Comparative Analysis of PM2.5 Air Quality Between Old and Newly Developed Residential Areas in Karbala City Using a Low-Cost Monitoring System

Hussein Abd Ali Hatif Alsaadi
Department of Medical Devices Engineering
Al-Zahrawi University College
Karbala, Iraq
e-mail: hussain.abdali@alzahu.edu.iq

***Abstract*—This study investigates air quality disparities in Karbala, Iraq, by comparing particulate matter smaller than 2.5 micrometers (PM2.5) concentrations between Hay Al-Abbas, an old densely populated neighborhood (site A), and Al-Muruj Residential Complex, a newly developed suburban area (site B). Both sites were geo-referenced using Global Positioning System (GPS) coordinates for accurate spatial comparison. Data were collected using a custom-built, low-cost monitoring system based on Arduino and PMS5003 sensors over three consecutive days in June 2025. Measurements were conducted at fixed times—midnight, morning, and afternoon—each with PM2.5 readings every five seconds for fifteen minutes, resulting in more than 1,600 data points per site. PM2.5, a key air quality indicator, was evaluated against the World Health Organization (WHO) daily limit of 25 µg/m³[14]. Results showed that site A had consistently higher PM2.5 levels than site B, often exceeding the guideline—especially during morning and midnight periods. These findings highlight the influence of urban density, waste burning, and city planning on particulate pollution in Karbala. Overall, the study confirms that older, densely built neighborhoods experience poorer air quality than newly planned areas, where improved urban design has helped reduce pollution.**

Keywords- PM2.5; Air Quality; Low-Cost Sensor; Urban Monitoring; Karbala .

I. INTRODUCTION

Air pollution remains one of the most serious environmental and health issues in Iraq's rapidly expanding cities. In Karbala, residents are exposed daily to several sources of pollution—including the widespread use of diesel generators in every neighborhood, random and uncontrolled waste burning, and heavy vehicle traffic on crowded city streets [1], [2]. These combined factors often result in concentrations of airborne particulate matter that exceed international safety standards, putting the health of local communities at risk. Among air pollutants, fine particulate matter less than 2.5 micrometers in diameter (PM2.5) is especially important as an indicator of air quality and as a risk factor for respiratory and cardiovascular diseases. Yet, despite its significance, there is a shortage of detailed, neighborhood-level PM2.5 data in Karbala. Most available information is limited to governmental stations, satellite observations, or generalized models that don't reflect the unique realities of different city districts. This study addresses this gap by directly comparing PM2.5 concentrations between two contrasting residential areas in Karbala. The first, site A (Hay Al-Abbas), is a central urban district where high population density has been further increased by unplanned, dense construction on once-agricultural land surrounding the old neighborhood. This irregular growth has brought more people, vehicles, and private generators into the area—making pollution sources more concentrated and varied. The second, site B (Al-Muruj Residential Complex), is a recently developed and fully planned neighborhood established as part of the city's latest urban expansion. In contrast to Hay Al-Abbas, Al-Muruj was designed with organized streets, designated green spaces, and modern infrastructure to accommodate future growth and offer quieter, healthier living conditions. Both areas experience the typical daily activities that contribute to air pollution in Karbala, but the scale and organization of each neighborhood differ sharply. By employing a custom-designed, low-cost monitoring system to collect high-frequency air quality measurements at multiple times of day in both locations, this research aims to reveal how differences in urban planning, population density, and local behavior shape air quality at the neighborhood level. The findings of this work are expected to inform future urban planning and practical policies to reduce air pollution as Karbala continues to grow.

The remainder of this paper is organized as follows: Section II reviews related work, Section III presents the methodology, Section IV reports the results, Section V discusses the findings, and Section VI concludes the paper and suggests future research directions.

II. RELATED WORK

Although air pollution is increasingly recognized as a critical urban and public health challenge in Iraq, detailed ground-level studies of air quality in Karbala remain rare. Most of the existing research in Iraq has focused on measurements from official government monitoring stations, major roads, or satellite-based models, which do not capture the variation between residential neighborhoods or reflect local sources of pollution such as diesel generators, random waste burning, and dense traffic. The use of low-cost laser-based optical particle sensors—such as the PMS5003—for neighborhood-scale air quality monitoring is still limited, particularly in Karbala.

Several recent studies have demonstrated the feasibility and value of using low-cost sensors for urban air quality assessment in other Iraqi cities. Abdullatif et al. [3] measured PM2.5 and PM10 along a main road in Karbala, showing substantial pollution fluctuations linked to traffic and weather. Other researchers have examined air quality in specific parks or compared urban landscapes, identifying PM2.5 as the dominant pollutant, especially during the summer and in densely built-up areas [4], [5]. Outside Karbala, distributed networks of low-cost sensors have been deployed in Mosul [6] and Sulaymaniyah [7], confirming the spatial and temporal complexity of particulate pollution and the benefit of high-frequency, local measurements.

However, there remains a clear lack of systematic, GPS-referenced, high-frequency air quality monitoring studies comparing both old and newly developed residential districts within a single Iraqi city. The present study aims to address this gap by providing one of the first direct, ground-level comparisons of PM2.5 concentrations between a historic city-center neighborhood (Abbas) and a modern residential district (Muruj) in Karbala, using a custom-built monitoring system and dense spatial sampling. By building on and extending the findings of previous work, this study offers practical data and insights to inform future urban planning and public health efforts in Iraq.

III. METHODOLOGY

A. Measurement System

A custom-built air quality monitoring system was developed to enable real-time field measurements in diverse urban environments. The core platform was based on an Arduino Mega microcontroller, selected for its multiple serial interfaces and high I/O capacity [6]. A PMS5003 laser-based optical particle sensor was integrated to measure both PM2.5 and PM1 concentrations, following best practices recommended in previous environmental sensor deployments [7],[8]. Temperature and relative humidity were monitored using a DHT22 sensor, while geographic location data were continuously logged via a u-blox NEO-6M GPS module with a ceramic antenna [9]. Sensor readings were visualized in real time using a compact OLED display [10], and all data were saved locally to a microSD card for subsequent analysis, as described in related open-source monitoring frameworks [11].

All components were securely assembled on a portable plastic board to facilitate field deployment (Figure 1). Power and wiring connections are shown schematically in (Figure 2). Power was supplied either by a USB power bank or a laptop [12], and the system could be monitored in real time via the Arduino IDE serial monitor as well as the OLED screen.

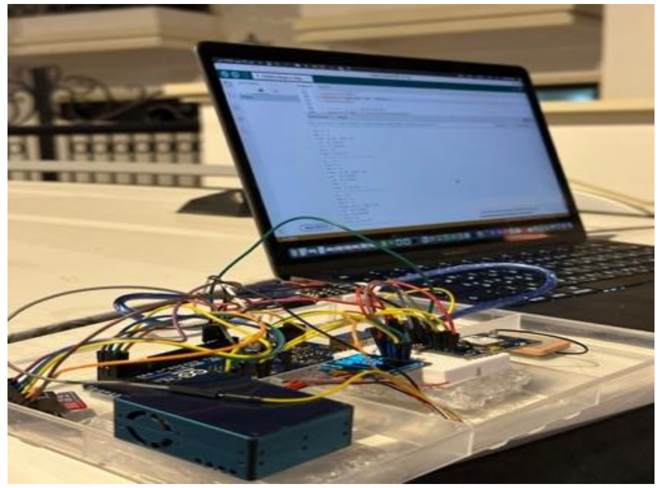

Figure 1. Assembled monitoring system in a typical field configuration.

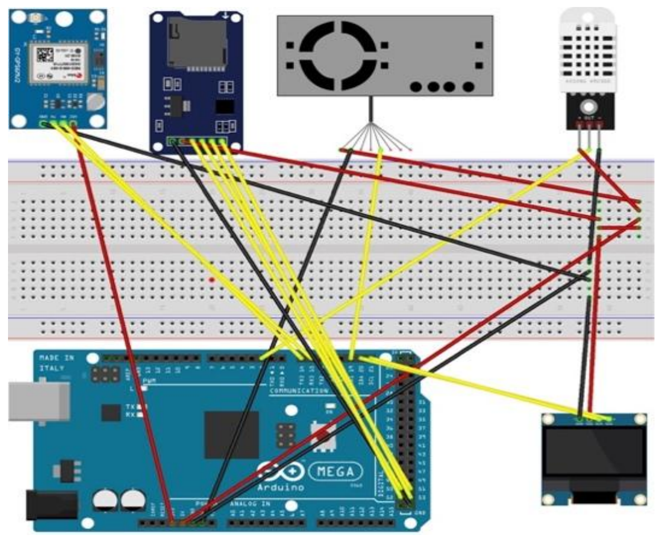

Figure 2. Schematic wiring diagram of all hardware connections.

B. Data Collection Protocol

Field measurements were carried out in two residential areas in Karbala: site A (Hay Al-Abbas; 32.6361°N, 44.0503°E), representing an old, central urban environment, and site B (Al-Muruj Residential Complex; 32.5341°N, 44.0209°E), representing a newly developed, fully planned extension of the city. Data were collected at three specific times each day—midnight (00:00), morning (09:00), and afternoon (17:00)—to capture diurnal air quality variation. Each site was sampled during nine independent sessions for each period, yielding a total of eighteen sessions per area.

During each session, the device was placed at a height of approximately 170 cm in an open area free from immediate pollution sources or airflow obstructions. The system remained stationary throughout the 15-minute measurement period, logging readings every five seconds (about 180 data points per session). Each measurement record included a timestamp, PM2.5, PM1, temperature, relative humidity, and GPS coordinates.

Prior to each session, a five-minute warm-up period was implemented to allow for sensor stabilization and GPS lock. Data collected during this period were excluded from the final analysis to ensure the accuracy of the results.

C. Data Storage and Processing

All measurement data were saved in CSV format on the SD card, with sequentially numbered entries and clearly labeled columns for time, geographic location, and all sensor values. After each session, files were transferred to secure storage and backed up for processing.

Data cleaning involved discarding all readings from the initial five-minute warm-up, as well as screening for missing or obviously erroneous values. No additional filtering was applied, since all retained data fell within expected operational ranges established during system validation. Cleaned datasets were then used for statistical analysis and visualization. The Arduino code used for sensor communication, data logging, and file management was custom-developed for this project and is publicly available for reference [13].

D. Site Access and Permissions

Access to site A (Hay Al-Abbas) was unrestricted, as it is a public and centrally located neighborhood. Entry to site B (Al-Muruj Residential Complex), however, required prior authorization since access is limited to residents, their guests, or authorized personnel. All necessary permissions were secured to enable unobstructed and ethical fieldwork. Environmental observations (such as local waste burning or unusual traffic) were also documented during each session.

IV. RESULTS

TABLE I. SUMMARY STATISTICS OF PM2.5, PM1, TEMPERATURE, AND RELATIVE HUMIDITY BY SITE AND PERIOD

Site	Period	Sample Count	PM2.5 (Mean ± SD)	Mean PM1 (µg/m³)	Mean Temp (°C)	Mean RH (%)
site A Abbas	Midnight	540	40.52 ± 15.56	37.06	34.72	26.12
site A Abbas	Morning	554	48.29 ± 30.97	41.14	45.86	25.52
site A Abbas	Afternoon	581	25.48 ± 15.01	23.83	43.77	15.89
site B Muruj	Midnight	550	20.43 ± 10.29	19.00	34.90	24.42
site B Muruj	Morning	541	34.55 ± 19.78	29.12	42.42	25.04
site B Muruj	Afternoon	567	10.66 ± 7.73	9.68	43.39	14.29

The mean PM2.5 concentration for each period and site was calculated as follows:

$$C_{mean} = \frac{1}{N}\sum_{i=1}^{N} C_i \tag{1}$$

where C_{mean} is the average PM2.5 concentration, N is the number of samples, and Ci is the i-th measurement, As shown in (1).

According to the World Health Organization (WHO), the recommended daily mean limit for PM2.5 is 25 µg/m³. Several of the observed mean values exceeded this guideline, particularly in Abbas during the morning (48.29 µg/m³) and midnight (40.52 µg/m³) periods, as well as in Muruj during the morning (34.55 µg/m³). These exceedances pose clear public health concerns.To further highlight the differencdes between the two sites, Table II provides a direct comparison of mean PM2.5 values, absolute and relative differences for each period.

TABLE II. OMPARISON OF MEAN PM2.5 CONCENTRATIONS BETWEEN SITE A (HAY AL-ABBAS) AND SITE B (AL-MURUJ RESIDENTIAL COMPLEX)

Period	Mean PM2.5 site A Abbas	Mean PM2.5 site B Muruj	Absolute Difference	Relative Difference (%)
Midnight	40.52	20.43	20.09	98.3%
Morning	48.29	34.55	13.74	39.8%
Afternoon	25.48	10.66	14.82	139.0%

As shown in Table II, PM2.5 concentrations were consistently higher in Abbas than in Muruj across all periods, with the largest relative difference observed in the afternoon.

The variation in PM2.5 concentrations is visualized in Figure 3.

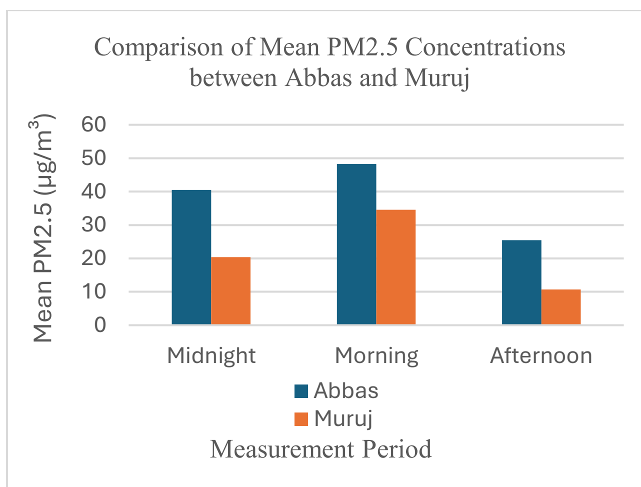

Figure 3. Comparison of Mean PM2.5 Concentrations between Abbas and Muruj across Measurement Periods.

Courtesy of IARIA Board and IARIA Press. Original source: ThinkMind Digital Library https://www.thinkmind.org

 ISBN: 978-1-68558-331-6

V. DISCUSSION

The results reveal clear spatial and temporal patterns in air quality across the two study sites. PM2.5 concentrations in site A (Hay Al-Abbas) were consistently higher than those measured in site B (Al-Muruj Residential Complex), and exceeded the WHO recommended daily mean in several periods. An independent samples t-test confirmed that the differences in mean PM2.5 concentrations between Site A (Abbas) and Site B (Muruj) were statistically significant across all time periods ($p < 0.001$).The standard deviation was also notably higher in site A, which can be attributed to transient spikes in pollution—often resulting from passing vehicles or short-term activities such as illegal waste burning in adjacent neighborhoods.

Field observations further supported these findings. During the measurement campaign, unauthorized waste burning was documented visually in site A, as captured in an aerial drone photograph (Figure 4). The image clearly shows multiple smoke plumes (highlighted with arrows) rising from various locations across the city, confirming that such activities are still present and can directly impact particulate concentrations in nearby residential areas.

Periods of adverse weather, such as the fifth morning session, were associated with citywide increases in particulate matter and higher variability in the readings. Afternoon measurements typically showed lower PM2.5 levels, possibly due to reduced human activity and cleaner atmospheric conditions. Morning sessions, by contrast, were likely impacted by waste burning, generator operation, and increased local activity. Although illegal waste burning rarely occurred within the measurement points themselves, the widespread use of diesel generators was a constant source of pollution in all residential areas.

The consistently lower and more stable PM2.5 levels recorded in site B (Al-Muruj Residential Complex) reflect the benefits of improved urban planning, limited traffic, and restricted access for non-residents. The selected measurement sites were representative residential side streets; it is expected that even quieter locations would have shown slightly lower readings.

The reliability of the PMS5003 sensor was confirmed by the strong agreement between the observed values and expectations based on personal experience and previous studies. Sampling was carried out during typical activity times and over several days, providing a representative assessment of daily air quality.

No significant differences in particulate concentrations were observed between holiday and regular working days, likely due to the residential nature of both sites. Occasional similarities in temperature between sites during afternoon periods were more likely the result of a general decline in urban activity than any direct meteorological effect.

Figure 4. Aerial photo of site A (Hay Al-Abbas), Karbala — smoke plumes (arrows) from unauthorized waste burning observed during fieldwork in July 2025.

VI. CONCLUSION AND FUTURE WORK

This study demonstrated that air quality, as measured by PM2.5 concentrations, was consistently poorer in site A (Hay Al-Abbas) compared to site B (Al-Muruj Residential Complex). The findings confirm that high population density, unplanned urban expansion, and the conversion of former agricultural land into dense residential neighborhoods have had a substantial negative impact on air quality in Hay Al-Abbas. In contrast, Al-Muruj benefited from more rigorous planning and stricter access policies, resulting in noticeably cleaner and more stable air quality.

Although the monitoring campaign lasted only three days, the repeated sessions were sufficient to capture clear differences. Longer-term deployments would provide more comprehensive seasonal insights.

The custom-built monitoring system developed for this project proved to be an effective and affordable solution for local air quality assessment. With modest enhancements—such as longer-term deployments, real-time wireless data transmission, or integration with additional environmental sensors—the device could provide even greater value for researchers and local authorities alike.

These results highlight the urgent need for municipal and local government action: reconsidering policies that allow the unregulated conversion of agricultural land for residential use, enforcing regulations against illegal waste burning, and encouraging the community to adopt cleaner energy sources. Public awareness campaigns about the health risks of air pollution are also essential.

While the measurement campaign was comprehensive and the system performed reliably, further research could expand on this work by deploying the device in additional neighborhoods, integrating more types of sensors, or collecting vertical air quality profiles using aerial platforms such as drones. Such efforts would offer deeper insight into pollution dynamics and support more effective urban planning and mitigation strategies for Karbala and similar cities.

Overall, this research demonstrates both the feasibility and importance of low-cost, community-driven environmental monitoring. The approach described here can easily be adapted for other urban contexts, providing critical data for improving air quality and public health outcomes.

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