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Assessment of Indoor Particulate Matter Concentrations Across Different Residential Microenvironments Using Portable Low-Cost Sensors

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Abstract: Indoor air quality is of great importance for human health as people spend a large part of their lives indoors. In this study, particulate matter (PM_1, $PM_{2.5}$, and PM_{10}) concentrations were monitored in three residential microenvironments — the living room, the kitchen, and the bedroom — in a house in Ballari, Karnataka, India, using a low-cost portable air quality monitor. In addition, both the indoor temperature and the relative humidity were monitored to examine their effects on particulate matter concentrations. Hourly measurements were taken over 15 consecutive days (March–April 2025), with five days of monitoring in each microenvironment. A temporal analysis found short-term increases in particulate matter concentrations during periods of increased household activity. The relatively high PM levels in the living room were likely due to the ingress of outdoor dust, whereas the bedroom had comparatively lower and more stable concentrations. The results showed clear differences in particulate matter levels among the areas under investigation. The kitchen had the highest average concentrations of PM_1 (21.57 µg/m³), $PM_{2.5}$ (28.63 µg/m³), and PM_{10} (32.88 µg/m³), this being mainly due to cooking, while the living room had the lowest average levels. Across all three microenvironments, the mean concentrations followed the order $PM_{10} > PM_{2.5} > PM_1$, indicating the presence of both coarse and fine particles indoors. The correlation analysis showed a weak link between relative humidity and particulate matter concentrations, indicating that indoor activities and ventilation had a greater impact on PM levels than humidity alone. The study as a whole show that low-cost sensors can be used to monitor indoor particulate matter and identify pollution hotspots in residential settings. The results stress the need for good ventilation and source control, especially in kitchens, to reduce exposure to indoor particulate matter and improve indoor air quality in homes.

Keywords: *Indoor Air Quality; Particulate Matter; Residential Microenvironments; Low-Cost Sensors; Relative Humidity; Kitchen Emissions; Temporal Analysis.*

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I. INTRODUCTION

Air pollution is one of the world's leading environmental health challenges, with millions of premature deaths each year. Although much attention has been focused on outdoor air pollution, people spend almost 90% of their time indoors; therefore, indoor air quality (IAQ) is an equally important aspect of human health [1]. Particulate Matter (PM) is considered one of the most harmful indoor air pollutants and is generally classified according to its aerodynamic diameter as PM_1 (≤1 µm), $PM_{2.5}$ (≤2.5 µm), and PM_{10} (≤10 µm). Particulate matter ($PM_{2.5}$) in the atmosphere is now one of the most serious air pollutants. It is well known from many studies that fine particles, particularly PM_1 and $PM_{2.5}$, can reach the alveolar region of the lungs and even enter the bloodstream, increasing the risk of chronic respiratory and cardiovascular [2]. Coarse particles (PM_{10}) mainly deposit in the upper respiratory tract but can still cause irritation and adverse health effects during prolonged exposure [3, 4].

Residential microenvironments such as living rooms, kitchens, and bedrooms exhibit distinct air quality characteristics because of differences in their functions and occupant behaviour. Kitchens are generally associated with elevated PM concentrations due to cooking activities, particularly frying and high-temperature cooking. In contrast, living rooms are influenced by occupant movement, ventilation, and outdoor air infiltration. Bedrooms often experience comparatively lower particulate matter levels but

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can still be affected by dust resuspension, cleaning activities, and ventilation patterns. Understanding these spatial variations is essential for identifying exposure risks and developing effective strategies to improve indoor air quality [5]. These particles do not stay in one place; they rapidly drift through hallways and doorways into neighbouring rooms, though their final concentrations depend heavily on home ventilation and layout [6].

Traditional reference-grade air quality monitoring instruments provide highly accurate measurements. These limitations restrict their application in continuous indoor monitoring, particularly in residential environments. In recent years, low-cost optical particle sensors have emerged as a practical alternative for indoor air quality assessment. These sensors enable real-time monitoring of particulate matter at relatively low cost, making them suitable for long-term measurements, large-scale monitoring networks, and community-based studies. Although low-cost sensors may exhibit certain limitations in measurement accuracy under varying environmental conditions, several studies have demonstrated their usefulness for monitoring temporal and spatial variations in indoor particulate matter when appropriately calibrated and validated [7, 8, 9, 10].

Environmental factors such as temperature and relative humidity (RH) also influence particulate matter concentrations and sensor performance. Relative humidity affects particle hygroscopic growth, causing fine particles to absorb moisture and increase in size, which may alter measured PM concentrations [11]. Temperature influences indoor ventilation, air circulation, and particle dispersion, thereby affecting the temporal variation of indoor particulate matter. Therefore, simultaneous monitoring of PM, temperature, and relative humidity provides a more comprehensive understanding of the dynamics of indoor air quality [12].

Although numerous studies have investigated indoor particulate matter, relatively few have compared PM_1, $PM_{2.5}$, and PM_{10} concentrations across different residential microenvironments using low-cost sensors under identical monitoring conditions. Such comparative assessments are particularly relevant in rapidly urbanising cities, where residents are exposed to both outdoor pollution and indoor emission sources.

Therefore, the present study aims to assess indoor particulate matter concentrations (PM_1, $PM_{2.5}$, and PM_{10}) in three common residential microenvironments—namely, the living room, kitchen, and bedroom—using a portable low-cost air quality sensor. In addition to particulate matter, temperature and relative humidity were monitored to evaluate their influence on indoor PM variations. The findings of this study are expected to provide valuable insights into the spatial distribution of indoor particulate matter within residential buildings and help residents become more aware of the air quality in their immediate surroundings, and encourage the adoption of simple measures to reduce exposure to particulate matter and improve indoor environmental health.

II. MATERIALS AND METHODS

- *Study Area*

The present study was conducted in a residential building located in Ballari, Karnataka, India (15.161924^0 N, 76.942187^0 E), a rapidly developing urban city characterized by residential, commercial, and transportation activities. Figure 1 shows the selected residential building, situated in a relatively calm neighbourhood, and located 500m from the National Highway (NH 167). On the left side of the building is a municipal park where residents regularly gather for walking and recreational activities, particularly in the early morning and evening. Pedestrian movement, waste burning, and nearby traffic may contribute to variations in local outdoor air quality. These outdoor conditions can influence indoor particulate matter concentrations through natural ventilation and air exchange.

The PM concentrations were measured inside the residence to assess indoor particulate matter under normal household conditions. The study focused on three commonly occupied residential microenvironments: the living room, kitchen, and bedroom. A Total of 3 people reside in the house, and all the rooms are naturally ventilated through windows and a main door, allowing regular exchange of air between the indoor and outdoor environments. The sources of PM in the residence include cooking activities, religious rituals involving incense burning, use of electric appliances, air conditioning, and outdoor air through windows and doors. Figure 2 shows the floor plan of the residence and the microenvironments, namely, the living room (4.572 m X 2.4384 m), Kitchen (2.4384 m X 3.6576 m), and Bedroom (3.048 m X 3.6576 m), where the sensors were placed.

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Fig 1 Location of the Study Site

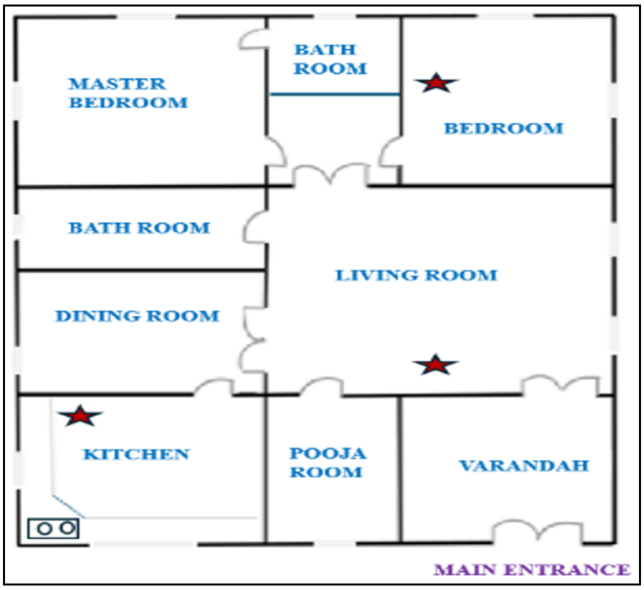

Fig 2 Floor Plan of the Residence with Sensor Placement Locations

➢ *Instrumentation*

Indoor air quality was monitored using a SMILEDRIVE Portable Air Quality Monitor (Version 1.0), a low-cost device designed for real-time environmental measurements. The instrument was used to measure particulate matter concentrations, including PM_1, $PM_{2.5}$, and PM_{10}, as well as indoor environmental parameters, including temperature and relative humidity. The monitor operates based on the optical light-scattering principle, in which airborne particles scatter a beam of light passing through the sensing chamber. The sensor analyses the intensity of the scattered light to estimate particle concentrations. The measured data are displayed instantly on the instrument's digital interface, enabling continuous real-time monitoring of indoor air quality.

➢ *Monitoring Procedure*

Indoor air quality monitoring was carried out over 15 consecutive days in a residential building during March–April 2025 under normal conditions, without altering daily activities. Measurements of PM_1, $PM_{2.5}$, PM_{10}, and meteorological parameters- temperature and relative humidity were recorded at 1-hour intervals throughout the monitoring period. The measurements were carried out in three different residential microenvironments: the living room, kitchen, and bedroom. The instrument was placed at a fixed location in each room, approximately 1.2 m (4 ft) above the floor, to represent the breathing zone of occupants. Measurements were first recorded in the living room for five consecutive days (21st March, 2025 to 26th March, 2025), after which the instrument was placed in the kitchen for the next five consecutive days (27th March, 2025 to 31st March, 2025), and finally in the bedroom for the last five consecutive days (01st April, 2025 to 05th April, 2025). The sensor was placed at the same location in each room throughout the monitoring period to ensure consistent data collection. This monitoring approach enabled a comparison of particulate matter concentrations and indoor environmental conditions across the three residential microenvironments under normal household activities.

➢ *Limitations of the Study*

The main limitation of this study is that the measurements in the living room, kitchen, and bedroom were not conducted simultaneously. Instead, monitoring was conducted sequentially, with five consecutive days of measurements in each microenvironment. As a result, differences in weather conditions and day-to-day variations may have influenced the observed particulate matter concentrations. In addition, the study was conducted in a single residential building in Ballari, Karnataka, over 15 days. Therefore, the findings may not represent all residential buildings or seasonal variations in indoor air quality.

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Furthermore, a low-cost sensor was used for monitoring, which may have lower accuracy than reference-grade instruments. Despite these limitations, the study provides valuable information on the variation of indoor particulate matter concentrations across different residential microenvironments. It serves as a useful baseline for future studies involving simultaneous monitoring over longer periods and in multiple residences.

III. RESULTS AND DISCUSSION

➢ *Temporal Variation of Indoor Particulate Matter Concentrations*

Figures 3(a–c), 4(a–c), and 5(a–c) show the hourly variation of PM_1, $PM_{2.5}$, and PM_{10} concentrations measured over five consecutive days in the living room, kitchen, and bedroom, respectively. In all three residential microenvironments, particulate matter concentrations varied throughout the day, indicating that indoor air quality changes continuously due to occupant activities, ventilation, and particle movement within the house. Although monitoring was carried out sequentially in each room, the daily patterns provide useful information on particulate matter behaviour across different residential microenvironments.

The hourly variations in concentrations of PM_1, $PM_{2.5}$ and PM_{10} in the living room are shown in Figures 3(a-c). It is clear from the figures that all three particulate matter fractions varied over the course of the day, indicating changes in indoor air quality due to various household activities and ventilation. Although the trend remained similar across all five days of the monitoring period, concentrations differed significantly.

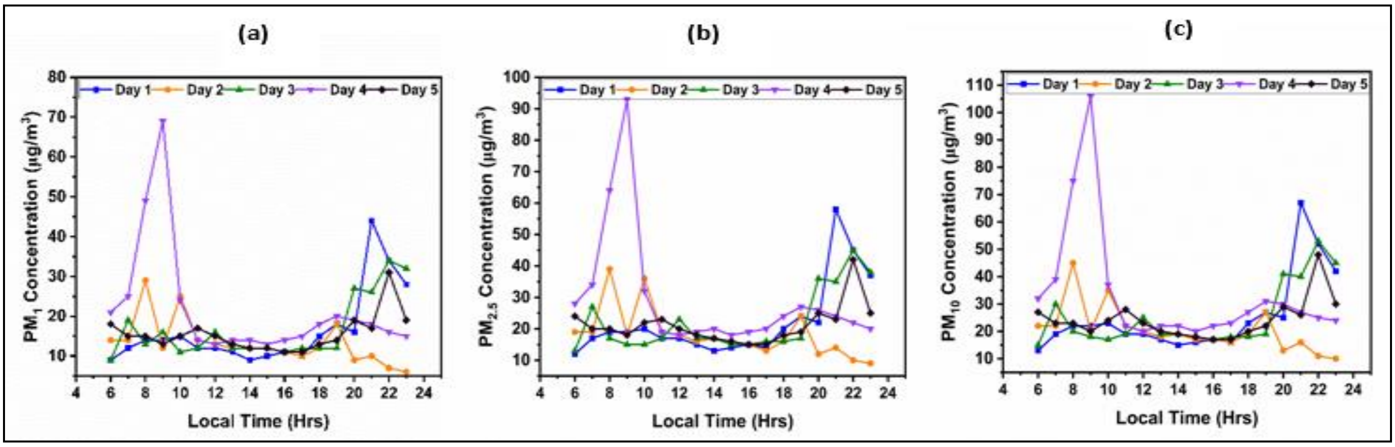

Fig 3 Hourly Variation of Indoor (a) PM_1, (b) $PM_{2.5}$, and (c) PM_{10} Concentrations, in the Living Room During Five Consecutive Monitoring Days

The PM_1, $PM_{2.5}$, and PM_{10} concentrations in the living room (Figure 3(a–c)) remained relatively stable during most hours of the day, with noticeable spikes occurring during the morning (08:00–10:00 h) and late evening (20:00–22:00 h). The highest morning concentrations were observed on Day 4, with PM_1, $PM_{2.5}$, and PM_{10} values reaching 69 µg/m^3, 93 µg/m^3, and 106 µg/m3, respectively. These values exceeded the World Health Organisation (WHO) 24-hour air quality guideline values for $PM_{2.5}$ (15 µg/m³) and PM_{10} (45 µg/m³), indicating short-term deterioration in indoor air quality during this period. The high concentrations recorded on Day 4 may be attributed to cleaning activities in the public park adjacent to the residential building. During the monitoring period, the living room window was open, allowing outdoor air to enter the indoor environment and resulting in an increase in particulate matter concentration. This is consistent with recent findings showing that window opening significantly increases the infiltration of outdoor particles indoors [13, 14], and that outdoor cleaning, sweeping, and landscaping activities are established sources of fugitive particulate matter emissions capable of elevating near-ground PM concentrations [15].

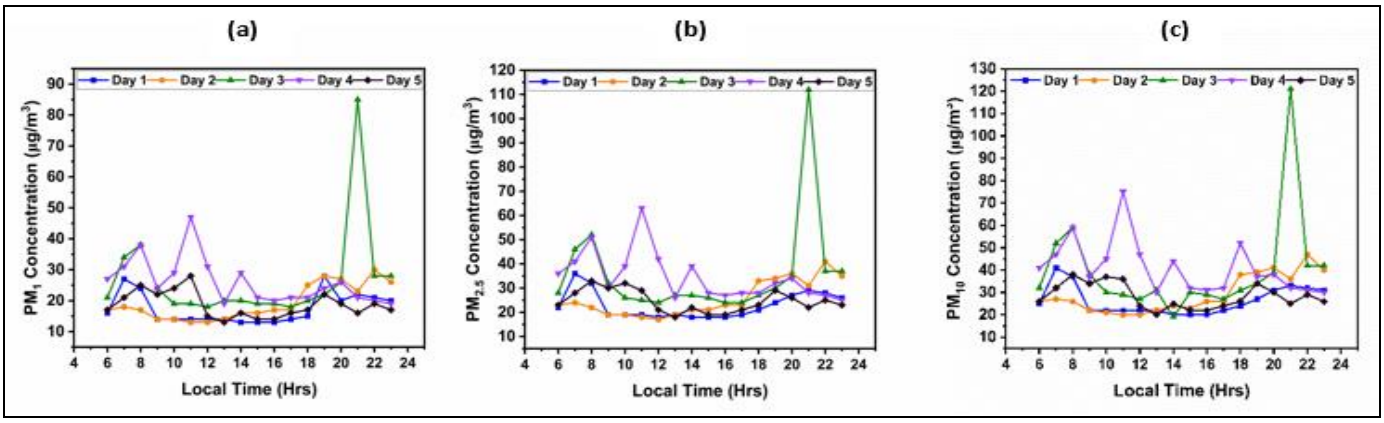

Fig 4 Hourly Variation of Indoor (a) PM_1, (b) $PM_{2.5}$, and (c) PM_{10} Concentrations in the Kitchen During Five Consecutive Monitoring Days

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Figures 4(a–c) show the hourly variation of PM_1, $PM_{2.5}$, and PM_{10} concentrations in the kitchen over five consecutive monitoring days. Compared with the living room, the kitchen exhibited greater temporal variation, with distinct peaks in the morning and evening. The highest concentrations were recorded on Day 3 at around 21:00 h, with PM_1, $PM_{2.5}$, and PM_{10} values of 85, 112, and 121 µg/m³, respectively. These elevated concentrations are likely associated with cooking activities, including frying and food preparation, which generate both fine and coarse particulate matter. Similar observations have been reported in recent studies, which identified cooking as the primary source of short-term increases in indoor particulate matter concentrations in residential kitchens [16, 17]. The results highlight the significant influence of cooking activities on indoor air quality and the importance of adequate kitchen ventilation to reduce particulate matter exposure.

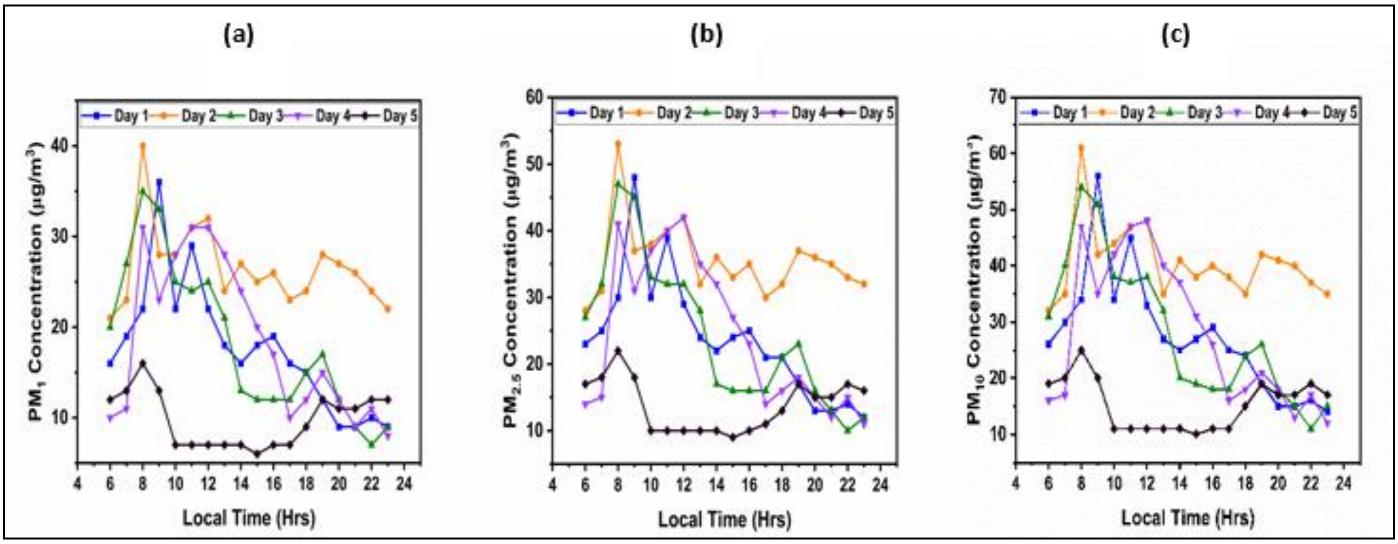

Fig 5 Hourly Variation of Indoor (a) PM_1, (b) $PM_{2.5}$, and (c) PM_{10} Concentrations in the Bedroom During Five Consecutive Monitoring Days

Figures 5(a–c) show the hourly variation of PM_1, $PM_{2.5}$, and PM_{10} concentrations in the bedroom during five consecutive monitoring days. Compared with the living room and kitchen, the bedroom exhibited relatively lower and more stable particulate matter concentrations, with noticeable peaks observed during the morning hours (07:00–10:00 h). The highest concentrations were recorded on Day 2, with PM_1, $PM_{2.5}$, and PM_{10} reaching 40, 53, and 61 µg/m³, respectively. These increases may be due to the presence of a greater number of occupant and their activities, natural ventilation, and the infiltration of particles from adjacent rooms or the outdoor environment. Similar observations have been reported: bedrooms generally have lower particulate matter concentrations than kitchens, with short-term variations mainly influenced by occupant activities and air exchange [17].

Overall, the temporal variation of PM_1, $PM_{2.5}$, and PM_{10} demonstrated that the characteristics and activities of each residential microenvironment strongly influenced indoor particulate matter concentrations. The kitchen exhibited the highest fluctuations due to cooking activities, while the living room and bedroom showed comparatively more stable concentration patterns with occasional short-term peaks.

- ➢ *Comparison of Mean PM Concentrations Among Residential Microenvironment*

Table 1 presents the descriptive statistics of indoor particulate matter, temperature, and relative humidity for the three monitored microenvironments. The kitchen exhibited the highest mean PM concentrations, whereas the living room recorded the lowest. In contrast, the bedroom had the highest mean relative humidity, highlighting the influence of room function on indoor environmental conditions.

Table 1 Hourly Averaged Descriptive Statistics of PM_1, $PM_{2.5}$, PM_{10}, Temperature and Humidity in Different Rooms

Parameters	Room	Mean	SD	Min	Max
PM_1 (µg/m³)	Living Room	16.7	9.30	6	69
	Kitchen	21.57	9.32	13	85
	Bedroom	18.12	8.45	6	40
$PM_{2.5}$ (µg/m³)	Living Room	22.54	12.24	9	93
	Kitchen	28.63	12.23	17	112
	Bedroom	24.36	10.97	9	53
PM_{10} (µg/m³)	Living Room	25.69	14.12	13	106
	Kitchen	32.88	13.77	19	121
	Bedroom	27.84	12.75	10	61
Temperature (°C)	Living Room	31.4	1.51	29	34
	Kitchen	32.12	1.59	29	35

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	Bedroom	29.14	2.42	19	32
Relative Humidity (%)	Living Room	44.39	8.90	26	62
	Kitchen	33.97	10.01	21	55
	Bedroom	50.03	9.99	26	68

SD- Standard Deviation; Min- Minimum value; Max-Maximum value

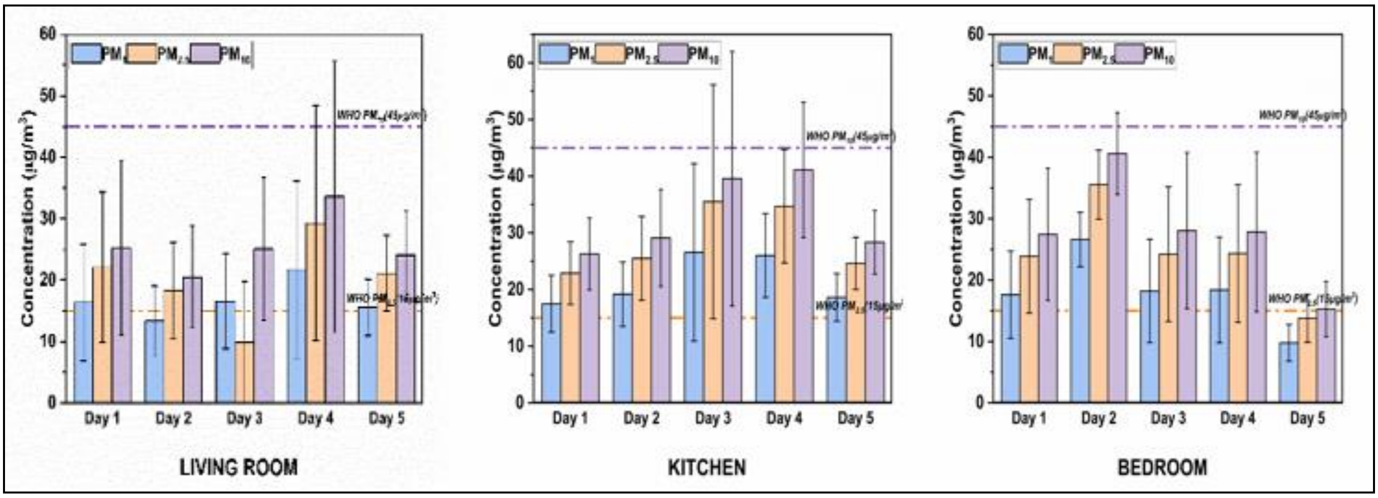

Fig 6 Mean Concentration of PM_1, PM2.5 and PM10 During Five Consecutive Monitoring Days in (a) Living Room (b) Kitchen, and (c) Bedroom

Figures 6(a–c) give the mean concentrations of PM_1, $PM_{2.5}$, and PM_{10} measured in the living room, kitchen, and bedroom during the monitoring period. The results indicate noticeable differences in particulate matter concentrations among the three residential microenvironments. The kitchen exhibited the highest mean concentrations for all particulate matter fractions during the 5-day monitoring period, with average values of 21.57 $\mu g/m^3$ (PM_1), 28.63 $\mu g/m^3$ ($PM_{2.5}$), and 32.88 $\mu g/m^3$ (PM_{10}). The higher concentrations in the kitchen can be attributed to cooking activities, which are recognised as major indoor sources of particulate matter. Emissions produced during frying, boiling, and other food preparation processes contribute significantly to the increase in both fine and coarse particles [18, 19].

The bedroom showed intermediate mean concentrations of 18.12 $\mu g/m^3$ (PM_1), 24.36 $\mu g/m^3$ ($PM_{2.5}$), and 27.84 $\mu g/m^3$ (PM_{10}). Although the bedroom is generally associated with fewer particle-generating activities, the measured concentrations suggest that indoor air quality was influenced by occupant movement, natural ventilation, and the transport of particles from other parts of the house. In contrast, the living room recorded the lowest average concentrations, with mean values of 16.70 $\mu g/m^3$ (PM_1), 22.54 $\mu g/m^3$ ($PM_{2.5}$), and 25.69 $\mu g/m^3$ (PM_{10}). The relatively lower concentrations may be due to better natural ventilation and the absence of direct indoor emission sources during most of the monitoring period.

Across all three microenvironments, the mean concentrations followed the order $PM_{10} > PM_{2.5} > PM_1$, indicating the presence of both coarse and fine particles indoors. The higher PM_{10} concentrations suggest that coarse particles generated by cooking activities, occupant movement, and dust resuspension contributed substantially to indoor particulate matter levels.

The observed trend is consistent with previous studies on residential indoor air quality, which reported that kitchens generally exhibit higher particulate matter concentrations than other indoor spaces due to cooking emissions [16, 17]. While bedrooms and living rooms generally experience lower average concentrations due to fewer direct emission sources. These findings are in agreement with the present study, highlighting the influence of room function and occupant activities on indoor particulate matter concentrations [20].

Overall, the comparison demonstrates that residential microenvironments exhibit distinct particulate matter characteristics, with the kitchen contributing the highest particle concentrations during the monitoring period. These findings emphasise the importance of improving kitchen ventilation and adopting appropriate cooking practices to reduce exposure to indoor particulate matter.

- *Relationship Between Relative Humidity and PM Concentrations*

Figures 7(a–c) illustrate the relationship between relative humidity (RH) and the concentrations of PM_1, $PM_{2.5}$, and PM_{10} in the living room, kitchen, and bedroom, respectively. In the living room (Figure 7a), a weak positive correlation was observed between RH and particulate matter concentrations, with correlation coefficients of 0.331, 0.327, and 0.324 for PM_1, $PM_{2.5}$, and PM_{10}, respectively. This suggests that particulate matter concentrations tended to increase slightly as relative humidity increased, although the relationship was not strong. The increase may be attributed to the hygroscopic growth of airborne particles at higher humidity and to the infiltration of outdoor air.

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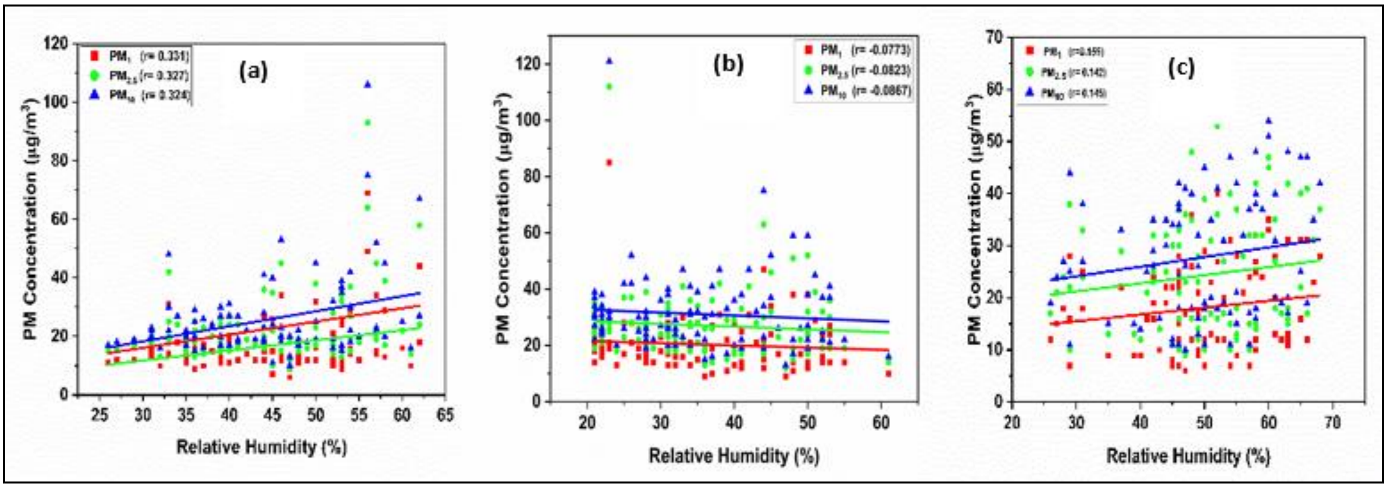

Fig 7 Scatter Plot of PM_1, $PM_{2.5}$, and PM_{10} Against Relative During Monitoring Days in (a) Living Room (b) Kitchen, and (c) Bedroom

In the kitchen (Figure 7b), a very weak negative correlation was observed between RH and particulate matter concentrations, with correlation coefficients ranging from −0.077 to −0.087. The weak relationship indicates that relative humidity had little influence on particulate matter levels in the kitchen. Instead, cooking activities were the dominant source of particulate matter, masking the effect of humidity on indoor particle concentrations.

The bedroom (Figure 7c) exhibited a weak positive correlation between RH and particulate matter concentrations, with correlation coefficients of 0.155, 0.142, and 0.145 for PM_1, $PM_{2.5}$, and PM_{10}, respectively. Although the correlation was weaker than in the living room, the results suggest a slight increase in particulate matter concentration as relative humidity increases. This behaviour may be associated with natural ventilation, occupant activities, and the movement of particles from adjacent indoor spaces.

Overall, the results indicate that relative humidity had only a weak influence on indoor particulate matter concentrations. In contrast, indoor emission sources and occupant activities played a more significant role in determining PM levels in the residential microenvironments. Other researchers have reported similar observations that indoor emission sources and occupant activities are the primary determinants of indoor PM concentrations rather than humidity alone [13, 21].

IV. CONCLUSION

This study assessed the concentrations of PM_1, $PM_{2.5}$, and PM_{10} in three residential microenvironments using a low-cost air quality monitor. The results showed clear variations in particulate matter concentrations among the living room, kitchen, and bedroom, demonstrating that indoor air quality is strongly influenced by room function and occupant activities. Among the three microenvironments, the kitchen exhibited the highest particulate matter concentrations and the greatest temporal variation due to cooking activities. In contrast, the living room and bedroom showed comparatively lower and more stable concentrations. Short-term peaks observed in the living room were likely due to outdoor particle infiltration and routine household activities. At the same time, the bedroom maintained relatively low PM levels, with occasional increases driven by occupant movement and natural ventilation.

The relationship between relative humidity and particulate matter concentrations was generally weak, indicating that indoor activities and ventilation had a greater influence on PM levels than humidity alone. Although the measurements were carried out sequentially rather than simultaneously, the study provides useful information on the temporal behaviour of indoor particulate matter in different residential microenvironments. The findings demonstrate that low-cost sensors can effectively monitor indoor air quality and identify pollution hotspots within residential buildings. Improving kitchen ventilation, minimising indoor particle-generating activities, and reducing the infiltration of outdoor dust can help lower indoor particulate matter exposure and improve the overall indoor environment.

This study contributes to understanding the characteristics of indoor particulate matter in residential buildings in Ballari, Karnataka. It provides baseline information to support future investigations into long-term monitoring, seasonal variation, and the assessment of additional indoor air pollutants using low-cost sensing technologies.

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