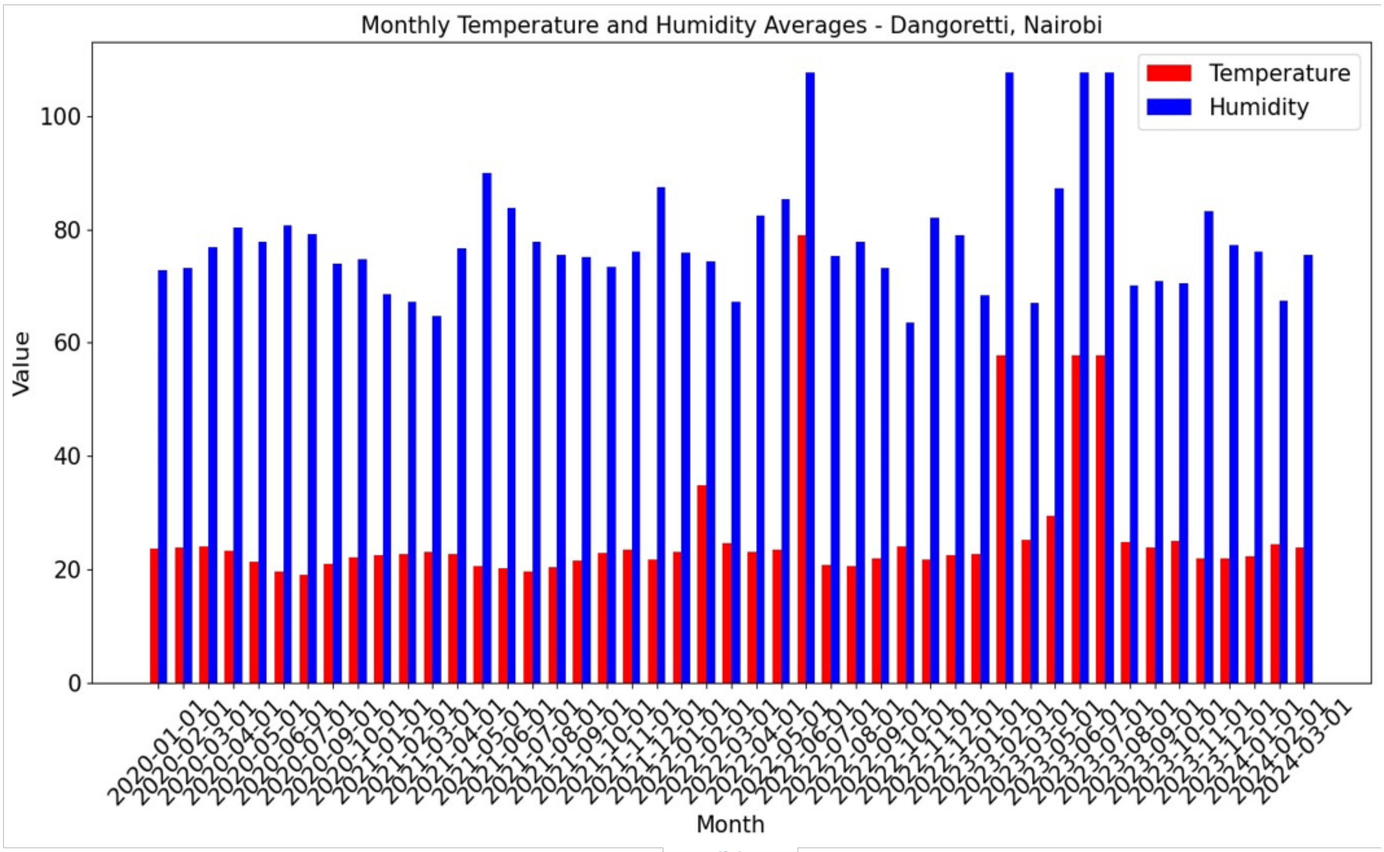
The analysis of annual mean PM2.5 and PM10 concentrations for Kisumu, as depicted in Figure 11, reveals several critical insights into air quality trends over the analyzed period. The data illustrate that both PM2.5 and PM10 levels fluctuate significantly throughout the year. Notably, PM2.5 concentrations exhibit higher values compared to PM10, which aligns with the general observation that finer particulate matter often shows more pronounced variations and can be more pervasive. The annual mean values for PM2.5 and PM10 are crucial for understanding the overall air quality, particularly in relation to established health guidelines.

Figure 5. Annual Mean PM2.5 and PM10 Concentrations in Kisumu. (The results depicts the significant fluctuation of particulate matter levels throughout the year, with PM2.5 concentrations generally higher than PM10. Both PM2.5 and PM10 levels frequently exceed the WHO recommended limits, indicating persistent air quality issues in the region).

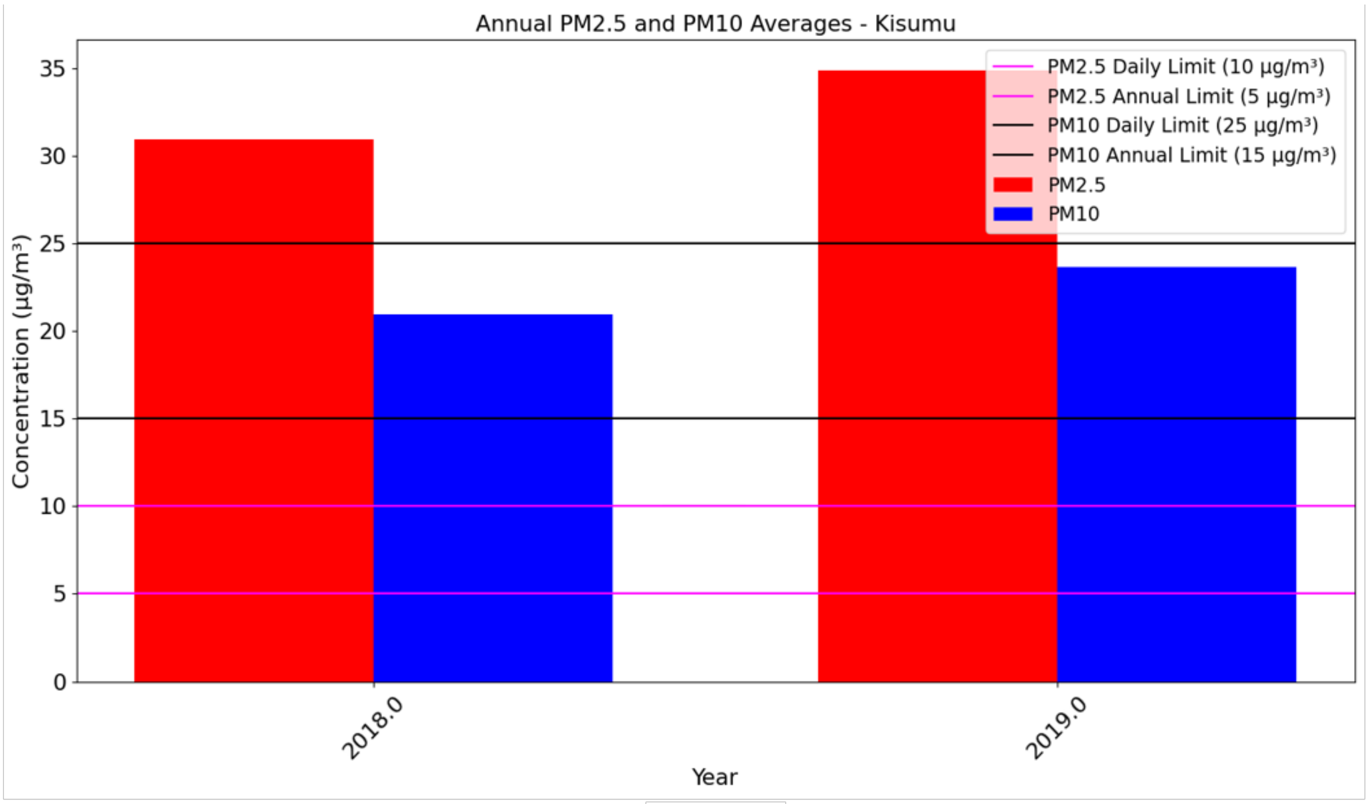
Figure 5(a) reveals a concerning pattern of persistent air quality violations in Kisumu. Annual average PM2.5 concentrations ranged from a substantial 23.36 μg/m³ to a critically high 65.67 μg/m³, consistently surpassing the WHO annual limit of 5 μg/m³. Similarly, PM10 levels, ranging from 17.29 μg/m³ to 69.95 μg/m³, also exceeded the WHO annual limit of 15 μg/m³. These findings align with previous research indicating widespread air quality issues in urban African cities (Petkova et al., 2013). The interplay between meteorological conditions and particulate matter is evident in Figure 5(b). Temperature and humidity exhibit complex relationships with PM2.5 and PM10 concentrations. While high-


Monthly PM2.5 and PM10 Averages - Dangoretti, Nairobi
PM2.5 Daily Limit (10 µg/m³)
PM2.5 Annual Limit (5 µg/m³)
PM10 Daily Limit (25 µg/m³)
PM10 Annual Limit (15 µg/m³)
PM2.5
PM10
Concentration (µg/m³)
Month

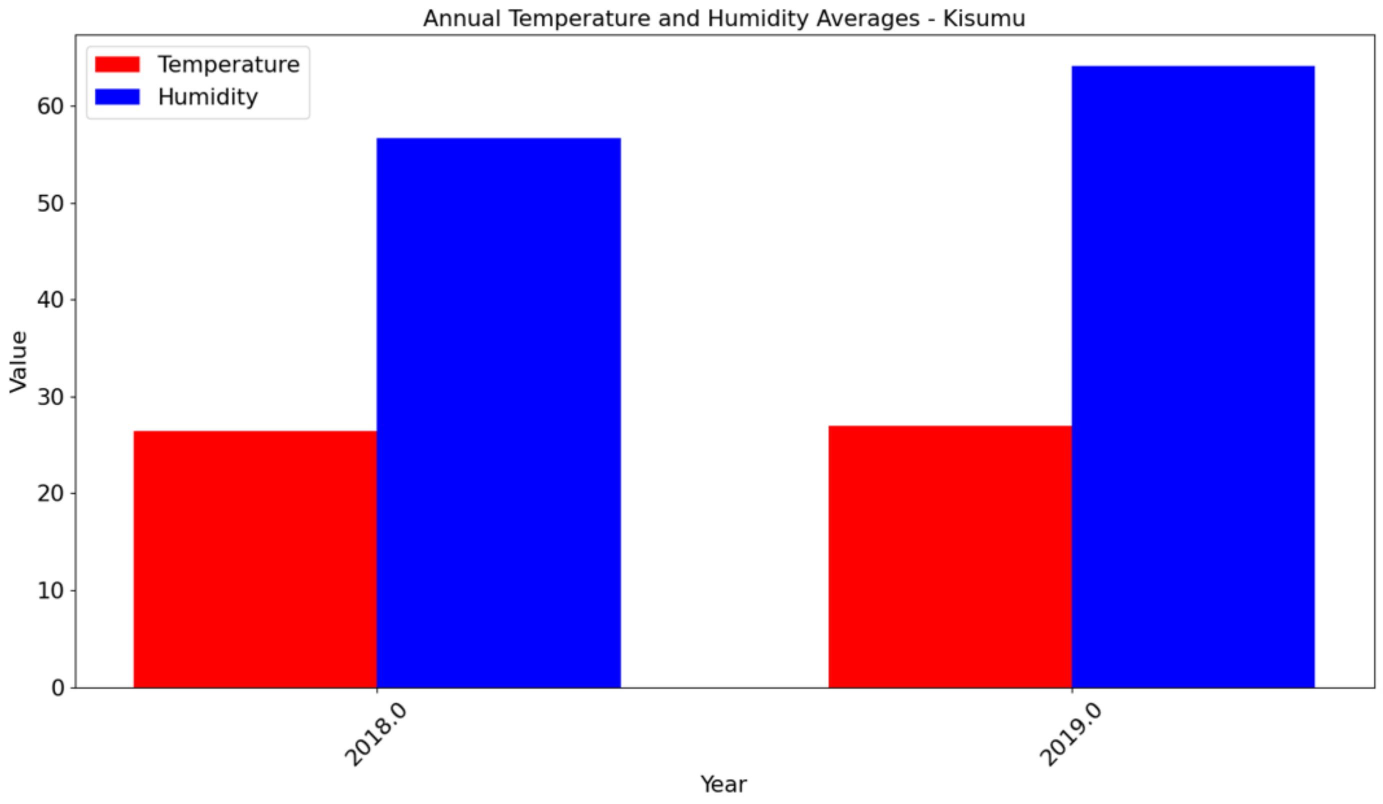
(a)


Monthly Temperature and Humidity Averages - Dangoretti, Nairobi
Temperature
Humidity
Value
Month

(b)


Annual PM2.5 and PM10 Averages - Kisumu
PM2.5 Daily Limit (10 µg/m³)
PM2.5 Annual Limit (5 µg/m³)
PM10 Daily Limit (25 µg/m³)
PM10 Annual Limit (15 µg/m³)
PM2.5
PM10
Concentration (µg/m³)
0
5
10
15
20
25
30
35
2018.0
2019.0
Year

(a)


Annual Temperature and Humidity Averages - Kisumu
Temperature
Humidity
Value
0
10
20
30
40
50
60
2018.0
2019.0
Year

(b)

er temperatures generally correlate with increased PM2.5 levels, likely due to enhanced photochemical reactions and increased emissions, the influence of humidity is more nuanced. High humidity can contribute to particle formation and growth, particularly in combination with elevated temperatures (Liyuan et al., 2017; Vaishali et al., 2023). However, under certain conditions, increased humidity might also lead to particle removal through precipitation. The combined analysis of Figures 5(a) and 5(b) underscores the significant impact of climatic factors on Kisumu's air quality. The occurrence of peak PM concentrations often coincides with specific meteorological conditions, highlighting the need to consider both emission sources and atmospheric processes when developing air quality management strategies. These findings are consistent with previous studies emphasizing the role of meteorology in influencing particulate matter levels in urban environments (Amnuaylojaroen et al., 2023). The persistent exceedance of WHO air quality guidelines for PM2.5 and PM10 in Kisumu underscores the urgent need for comprehensive air quality management measures. Reducing emissions from both stationary and mobile sources, coupled with effective strategies to mitigate the impact of meteorological factors, is crucial to protect public health. Additionally, continuous monitoring of air quality and meteorological parameters is essential for understanding the complex interplay between these factors and for evaluating the effectiveness of implemented interventions.

Seasonal Variations in PM2.5 and PM10 Concentrations in Kisumu

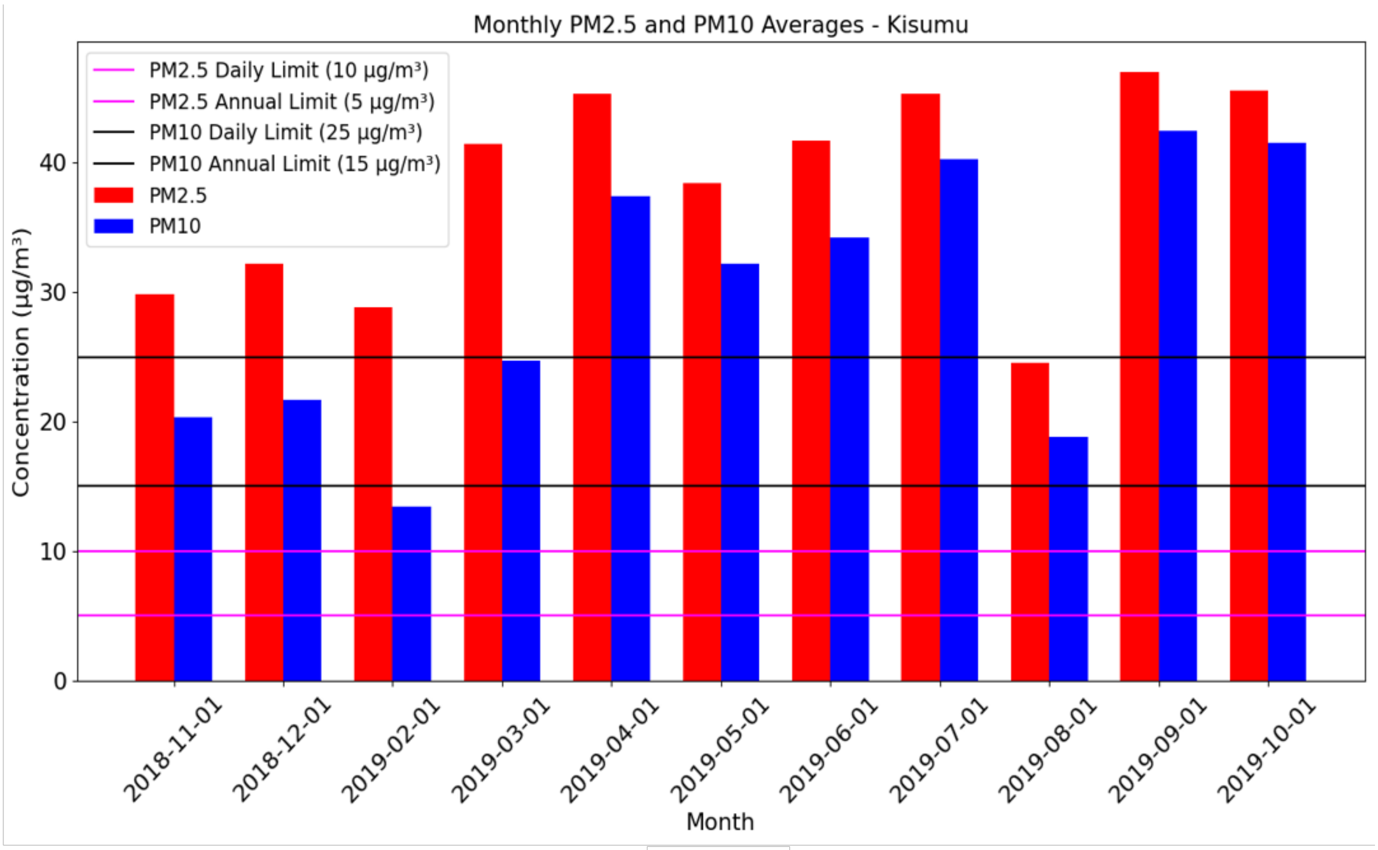
The monthly analysis of PM2.5 and PM10 concentrations in Kisumu, as illustrated in Figure 6, provides critical insights into the variations in air quality throughout the year. The results reveal notable fluctuations in particulate matter levels, with distinct peaks and troughs observed across

Figure 6. Monthly Mean PM2.5 and PM10 Concentrations in Kisumu. (The results highlights the significant fluctuations in particulate matter levels throughout the year, with notable peaks in October 2019 for both PM2.5 and PM10. These peaks, coinciding with higher temperatures, suggest a strong correlation between temperature and elevated particulate matter concentrations).

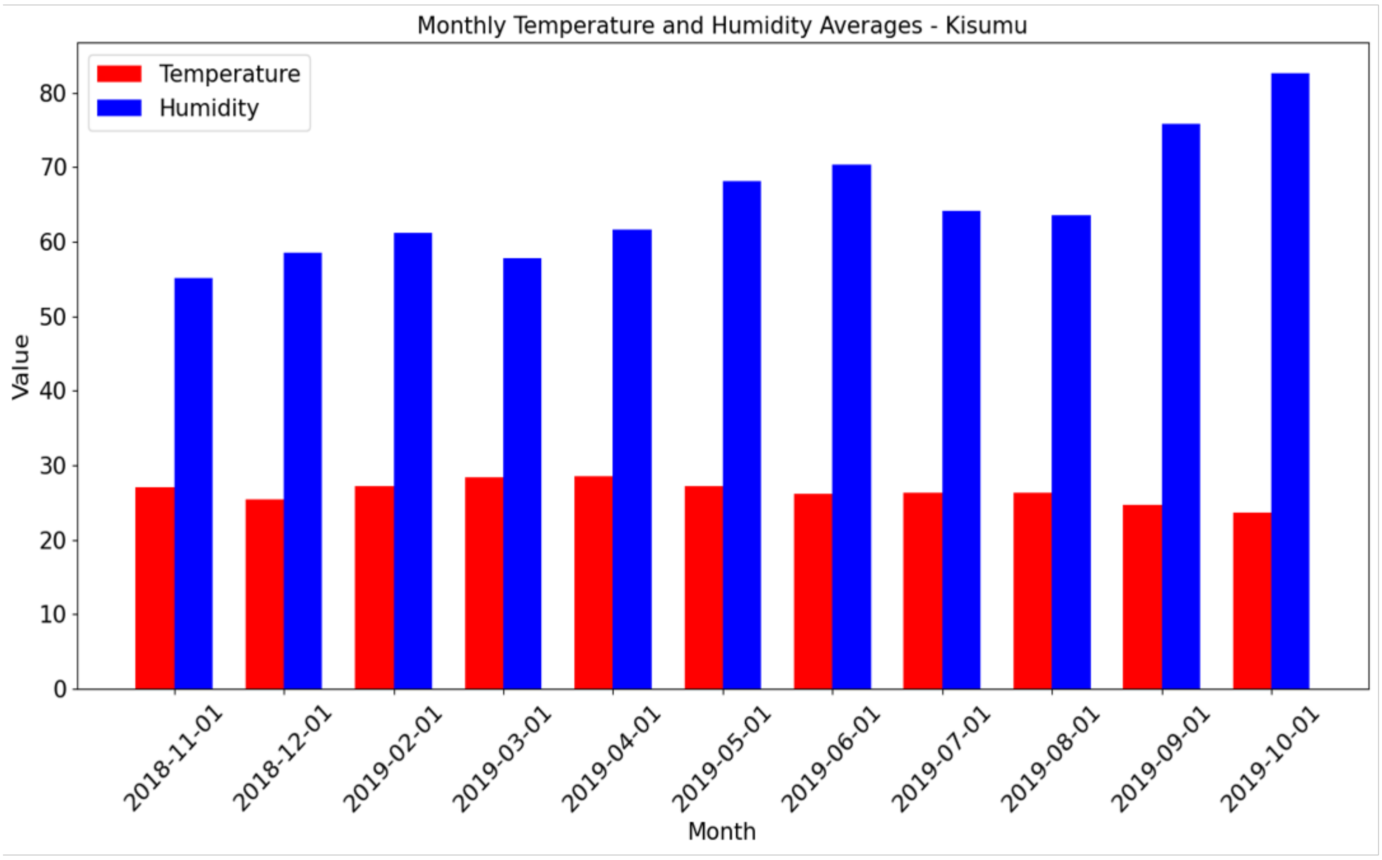
Figure 6(a) reveals a critical air quality situation in Kisumu, with PM2.5 and PM10 concentrations consistently exceeding WHO guidelines (*"Recommendations on Classical Air Pollutants,"* 2021). The peak in October 2019, where PM2.5 reached 80.31 µg/m³ and PM10 74.66 µg/m³, is particularly alarming. These elevated levels indicate a significant public health risk and align with studies reporting severe air pollution in urban African settings (*Petkova et al.*, 2013). The interplay between temperature and particulate matter is evident in **Figure 6(b**). While a clear correlation between higher temperatures and increased PM2.5 is observed, the relationship with PM10 and humidity is more complex. The peak PM2.5 concentration in October 2019 coincided with a temperature of 45.74°C, suggesting temperature as a potential driver of PM formation or resuspension. However, the lack of a consistent correlation between humidity and PM10 levels indicates the need for further investigation into the role of moisture in particulate matter dynamics.The findings underscore the complex factors influencing air quality in Kisumu. While temperature appears to be a primary driver of PM2.5 levels, other meteorological factors and anthropogenic emissions likely contribute to the overall air pollution burden. The consistent exceedance of WHO air quality standards emphasizes the urgent need for comprehensive air quality management strategies. To effectively address the issue, a combination of measures is required. This includes monitoring and modeling of air pollutants and meteorological parameters, identifying major emission sources, implementing emission control technologies, promoting public awareness, and developing sustainable urban planning strategies. By addressing these factors, Kisumu can work towards improving air quality and protecting public health.

Annual PM2.5 and PM10 Concentrations and Meteorological Influences in Meru

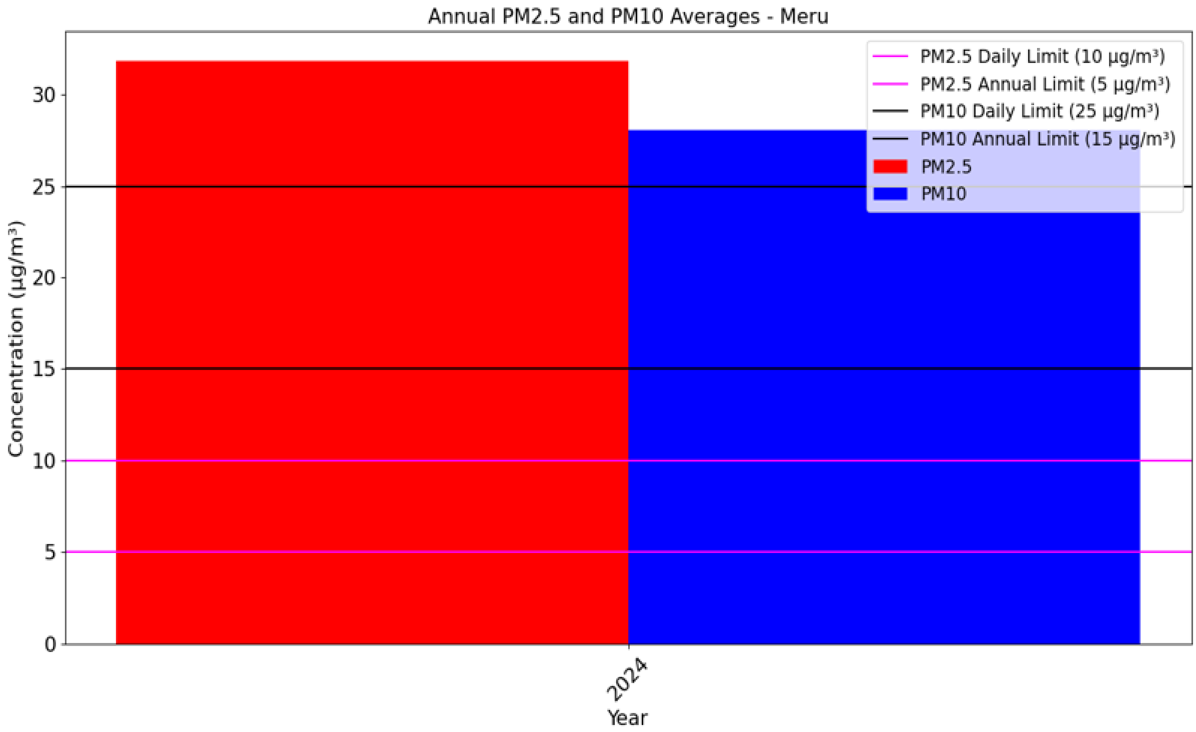
The analysis of annual mean PM2.5 and PM10 concentrations in Meru, as depicted in Figure 7, reveals significant insights into the relationship between particulate matter levels and meteorological conditions. The annual averages for PM2.5 and PM10 concentrations are crucial for understanding the long-term air quality and its implications for public health. For Meru, the annual mean concentration of PM2.5 was 26.5 µg/m³, and for PM10, it was 42.3


Monthly PM2.5 and PM10 Averages - Kisumu
PM2.5 Daily Limit (10 µg/m³)
PM2.5 Annual Limit (5 µg/m³)
PM10 Daily Limit (25 µg/m³)
PM10 Annual Limit (15 µg/m³)
PM2.5
PM10
Concentration (µg/m³)
0
10
20
30
40
2018-11-01
2018-12-01
2019-02-01
2019-03-01
2019-04-01
2019-05-01
2019-06-01
2019-07-01
2019-08-01
2019-09-01
2019-10-01
Month

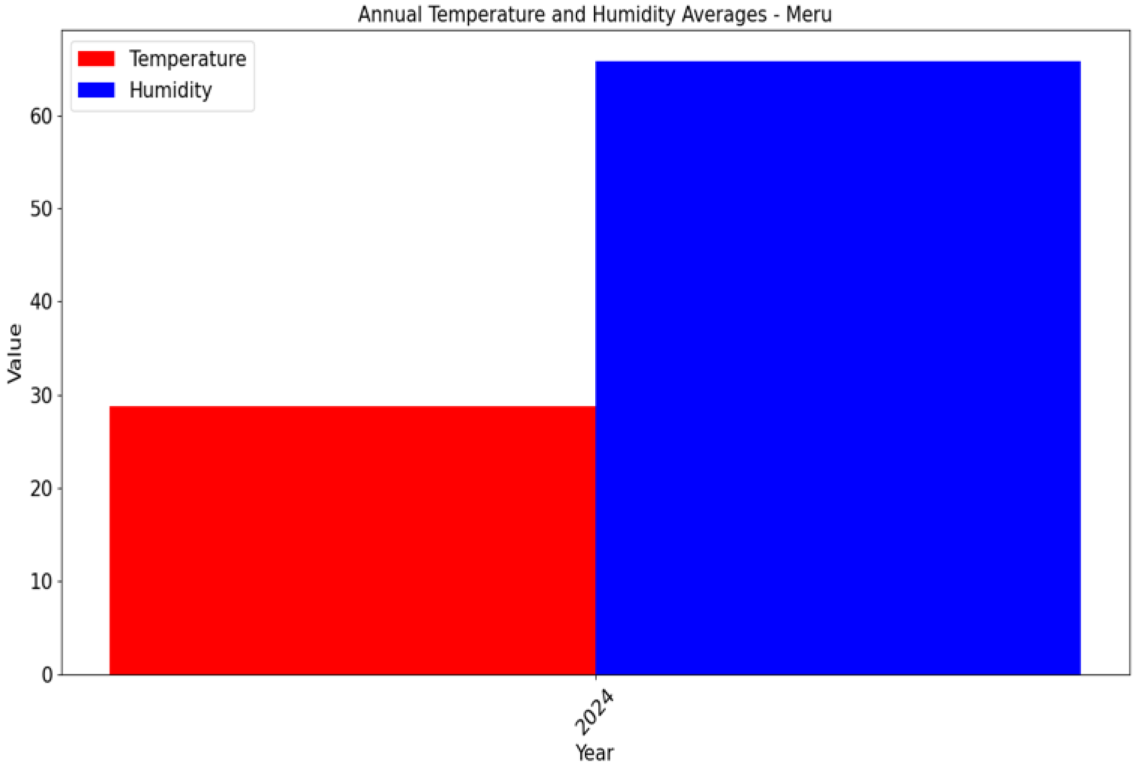
(a)


Monthly Temperature and Humidity Averages - Kisumu
Temperature
Humidity
Value
0
10
20
30
40
50
60
70
80
2018-11-01
2018-12-01
2019-02-01
2019-03-01
2019-04-01
2019-05-01
2019-06-01
2019-07-01
2019-08-01
2019-09-01
2019-10-01
Month

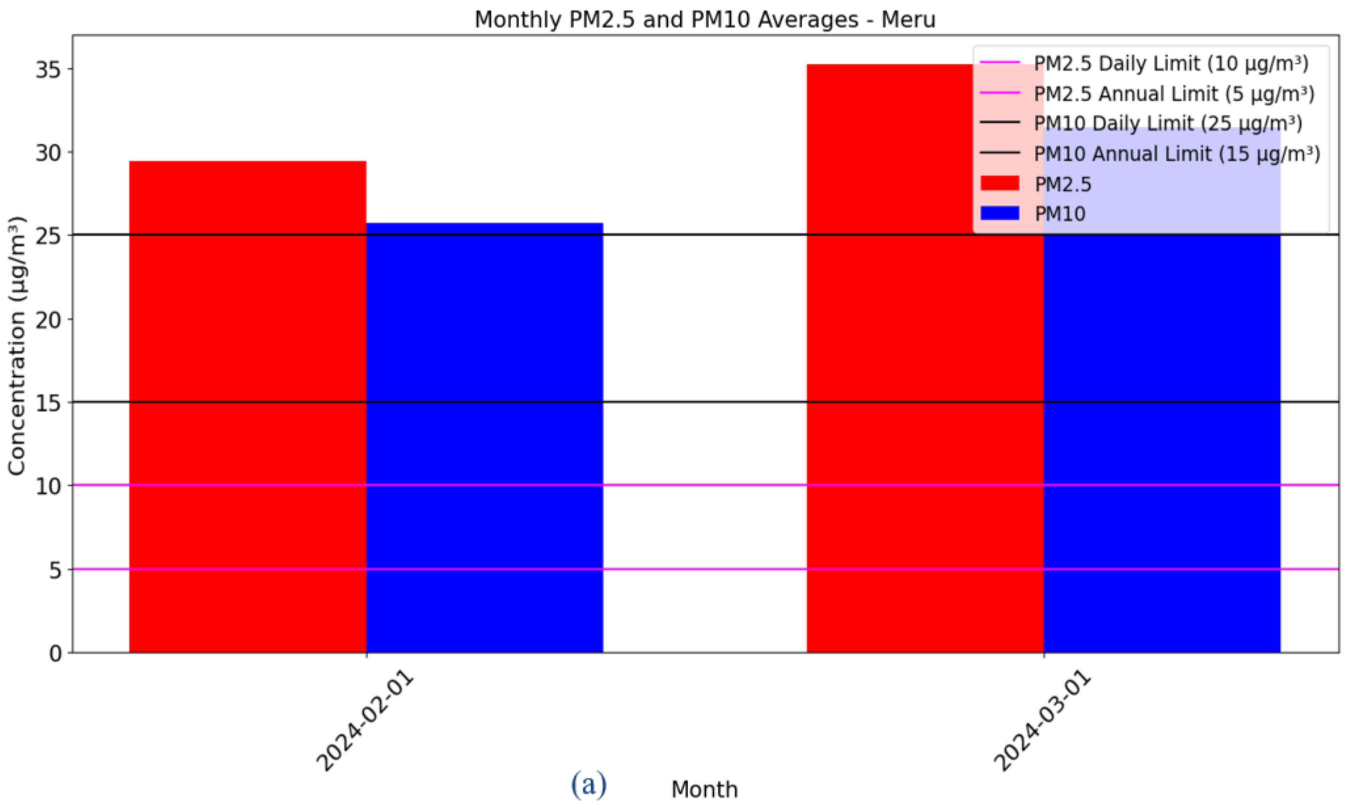
(b)


Annual PM2.5 and PM10 Averages - Meru
PM2.5 Daily Limit (10 µg/m³)
PM2.5 Annual Limit (5 µg/m³)
PM10 Daily Limit (25 µg/m³)
PM10 Annual Limit (15 µg/m³)
PM2.5
PM10
Concentration (µg/m³)
0
5
10
15
20
25
30
2024
Year

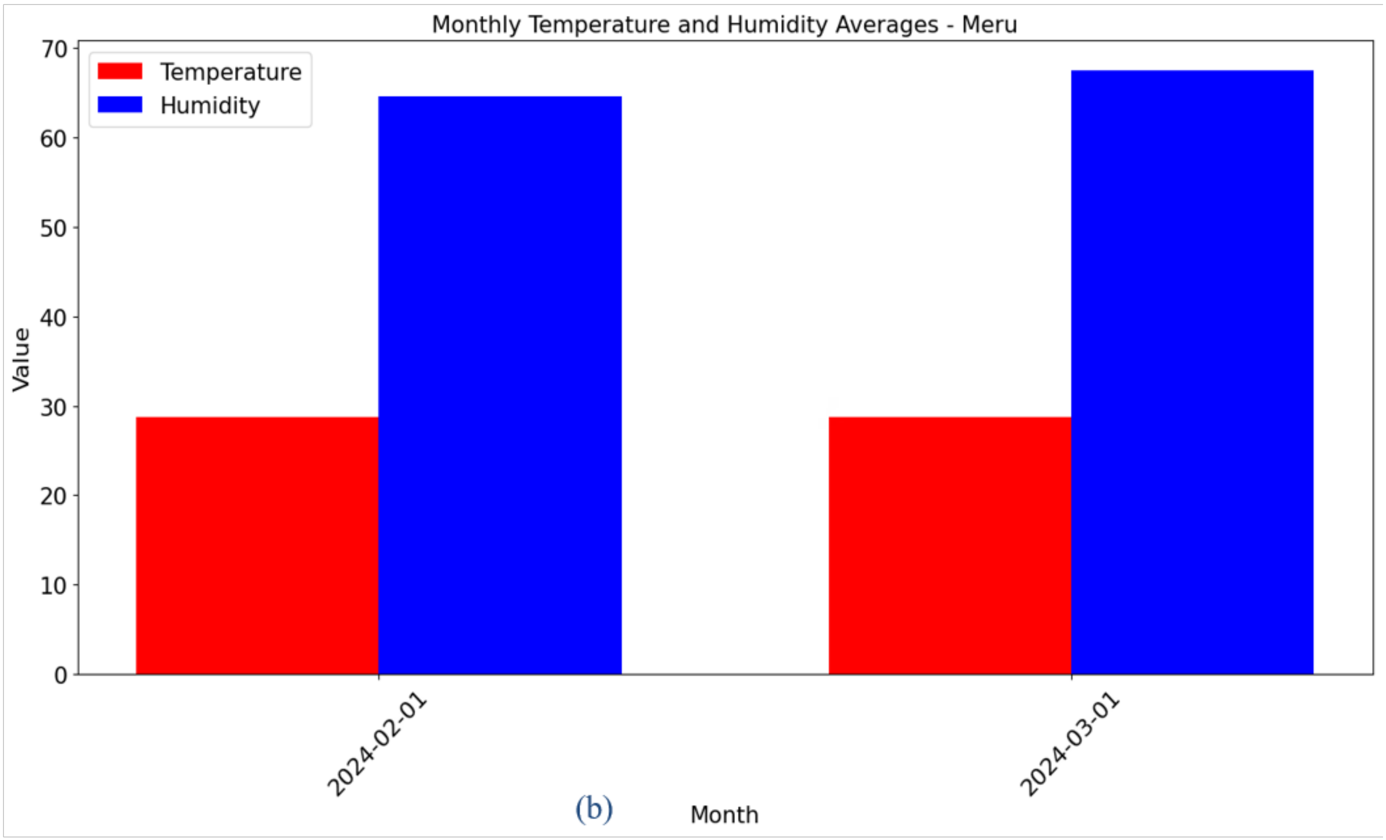
(a)


Annual Temperature and Humidity Averages - Meru
Temperature
Humidity
Value
0
10
20
30
40
50
60
2024
Year

(b)


Monthly PM2.5 and PM10 Averages - Meru
PM2.5 Daily Limit (10 µg/m³)
PM2.5 Annual Limit (5 µg/m³)
PM10 Daily Limit (25 µg/m³)
PM10 Annual Limit (15 µg/m³)
PM2.5
PM10
Concentration (µg/m³)
35
30
25
20
15
10
5
0
2024-02-01
2024-03-01
Month

(a)


Monthly Temperature and Humidity Averages - Meru
Temperature
Humidity
Value
70
60
50
40
30
20
10
0
2024-02-01
2024-03-01
Month

(b)

μg/m³. These values indicate a consistently high level of particulate pollution throughout the year.

Figure 7. Annual Mean PM2.5 and PM10 Concentrations in Meru. (The anaysis highlights the persistently high levels of particulate matter throughout the year, with annual mean concentrations of PM2.5 at 26.5 μg/m³ and PM10 at 42.3 μg/m³, both significantly exceeding WHO recommended limits. This underscores a severe air quality issue with potential adverse health impacts).

Figure 7(a) reveals a concerning trend in Meru's air quality, with annual average PM2.5 concentrations significantly exceeding the WHO's stringent annual limit of 5 μg/m³. Similarly, PM10 levels surpass the recommended annual limit of 15 μg/m³, indicating a substantial public health risk due to prolonged exposure to elevated particulate matter. These findings align with previous studies highlighting the prevalence of poor air quality in many urban and rural areas across developing countries (deSouza, 2020; *Zhang et al.*, 2022). The interplay between meteorological factors and particulate matter becomes evident in Figure 7(b). Meru's annual average temperature of 22.3°C and humidity of 66.8% provide a baseline for understanding these influences. While higher temperatures can accelerate atmospheric chemical reactions, potentially increasing particulate formation, the role of humidity is more complex. Previous research suggests that while higher humidity can enhance particle growth and removal through precipitation, it can also lead to increased hygroscopic growth of existing particles, impacting their size distribution and potential health effects (*Liyuan et al.*, 2017). The correlation between elevated PM concentrations and temperature, as observed in Figure 7(a) and 7(b), underscores the importance of considering climatic factors in air quality management. Warmer periods may exacerbate air pollution episodes, demanding targeted interventions during these times. However, the relationship with humidity is less straightforward and requires further investigation to understand its precise impact on particulate matter dynamics in Meru. The consistent exceedance of WHO air quality guidelines for both PM2.5 and PM10 in Meru necessitates comprehensive and sustained air quality management strategies. Addressing both emission sources and meteorological influences is crucial for effectively reducing public health risks. Further research is needed to elucidate the specific factors driving particulate matter levels in the region, including the role of land use, biomass burning, and industrial emissions.

Monthly Mean PM2.5 and PM10 Concentrations in Meru, February and March 2024

The analysis of monthly mean PM2.5 and PM10 concentrations in Meru, as depicted in Figure 8, provides a detailed view of air quality trends throughout February and March 2024.

Figure 8. Monthly Mean PM2.5 and PM10 Concentrations in Meru, February and March 2024. (The results highlights the variations in particulate matter levels over the months, with notable peaks in PM2.5 and PM10 concentrations significantly exceeding WHO daily limits, reflecting episodes of poor air quality).

The data presented in Figure 8(a) reveal significant air quality challenges in Meru during February and March 2024. PM2.5 concentrations exhibited extreme variability, ranging from negligible levels to alarming peaks that substantially exceeded the WHO's stringent daily limit of 10 μg/m³. Notably, February 5th witnessed a particularly severe pollution episode, with PM2.5 reaching 127.03 μg/m³, a value far surpassing the WHO's guideline. A similar pattern was observed for PM10, indicating a broader spectrum of air pollution. These findings are consistent with previous studies reporting episodic pollution events in urban and rural African settings (*Petkova et al.*, 2013). The interplay between meteorological conditions and air quality is evident in Figure 8(b). Temperature and humidity fluctuated considerably during the study period. While a definitive causal relationship cannot be established without further analysis, the observed correlation between elevated PM levels and specific meteorological conditions suggests that factors such as temperature inversions, atmospheric stability, and hygroscopic growth of particles might have contributed to the pollution episodes. The exceedance of both daily and annual WHO air quality standards underscores the critical need for effective air quality management in Meru. Prolonged exposure to such high PM concentrations poses significant health risks to the population, including respiratory and cardiovascular diseases (*Wan Mahiyuddin et al.*, 2023). To mitigate these risks, a comprehensive approach is required, encompassing air quality monitoring, source identification, emission control measures, and public health interventions. Furthermore, research into the specific factors driving the observed pollution patterns is essential to inform targeted mitigation strategies.

It is crucial to note that the data presented here represent a limited timeframe. To fully assess the long-term air quality trends and their implications for public health, continuous monitoring and analysis are necessary. Additionally, exploring the spatial distribution of air pollution within Meru would provide valuable insights into the sources and impacts of pollution.

Discussion

The study investigates particulate matter (PM) pollution levels in three urban centers in Kenya—Nairobi, Kisumu, and Meru—by employing low-cost IoT PM particle counters with a high temporal resolution of five seconds. Real-time data collection from multiple sites within each city reveals that PM levels consistently surpass the World Health Organization (WHO) recommended thresholds, reinforcing findings from previous studies conducted in similar settings. This persistent exceedance underscores the severity of urban air pollution in Kenya and the pressing need for mitigation strategies to alleviate its adverse health effects. Despite the geographical diversity of the study sites, including both extensively studied cities such as Nairobi and relatively underexplored locations like Kisumu and Meru, elevated PM pollution remains a common trend. The consistency of these findings across diverse urban environments highlights the pervasive nature of air pollution and the necessity for targeted interventions. Alignment with prior research further substantiates the urgency of addressing air quality concerns in Kenya. Studies such as those by Kinney et al. (2011) and Westervelt et al. (2021) have previously documented elevated PM levels in urban areas, and the present study provides additional empirical evidence reinforcing this trend. By demonstrating that PM pollution consistently exceeds WHO guidelines, the findings contribute to the growing body of knowledge on air quality and emphasize the need for immediate action. The integration of advanced technology with comprehensive data collection offers valuable insights into the extent of pollution, facilitating evidence-based policymaking to address this critical public health issue. The high temporal resolution of the adopted methodology allows for a nuanced analysis of pollution patterns, capturing fluctuations in PM levels throughout the day. This granular data identifies peak pollution periods, offering crucial insights for the design of effective interventions, such as optimizing traffic management strategies during rush hours or rescheduling industrial activities to minimize air quality degradation. Such targeted approaches can significantly reduce exposure to harmful pollutants, thereby enhancing urban air quality and safeguarding public health. Beyond temporal patterns, spatial analysis reveals disparities in PM pollution across different neighborhoods within each city. The identification of pollution hotspots—particularly in areas near industrial zones and major traffic corridors—enables the formulation of location-specific mitigation strategies. Mapping these high-risk zones provides valuable guidance for urban planning decisions, such as the strategic placement of green spaces to act as natural air filters or the implementation of low-emission zones. Addressing pollution at the neighborhood level ensures that interventions are both effective and equitable, particularly for vulnerable communities disproportionately affected by poor air quality. The deployment of low-cost IoT sensors further demonstrates the feasibility of establishing extensive air quality monitoring networks in resource-constrained settings. The affordability and scalability of these sensors enable continuous, real-time monitoring, which is essential for both immediate response measures and long-term environmental planning. Encouraging the widespread adoption of such technology could facilitate broader and more comprehensive air pollution assessments across Kenya and beyond, ultimately enhancing the effectiveness of air quality management initiatives. Comparative analysis with WHO thresholds offers critical insights into the suitability of Nairobi, Kisumu, and Meru as habitable urban environments. Persistent exceedance of recommended PM limits raises concerns about long-term public health implications, necessitating decisive policy action. The findings underscore the importance of equipping policymakers and urban planners with robust, data-driven insights to formulate targeted strategies aimed at reducing PM pollution. These strategies could include stricter regulations on industrial emissions, the promotion of cleaner transportation options, and the integration of sustainable urban planning practices. Strengthening regulatory frameworks and fostering interdisciplinary collaboration will be essential in ensuring sustainable air quality improvements. Addressing PM pollution requires a multifaceted approach that integrates technological innovation, policy reform, and community engagement. The study's findings provide a foundation for evidence-based decision-making, empowering stakeholders to implement interventions that foster cleaner air and healthier living conditions in Kenyan cities. Through strategic action and sustained commitment, the adverse impacts of air pollution can be mitigated, paving the way for a healthier urban future.

Conclusion

The persistent and often overlooked challenge of air pollution in urban environments demands rigorous, data-driven evaluations. Although previous studies have highlighted air quality concerns in specific Kenyan cities, a broader assessment encompassing diverse urban settings with high-resolution real-time data remains essential. Addressing this gap, the study utilizes low-cost IoT sensors to monitor PM levels in Nairobi, Kisumu, and Meru, offering novel insights into the spatial and temporal dynamics of air pollution. A systematic comparison with WHO air quality guidelines not only affirms the severity of the issue but also quantifies the degree to which public health is at risk. The consistent exceedance of recommended thresholds across all study sites highlights the critical need for targeted interventions to safeguard human well-being. Reinforcing existing evidence on the link between elevated PM levels and adverse health outcomes, the findings underscore the urgency for immediate action. Access to granular, real-time data enhances the ability of policymakers and urban planners to make informed decisions, ensuring a proactive approach to air quality management. Identifying pollution hotspots and temporal variations enables the formulation of tailored mitigation strategies, including the promotion of clean transportation, optimization of industrial processes, and expansion of urban green spaces. Strengthening the foundation for sustainable urban development, this study emphasizes the necessity of integrating air quality considerations into policy frameworks. Implementing evidence-based interventions has the potential to reduce pollution levels, enhance environmental resilience, and ultimately improve public health.

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