Comparative Analysis of Indoor and Outdoor Particulate Matter Concentrations and Air Quality in Ogbomoso, Nigeria

Musibau O. Jelili, Adeniyi S. Gbadegesin, Abimbola T. Alabi

Department of Urban and Regional Planning, Faculty of Environmental Sciences, Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria

Corresponding author: Abimbola T. Alabi
abimbolaalabit@gmail.com

Introduction

Air pollution has been a serious environmental problem for many years and is becoming a greater issue globally. Particulate matter in ambient air presents a risk to human health, particularly after prolonged exposure. Air quality problems are experienced in both developed and developing countries and epidemiological studies have demonstrated correlational and causal relationships with various ailments. The International Agency for Research on Cancer (IARC) revealed that worldwide 223,000 lung cancer deaths in 2010 resulted from air pollution. Air pollution is considered the world’s largest single environmental health risk, responsible for one in eight total global deaths.

Both indoor and outdoor air pollution present a major challenge, although studies often show mortality from indoor air pollution to be twice that of outdoor air pollution. This problem is even greater in developing countries. According to the World Health Organization (WHO), more than two-thirds of the global estimates of mortality from indoor air pollution occur in Southeast Asia and sub-Saharan Africa. In Nigeria, the use of biomass cooking fuels, unclean energy sources, unsanitary waste disposal techniques and other activities which release gaseous and particulate pollutants into the indoor and outdoor environments are common. This highlights the need for the examination of air quality in urbanizing settlements in Nigeria.

Background. Airborne particulates are an issue in many urban regions around the world and their detrimental impact on human health has increasingly become a public health concern. Objectives. The aim of the present study was to examine particle pollution in an urban settlement in Nigeria. This study examines the extent, spatial variation, and sources of indoor and outdoor particulate matter (PM) concentrations in Ogbomoso, Nigeria.

Methods. The survey research method was adopted. Sampling included 385 buildings across selected precincts and different residential zones in the town of Ogbomoso. Particulate matter analytes (PM₁₀, PM₂.₅, and PM₁) within/around each building were measured with a particle counter and details on domestic utilities/practices were obtained with a questionnaire. Analysis of variance was used to determine inter-zonal variations in PM levels and simple linear regression was used to analyze the relationship between indoor and outdoor air quality.

Results. Indoor and outdoor respirable particle (PM₂.₅) concentrations were lower than the World Health Organization (WHO) Interim Target limit of 75 μg/m³, while concentrations of inhalable particles (PM₁₀) were higher than the set limit of 150 μg/m³ for daily averages. Coarse particles dominated, with an accumulative PM₁₀/PM₁ ratio of 0.24. The inter-zonal analysis of PM concentrations revealed that indoor and outdoor PM levels varied significantly by residential zone (p = 0.0005; p = 0.01, respectively). Regression analysis showed a significant but weak relationship between indoor and outdoor PM levels (r = +0.221), while the coefficient of determination (R² = 0.049) showed that only about 5% of the variation in indoor air quality was associated with outdoor air quality. Particle pollution inducers were identified in the residents’ waste disposal methods and adopted fuels/energy sources, with firewood and charcoal linked with increased concentrations of particulate matter.

Conclusions. Air quality was relatively poor in the study area given observed particulate matter concentrations. Cleaner fuels, effective waste management systems and improved roads are needed to foster better air quality in the study area.

Competing Interests. The authors declare no competing financial interests.

Keywords. air quality, particulate matter, residential zones.

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pollen, dander, airborne smoke, and soot as well as liquid droplets from fuel combustion. According to the World Bank, the amount of suspended PM, usually measured in micrograms per cubic meters of air, is one of the most important indicators of air quality. There are often differences in the constituents of indoor and outdoor air pollution according to pollution sources, yet airborne particulates are notably common, making PM a good indicator for examining differences between indoor and outdoor air quality.

There is a growing need for empirical investigations into indoor and outdoor air quality with regard to airborne particulates. Few such studies have been conducted in developing countries. Air quality studies in Nigeria often address either indoor air quality in rural areas or outdoor air quality in industrialized regions, addressing primarily solid fuel use in the former and vehicular/industrial emissions in the later. There have been few studies set in residential urbanizing settlements and still fewer exploring differences between indoor and outdoor air quality. The present study examines air quality in Ogbomoso, Nigeria and provides insight into the extent, spatial variation and interconnection between indoor and outdoor air quality.

**Particulate matter**

Particulate matter is used to describe condensed phase (solid or liquid) particles suspended in the atmosphere and it is categorized by size, specifically by aerodynamic diameter in microns (millions of a meter). The potential for causing health problems is directly linked to the size of the particles; small particles are generally thought to be more damaging to health. Three PM analytes are often considered in air quality studies viz: PM$_{10}$ (coarse particles less than 10 μm), PM$_{2.5}$ (fine particles less than 2.5 μm) and PM$_{1}$ (ultrafine particles between 0.1 and 1 μm), and their health implications are well documented. The fine particles of PM$_{2.5}$ (respirable particles) pass through the nose and are deposited in the windpipe or lungs, where as PM$_{10}$ (inhalable particles) are deposited on the hairs in the nose or at the bends of the nasal passages; both are causal factors for respiratory and cardiovascular morbidity.

However, PM$_{1}$ is a stronger risk factor for mortality than PM$_{10}$, while PM$_{1}$ which is smaller in size, is considered more harmful than both as it is likely to reach deeper into the respiratory system carrying with it more toxins from anthropogenic emissions.

Long term exposure to particulate matter has been linked with acute respiratory morbidity in the form of pneumonia and asthma. Diesel exhaust—a major contributor to PM pollution—has been linked to acute vascular dysfunction and increased thrombus formation. Moreover, air pollution from fine particulates (PM$_{2.5}$) is estimated to be responsible for about 3% of adult cardiopulmonary disease mortality; about 5% of trachea, bronchus, and lung cancer mortality; and about 1% of mortality in children from acute respiratory infection in urban areas worldwide. According to Cohen et al., this amounts to about 0.8 million (1.2%) premature deaths and 6.4 million (0.5%) lost life years.

Recently, studies in Nigeria have explored the extent of PM pollution. Particulate loads have been found to range between 40 μg/m$^3$ and 98 μg/m$^3$ in sixteen Niger Delta communities, exceeding the World Bank standards for annual mean. Total suspended particles have similarly been found to exceed existing (Nigerian) Federal Environmental Protection Agency’s standards in the Niger Delta region. A study in Lagos using an air quality index derived from computations with set standards revealed very poor air quality from suspended PM across selected sampling locations and zones within the state. Furthermore, a cross-sectional study across six Nigerian megacities (Aba, Abuja, Lagos, Kano, Maiduguri and Port Harcourt) showed that daily PM$_{10}$ mass loads exceeded the WHO set limits, with the exception of Abuja, while Aba had the highest PM$_{10}$ concentration levels. Most of these studies have, however, focused on metropolitan areas, especially in the Niger Delta region of Nigeria.

**Methods**

The present study took place in Ogbomoso, an urbanizing town in southwestern Nigeria, and covered Ogbomoso North and Ogbomoso South Local Government Areas in 2016. With an estimated population of 354,617, these two local government areas in the Ogbomoso Region constitute Ogbomoso Township. Ogbomoso Township

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**Abbreviations**

| Abbreviation | Description |
|--------------|-------------|
| CPMag | Cumulative particulate matter aggregate |
| I/O | Indoor/outdoor |
| PM | Particulate matter |
| WHO | World Health Organization |
Figure 1 — Map of the study area showing sampled precincts and residential zones

Source: Google Earth 2016 imagery updated by authors’ field survey; Afon\textsuperscript{21}; Jelili \textit{et al.} \textsuperscript{22}
can be delineated into three major residential zones (core, transition and suburban) largely stemming from the pre-colonial, colonial and post-independence phases of the development in the country, respectively, and form the ecological zones of a traditional African city. The core residential zone, which is the innermost and oldest part of the town, consists of the king’s palace, some traditional landmarks, the king’s market and buildings connected mostly by footpaths and narrow access roads. People indigenous to the town dominate the area. The houses are built in compounds, usually circular in shape, with a large central area where families meet or play, although this quintessential structure is being slowly being eroded by some newly built buildings. Small-scale retail and indigenous business outfits are the most common activities in this zone. Surrounding the core area is the transition (intermediate) zone. This zone houses the growing numbers of middle-income residents, primarily employed in the formal sector. The transition zone is the bridge between the core and suburban zones. It has a greater proportion of tenement houses, a higher population density than the other two zones and is dominated by mixed wholesale commercial and tertiary activities. The last zone, the suburban zone, is also called the commuter zone. This zone lies along lines of rapid transit beyond the city limits and is essentially an area of high-income developments, often landscaped and well laid-out and inhabited mostly by high income earners. The above-mentioned ecological zones were used to organize this study (Figure 1).

Following the design of a previous study, “Intra-urban pattern and determinants of indoor air quality in Ogbomoso, Nigeria”, the survey covered 54 residential precincts scattered across the township, half of which were selected for sampling but evenly spread to prevent clusters and ensure representativeness (Figure 1). Twenty-seven (27) precincts were selected with 6, 12 and 9 in the core, transition and suburban zones, respectively (a ratio of 2:4:3), based on their respective human and housing population sizes. Given the need to collect indoor and outdoor PM data simultaneously, residential buildings were used as a basis for data collection. Buildings in the selected precincts were counted using Google Earth. A total of 10% of the buildings were selected for sampling via random systematic sampling, using an interval of eight alternately along both sides of the road. Ethical approval was granted from the Postgraduate Committee of the Department of Urban and Regional Planning, Ladoke Akintola University of Technology at a pre-data postgraduate seminar.

A total of 385 buildings (73,187 and 125) from the core, transition and suburban zones, respectively, were sampled and data collected over a period of four weeks during the rainy season. In each building, a questionnaire was administered to an adult resident and the GT-531 mass particle counter (Met One Instruments, Inc.) was used for PM data collection. Consent was obtained for the survey in buildings as residents were informed of the nature of the study and the safety of the particle counter prior to requests to take air samples and administering the questionnaire (Supplemental Material). The questionnaire was designed to elicit information on housing characteristics, domestic utilities and other practices. Data collection included building type, ventilation, cooking practices, waste disposal and household energy use. The PM1, PM2.5 and PM10 levels in the living room and immediate surroundings were obtained with a particle counter. Recorded PM concentrations were then computed, and aggregate scores compared with WHO standards. Base-10 log transformation was used for normalizing obtained PM data. Analysis of variance and correlation were carried out to analyze the inter-zonal variations of indoor and outdoor air quality, as well as the relationship between both.

Results

The indoor and outdoor mean concentrations for PM1, PM2.5 and PM10 were computed and presented per precinct in Table 1. For ultrafine particles, the highest mean indoor and outdoor readings were 32.3 μg/m³ and 35.5 μg/m³, respectively. For fine particles, the highest mean indoor reading was 51.4 μg/m³ and highest outdoor reading was 60.5 μg/m³. For coarse particles, the highest mean indoor and outdoor readings were 230.8 μg/m³ and 382.7 μg/m³, respectively. The cumulative mean indoor and outdoor PM1, PM2.5 and PM10 for the study area were 23.6 μg/m³ and 27.7 μg/m³; 41.6 μg/m³ and 46.3 μg/m³; and 175.5 μg/m³ and 188.8 μg/m³, respectively. With regard to PM10/PM2.5 ratio, the cumulative mean for the study area was 0.24 (Table 2) while the indoor/outdoor (I/O) PM ratios for the ultrafine, respirable and inhalable particles were 0.84, 0.90 and 0.92 (Table 3).

Observed PM pollution inducers

Table 4 presents the housing or building characteristics in the study area, which were mainly rooming types (57.7%). Flats constituted 27.5% of buildings, traditional buildings 13.0%, while duplexes were the least represented at 1.8%. About 52.2% of buildings were serviced by un-tarred roads. Louvre, side-hung and sliding windows were the most common.
| Zone          | No. | Selected Precincts | Sampled buildings | Outdoor mean (μg/m³) | Indoor mean (μg/m³) |
|--------------|-----|--------------------|-------------------|----------------------|---------------------|
|              |     |                    |                   | PM₁  | PM₂₅  | PM₁₀ | PM₁  | PM₂₅  | PM₁₀ |
| Core area    | 1   | Oja Igbọ            | 13                | 30.9 | 44.9  | 172.8 | 26.6 | 45.3  | 168.1 |
|              | 2   | Isale Ora           | 13                | 35.1 | 58.4  | 328.5 | 24.3 | 44.8  | 178.0 |
|              | 3   | IsaleAfon           | 15                | 25.7 | 40.9  | 173.5 | 25.8 | 41.7  | 177.3 |
|              | 4   | Orita Merin         | 9                 | 24.9 | 41.0  | 172.1 | 26.3 | 45.4  | 200.8 |
|              | 5   | OkeAgbẹde           | 15                | 26.4 | 43.8  | 182.2 | 24.1 | 41.8  | 154.5 |
|              | 6   | Ora                 | 8                 | 31.1 | 46.1  | 189.9 | 24.2 | 47.6  | 186.3 |
| Transition   | 7   | Ilẹẹwe              | 22                | 33.6 | 38.4  | 187.9 | 24.2 | 41.3  | 154.9 |
|              | 8   | Alasa layout        | 12                | 31.2 | 50.7  | 253.3 | 32.3 | 51.4  | 230.8 |
|              | 9   | Sanuaje             | 20                | 28.4 | 54.0  | 214.5 | 25.6 | 48.8  | 189.4 |
|              | 10  | OkeAlapata          | 10                | 22.3 | 42.3  | 154.7 | 22.9 | 40.3  | 159.6 |
|              | 11  | California          | 16                | 23.6 | 36.9  | 162.9 | 22.2 | 36.2  | 172.3 |
|              | 12  | Care Taker          | 15                | 23.0 | 36.2  | 140.5 | 26.6 | 41.7  | 184.9 |
|              | 13  | Osupa               | 11                | 30.7 | 56.8  | 267.7 | 25.1 | 49.6  | 218.9 |
|              | 14  | Randa               | 7                 | 28.8 | 53.9  | 278.6 | 22.6 | 46.3  | 220.8 |
|              | 15  | Apake               | 13                | 30.9 | 54.2  | 382.7 | 22.9 | 40.9  | 189.2 |
|              | 16  | Sabo                | 7                 | 31.8 | 46.0  | 208.5 | 23.2 | 36.1  | 194.7 |
|              | 17  | Stadium             | 48                | 26.2 | 42.6  | 150.2 | 25.1 | 40.3  | 195.8 |
| Suburban     | 18  | Orita Nairu         | 6                 | 35.5 | 60.5  | 314.4 | 22.9 | 48.9  | 221.5 |
|              | 19  | Ajileté Estate      | 7                 | 17.8 | 26.5  | 96.8  | 17.9 | 28.7  | 168.7 |
|              | 20  | Iwagba              | 13                | 27.6 | 48.8  | 164.3 | 20.0 | 37.6  | 170.5 |
|              | 21  | Baptist High Scl.   | 14                | 27.7 | 45.8  | 168.0 | 20.6 | 36.9  | 148.8 |
|              | 22  | Babi                | 11                | 21.9 | 35.3  | 136.0 | 19.8 | 32.3  | 144.8 |
|              | 23  | Hamama              | 21                | 29.3 | 52.0  | 193.8 | 22.3 | 45.1  | 157.3 |
|              | 24  | Adenike             | 30                | 26.5 | 42.1  | 149.8 | 20.9 | 37.5  | 154.7 |
|              | 25  | Aare Ago            | 8                 | 31.3 | 55.9  | 179.4 | 21.1 | 48.1  | 145.8 |
|              | 26  | Low Cost            | 7                 | 23.9 | 36.4  | 98.2  | 18.8 | 30.3  | 142.7 |
|              | 27  | Apostolic           | 14                | 23.7 | 42.1  | 162.8 | 23.7 | 40.4  | 145.7 |
| Cumulative mean | 385 |                    |                   | 27.7 | 46.3  | 188.8 | 23.6 | 41.6  | 175.5 |

Sampling time range per building: 45 minutes-1 hour.

Table 1 — Indoor and Outdoor PM Concentrations
**Research**

**Figure 2 — Indoor-outdoor PM$_{2.5}$ levels across residential precincts**

**Figure 3 — Indoor-outdoor PM$_{10}$ levels across residential precincts**
Table 2 — $PM_{2.5}/PM_{10}$ Ratios in Ogbomoso

| Mean (µg/m³) | Core | Transition | Suburban |
|--------------|------|------------|----------|
| PM$_{2.5}$  | 43.8 | 42.8       | 38.4     |
| PM$_{10}$   | 174.3| 190.6      | 153.8    |
| PM$_{2.5/10}$ | 0.25 | 0.22       | 0.25     |

Table 3 — Indoor/Outdoor PM Ratios in Ogbomoso

| Residential zone | PM$_{1}$ | PM$_{2.5}$ | PM$_{10}$ |
|------------------|----------|------------|-----------|
| Indoor (µg/m³)   | Outdoor (µg/m³) | I/O | Indoor (µg/m³) | Outdoor (µg/m³) | I/O | Indoor (µg/m³) | Outdoor (µg/m³) | I/O |
| Core area        | 24.8     | 29.5       | 0.84      | 43.8         | 46.9     | 0.93      | 174.3         | 212.7     | 0.82  |
| Transition       | 25.0     | 27.9       | 0.90      | 42.8         | 47.6     | 0.90      | 190.6         | 200.8     | 0.95  |
| Suburban         | 20.9     | 26.2       | 0.79      | 38.4         | 43.9     | 0.87      | 153.8         | 157.0     | 0.98  |
| Mean             |          |            | 0.84      |              | 0.90     |           |              | 0.92      |

Window types at 44.9%, 27.5% and 25.5%, respectively.

Kerosene and charcoal were the dominant forms of cooking fuels, used by 92.5% and 66.0% of the population, respectively, followed by firewood (20.5%), while the least used was sawdust (Table 5). Moreover, 55.6% of the residents used personal gasoline generators and only one-third (32.7%) of the buildings did not have a generator. Almost 70% of the residents (40.8%; 29.1%) practiced refuse burning and a very small proportion (5.5%) were serviced by garbage collection trucks.

Spatial variation in PM levels within the study area

To explore the variation of air quality across the residential zones in Ogbomoso, PM$_{1}$, PM$_{2.5}$, and PM$_{10}$ were merged into a composite index of cumulative particulate matter aggregate (CPMag) used as a surrogate measure of air quality and then analyzed over the 385 sampling points within the 27 precincts across the 3 residential zones using analysis of variance. Table 6 presents the results for the indoor CPMag where the transition zone, had the highest indoor CPMag (83.54 µg/m³). Next was the core area with a CPMag of 79.65 µg/m³, while the suburban zone had the lowest indoor CPMag level (68.29 µg/m³). The observed differences in indoor CPMag across the zones were statistically significant with an alpha level of 0.05 [F$_{2, 382}$ =
25.024; \( p = 0.0005 \ (< 0.05) \). Hence, indoor air quality varied significantly within the residential zones. Tukey HSD post-hoc test further explains the variation. While there was no statistically significant difference between the indoor CPMag of the core area and that of the transition zone \( [p \, \text{value} = 0.304 \ (> 0.05)] \), the indoor CPMag of the suburban zone differed significantly from both \( [p \, \text{value} = 0.005 \ (> 0.05)] \). Since the suburban zone had the lowest indoor CPMag, the zone therefore had significantly better indoor air quality than the other residential zones.

Variations in the outdoor CPMag are presented in Table 7. The core area had the highest outdoor CPMag level \((87.52 \, \mu g/m³)\), followed by the transition zone \((81.62 \, \mu g/m³)\), while the suburban zone had the lowest level \((69.68 \, \mu g/m³)\). The difference was statistically significant with an alpha level of \( 0.05 \) \( (F_{2, 382} = 7.522; \ p = 0.01) \). Hence, outdoor air quality also varied significantly across the residential zones. The Tukey HSD post-hoc test indicated that the outdoor air quality of the suburban zone was significantly better than that of the core area \( (p = 0.01) \), while the difference between the mean CPMag scores for suburban and transition zones was not significant \( [p = 0.06 \ (> 0.05)] \). This implies that the suburban zone, although a lower score than the transition area, cannot be said to be significantly better than the transition zone with respect to outdoor CPMag.

Correlation analysis was used to explain the relationship between indoor and outdoor air quality. It showed a linear relationship between the indoor and outdoor CPMag with a significant positive correlation of +0.221. This correlation coefficient, which was less than 0.49, is weakly positive.24 The positive correlation, although weak, implies that indoor PM level increased without door PM level in the study area. The linear regression model was statistically significant \( (F_{1, 383} = 19.731; \ p = 0.0005) \) and from the regression model (Figure 4), the coefficient of determination \( (R^2) \) was 0.049.

## Discussion

As shown in Table 1, the obtained cumulative mean concentrations for indoor and outdoor respirable particles \( (PM_{2.5}) \) of \( 41.6 \pm 10.1 \, \mu g/m³ \) and \( 46.3 \pm 8.0 \, \mu g/m³ \) respectively, were lower than the WHO Interim Target 1 limit of \( 75 \, \mu g/m³ \).25 It should be noted that the Interim Target 1 used as the baseline is higher than the WHO’s air quality guideline levels and was proposed by the WHO Working Group to promote steady progress towards meeting air quality guidelines objectives in developing countries where pollution levels frequently exceed recommended guidelines.25 Hence, particle pollution from respirable particles in Ogbomoso was considered to be within the acceptable limit. On the other hand, the cumulative mean concentrations of indoor and outdoor inhalable particles \( (PM_{10}) \), \( 175.8 \pm 54.3 \, \mu g/m³ \) and \( 188.8 \pm 122.0 \, \mu g/m³ \) respectively, were higher than WHO Interim Target 1 limit of \( 150 \, \mu g/m³ \) for daily averages. These findings are consistent with findings on PM pollution across six selected major cities in Nigeria where the daily \( PM_{10} \) mass loads also exceeded the WHO prescribed daily limit but the \( PM_{2.5} \) values were within the set limit.19

Five air quality levels, based on \( PM_{10} \) concentration, were established by the Urban Air Quality Management Strategy in Asia, with \( 0-6 \, \mu g/m³ \) categorized as good; \( 60-120 \, \mu g/m³ \) as moderate; \( 121-350 \, \mu g/m³ \) as unhealthy;
Researchers have used these benchmarks, outdoor air quality in Ogbomoso Township measured via inhalable particles (PM\textsubscript{10}), although not hazardous, can be described as unhealthy. The recorded indoor and outdoor inhalable particles in the study area (175.8 and 188.8 μg/m\textsuperscript{3}) were higher than the set limit, although greater concentrations, higher than 300 μg/m\textsuperscript{3}, have been recorded in Bangladeshi households as well as in Aba, Port Harcourt, and Lagos–all highly industrialized Nigerian cities.\textsuperscript{26-29}

### Indoor and outdoor PM levels

The mean PM\textsubscript{2.5} and PM\textsubscript{10} levels in Table 1 were plotted across precincts and the trend analyzed in Figures 2 and 3. For both PM\textsubscript{2.5} and PM\textsubscript{10}, the indoor levels lagged behind, suggesting that outdoor levels of inhalable and respirable particles were higher than the indoor levels. Nonetheless, indoor levels of inhalable particles were higher than the WHO limits and a significant contributor to this was cooking fuel. Most residents use more than one cooking fuel, and cumulatively, kerosene was the dominant cooking fuel used by 92.5% of the population (Table 3). Charcoal and firewood were reportedly used in 66.0% and 20.5% of homes, respectively. With biomass fuel predominant in the study area, the resulting emissions were a major source of particulate matter and volatile organic compounds.\textsuperscript{30-32}

Although there were points where indoor PM\textsubscript{2.5} and PM\textsubscript{10} levels exceeded outdoor levels, the trend showed that air pollution in the ambient outdoor environment was generally greater than pollution within buildings. Outdoor PM sources in the study area, typical of urbanizing traditional towns, include vehicle exhausts along roads (largely service cars, trucks and heavy vehicles), indiscriminate open refuse burning and gasoline generator exhausts from residences or commercial establishments, given the erratic power supply.\textsuperscript{10,33} Most dwellings were connected by an array of distributors and access roads, of which only 36.9% were tarred (Table 4). The lack of unpaved roads fosters dust circulation, and hinders efficient road traffic, leading to congestion, vehicle idling and proliferation of exhausts within the environment. Nearly half (40.8%) of residents burn their refuse around their residential premises and one third (29.1%) in communal open dumps (Table 5), making intermittent dumpsite fumes a common occurrence. Moreover, with 67.3% of buildings using gasoline generators, given the inadequate public electricity supply, generator emissions are widespread, causing noise, oxides of carbon, nitrogen, sulfur, and particulate matter.\textsuperscript{34}

Figures 2 and 3 also show that PM\textsubscript{2.5} and PM\textsubscript{10} concentrations both share a similar pattern from the core area to the suburban area. For both, the
levels appear to reach their peak in the transition zone and decrease towards the suburban zone. This is especially true of indoor PM$_{10}$ concentrations which steadily increased in the core area (core 1-4), reached its peak in the transition zone (transition 8) and gradually decreased towards the suburban zone (suburban 25-27). Both the highest levels for indoor PM$_{2.5}$ (51.4 μg/m$^3$) and outdoor PM$_{10}$ (382.7 μg/m$^3$) were recorded in precincts 8 and 18 of the transition zone, respectively. The highest mean indoor PM$_{10}$ (230.8 μg/m$^3$) and outdoor PM$_{10}$ (382.7 μg/m$^3$) levels were similarly recorded in the precincts of the transition zone, which was also the case for ultrafine particles (Table 1).

Particulate matter variation across residential zones

The spatial pattern of pollution concentrations over a given area depend on the number, type, strength and distribution of various sources, and on the diffusion potential of the atmosphere, as patterns will change somewhat according to prevailing weather conditions. However, the basic underlying pattern of air pollution concentrations over a given area generally remains fairly constant with some areas having generally higher levels than other areas and given a wide enough number of sampling points as in the present study, this pattern can be revealed. Results from

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**Table 6 — Indoor PM Aggregate (PM$_{1}$, PM$_{2.5}$ and PM$_{10}$)**

| Residential zone | No. | Mean (log transformation) | Mean (μg/m$^3$) | SD | Standard Error | 95% confidence interval for mean |
|------------------|-----|---------------------------|----------------|----|----------------|--------------------------------|
| Core             | 73  | 1.9012                    | 79.65          | .08087 | .00947 | 1.8823 - 1.9200 |
| Transition       | 187 | 1.9219                    | 83.54          | .10702 | .00783 | 1.9064 - 1.9373 |
| Suburban         | 125 | 1.8407                    | 68.29          | .09974 | .00892 | 1.8230 - 1.8583 |
| Total            | 385 | 1.8916                    | 77.91          | .10627 | .00542 | 1.8809 - 1.9022 |

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**Table 7 — Outdoor PM Aggregate (PM$_{1}$, PM$_{2.5}$ and PM$_{10}$)**

| Residential zone | No. | Mean (log transformation) | Mean (μg/m$^3$) | SD | Standard Error | 95% confidence interval for mean |
|------------------|-----|---------------------------|----------------|----|----------------|--------------------------------|
| Core             | 73  | 1.9421                    | 87.52          | .18866 | .02208 | 1.8981 - 1.9861 |
| Transition       | 187 | 1.9118                    | 81.62          | .20362 | .01489 | 1.8824 - 1.9412 |
| Suburban         | 125 | 1.8431                    | 69.68          | .17309 | .01548 | 1.8125 - 1.8738 |
| Total            | 385 | 1.8952                    | 78.56          | .19459 | .00992 | 1.8757 - 1.9147 |
Figure 4 — Indoor/outdoor CPMag scatter plot

Figure 5 — Indoor/outdoor CPMag studentized residual plot
the survey confirmed this notion as it showed that air quality varied within the residential zones in Ogbomoso. As shown in Tables 6 and 7, the lowest indoor CPMag was recorded in the suburban zone (68.29 μg/m³) and was statistically different from that of the core area (79.65 μg/m³) and transition (83.54 μg/m³) zones. Similarly, the lowest outdoor CPMag was recorded in the suburban zone (69.68 μg/m³) and though not statistically different from the transition zone (81.62 μg/m³), was significantly different from that of the core area (87.52 μg/m³). Consequently, the transition zone had the worst indoor air quality; the core area, the worst outdoor air quality; while the suburban zone has the best general air quality.

The results can be further explained by residents’ domestic utilities and practices which are presented in Table 8, as previously reported. Burning of refuse is widely practiced by 70% of the residents (Table 5), and according to the chi square analysis, this did not vary significantly across the three zones. Hence, other factors like traffic intensity were most likely responsible for the low outdoor air quality in the core area. The core area, as seen in Figure 1, forms the center of an array of distributor and major roads. The chi square test also showed that ownership
of gasoline generators varied across residential zones and the transition zone had the highest proportion of generators (45.3%). The majority of these were often situated near dwelling units. Unclean cooking fuels (charcoal and firewood) also exhibited significant variations across the zones with the transition zone again having the highest proportion (45.7% and 43.0%, respectively), perhaps explaining why the zone has the worst indoor air quality. These findings agree with the WHO report that 56% of people in developing countries rely on solid fuels for cooking, the burning of which produces extremely high levels of indoor air pollution and can raise indoor PM$_{10}$ to 3000 μg/m$^3$.\cite{6,36}

The cumulative PM$_{2.5}$/PM$_{10}$ ratio for the study area was 0.24 (Table 2). This ratio is useful for identifying emission sources of particulate matter.\cite{37} A high PM$_{2.5}$/PM$_{10}$ ratio signifies dominance by fine particles, while a low ratio implies dominance by coarse particles. In other words, the higher the PM$_{2.5}$/PM$_{10}$ ratio, the lesser dominance of coarse particles. This ratio in Ogbomoso was similar to those of Aba (0.18), Lagos (0.29) and Port Harcourt (0.23).\cite{19} Sampled PM$_{2.5}$/PM$_{10}$ ratios in Nigerian cities revealed that the PM size fraction is dominated by coarse particles, a finding further strengthened by the situation in Ogbomoso.\cite{37} Using analysis of variance, the difference in the PM$_{2.5}$/PM$_{10}$ ratio across the zones was statistically significant at an alpha level of 0.05 both for indoor ($F_{2,382} = 5.351; p = 0.05$) and outdoor ($F_{2,382} = 11.732; p = 0.0005$) environments.

The Tukey HSD post-hoc test revealed that the indoor PM$_{2.5}$/PM$_{10}$ ratio of the transition zone was significantly different from that of the core area and suburban zone (p value = 0.036; 0.013), while the outdoor PM$_{2.5}$/PM$_{10}$ ratio of the suburban zone was significantly different from the core and transition zone (p value = 0.0005; 0.002). The transition zone (Table 2) had the least indoor PM$_{2.5}$/PM$_{10}$ ratio (0.22), while the suburban zone has the highest outdoor PM$_{2.5}$/PM$_{10}$ ratio (0.28). Hence, it can be deduced that although coarse particles generally dominate the PM size fraction in Ogbomoso, they are significantly higher in the transition zone's indoor...
environment and lower in the suburban’s zone outdoor environment. This conclusion is further corroborated by the trend observed in Figure 3. With the transition zone having a significantly higher proportion of use of gasoline generators and unclean cooking fuels (Table 8), such activities were likely responsible for the higher levels of coarse particles.

**Indoor/outdoor PM relationship**

The disparity in indoor and outdoor air quality is often explained by the I/O ratio. The hourly average concentrations in the study area were used to calculate the average I/O ratio (Table 3), resulting in ratios of 0.84, 0.9 and 0.92 for PM1, PM2.5, and PM10, respectively. These were considerably low, compared to the average I/O ratios of 3.74, 2.88, and 1.71, respectively, for PM1, PM2.5, and PM10, in urban residential sites of Pakistan. Indoor/outdoor ratios close to unity are considered negligible, and are often due to open windows. Three mechanisms influence I/O airflow, including mechanical ventilation, natural ventilation and infiltration. Natural ventilation permeates buildings primary via windows and through doors, cracks and other openings. Windows particularly enable pollutant penetration into the indoor space, as residents open them to allow as much air as possible into buildings, given the prevailing hot climate typical of the tropics.

It is noteworthy that 53% of the population used sliding windows and side-hung (25.5%; 27.5%), window types that allow for unobstructed inflow of air (Table 4). These windows are more rigid and less effective for controlling ventilation, unlike louvers that have mechanisms for managing air flow and are slightly more effective (Table 9). The dominance of the rooming building type (57.7%) exacerbates the situation. These are dwellings with a long narrow passage separating rows of directly opposite rooms with single widows. This situation, coupled with the poor public power supply, relative absence of mechanical ventilation and in filtration from building cracks or leaks, allows outdoor air pollutants to easily penetrate the indoor environment, which could narrow the I/O ratio. Enquiries into the influence of ventilation systems on indoor particle concentration shows that I/O ratios range from 0.25-0.60 for particles larger than 1 μm (PM2.5 and PM10) in apartments with natural ventilation. This is not far off from the 0.82-0.98 range (Table 3) observed in the study area.

There was a weak but significant positive linear relationship between indoor and outdoor CPMag as revealed in the correlation analysis. Indoor PM level increased with outdoor PM level in the study area. The resulting coefficient of determination (R2) was, however, far from 1 (Figure 4), so the resulting regression equation was not useful for making predictions. All the underlying assumptions for regression analysis were met as the studentized residual plot shows a random scatter of the points i.e. independence with variance and no values beyond the ±3 SD reference lines (no significant outliers), as seen in Figures 4 and 5.

Consequently, the low R2 in the results implies that outdoor PM aggregate does not explain much of the variability in the indoor PM aggregate. Only 4.9% (= 5%) of the total variation in indoor PM aggregate was associated with outdoor PM aggregate. The low R2 (5%) in Ogbomos was unlike the findings for the German city of Erfurt where the R2 was 86%, showing very strong correlations for indoor and outdoor respirable particles (PM10) with outdoor PM2.5 levels explaining most (80%) of the indoor variation of PM10. However, the aforementioned study was carried out under more controlled conditions as no indoor sources of particles were present in the rooms and no human activities occurred during the measurement periods in contrast to the setting in Ogbomoso. With only 5% of the total variation in indoor PM levels associated with those of outdoor levels, the remaining 95% can only be accounted for by indoor or within-building factors such as building types and materials, and more importantly indoor utilities and cooking practices. It is thus reasonable, given the low R2 value, to suggest that although outdoor PM levels significantly affect indoor levels, indoor activities (domestic heating and cooking) were the major sources of emissions impairing indoor air quality in the study area.

**Conclusions**

Air quality is an important factor in safeguarding human health, thus the present study analyzed airborne particulate matter facets (ultrafine, inhalable and respirable), zone-specific facets (core, suburban and transition zone) and indoor-outdoor facets. Air quality was relatively poor in Ogbomoso, especially with regard to inhalable particles. Only the suburban part of the town had good air quality. While the current situation was not as hazardous as some industrialized cities within and outside the country, PM should be kept from reaching hazardous levels.

Given the situation in the study area, appropriate measures are needed to improve air quality, especially indoor air quality. Considering the observed intra-urban variation of PM levels, efforts should be prioritized in the transition zone. While outdoor air
pollution affects indoor air quality owing to infiltration and ventilation, indoor activities appear to contribute more to indoor air pollution than outdoor sources. Hence, good indoor air quality is best achieved by dealing with domestic utilities and practices within traditional urbanizing settlements. A good place to begin such efforts would be a shift from the prevalent use of biomass cooking fuels (firewood, charcoal, sawdust) and personal generator sets to cleaner energy sources. This can be achieved by revitalizing hydroelectricity and improving access to alternatives like liquefied petroleum gas and solar power.

Effective waste management is also imperative. Sanitary landfills are a safer and healthier means of refuse disposal and should be adopted, while open dumps should be discouraged, and stringent measures enforced where needed. The transportation system within the city could also be improved by rehabilitating poorly tarred and un-tarred roads to reduce vehicle idling and dust propagation. Most importantly, the inter-city commute of commercial heavy trucks through the town should be rerouted via the outskirts by construction of alternate express ways, like ring roads, to prevent unnecessary traffic congestion within the town. These steps to be taken by local and state governments can mitigate pollutant emissions from domestic and vehicular combustion processes in the study area.

It is hoped that the insights provided in the present study will help foster a better understanding and promotion of cleaner ambient air quality in urban areas.

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