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METROLOGICAL CHANGES IN AMBIENT AIR QUALITY OF RARE AND DENSE AREA IN VARANASI (U.P.)

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Abstract

The study assessed ambient and indoor air quality at different roadside and residential locations categorized according to traffic density, housing type, and pollution intensity. The monitored pollutants included carbon oxides (COx), sulfur dioxide (SO_2), nitrogen oxides (NOx), and suspended particulate matter (SPM). The findings revealed significant seasonal and spatial variations in pollutant concentrations, with winter months generally exhibiting the highest levels and monsoon months the lowest. At the roadside locations, S1 rare area (Lanka and Bhojubeer) and S2 dense area (Godauliya and Lahurabeer), pollutant concentrations were strongly influenced by vehicular traffic and local environmental conditions. Roadside area (S2) recorded considerably higher concentrations of COx, NOx, SO_2, and SPM than the relatively less congested S1 location. SPM emerged as the dominant pollutant at both sites, frequently reaching very high levels during winter and post-monsoon periods. Reduced atmospheric dispersion, increased vehicular emissions, road dust resuspension, and combustion activities contributed to elevated pollution during these months. In contrast, rainfall and improved ventilation during the monsoon season significantly lowered pollutant concentrations. Indoor air quality investigations were conducted in both low-category and advanced-category houses located in narrow lanes and roadside environments. Results showed that indoor pollutant concentrations closely reflected outdoor pollution conditions, indicating a strong influence of ambient air on indoor environments. Houses situated in highly polluted areas exhibited elevated levels of COx, NOx, SO_2, and SPM throughout the year. Among all indoor environments, low-category houses located in narrow lanes generally recorded the highest pollutant concentrations. Kitchens consistently showed slightly higher concentrations of gaseous pollutants compared to living rooms, highlighting the impact of cooking-related emissions. However, living rooms often displayed elevated particulate matter levels due to infiltration of outdoor pollutants. Advanced-category houses exhibited lower pollutant concentrations than low-category houses, suggesting that improved building design, better ventilation systems, and superior construction materials can reduce indoor exposure to air pollutants. Roadside residences experienced greater indoor pollution than houses located in relatively sheltered narrow-lane environments. The influence of continuous vehicular emissions was particularly evident in elevated concentrations of COx and SPM. Advanced-category houses situated near busy roads also recorded significant pollutant loads despite their improved housing conditions, indicating that proximity to traffic sources remains a major determinant of indoor air quality.

Keyword: *Ambient Air Quality, Varanasi, Metrological changes*

Intrduction

Ambient air quality describes the condition of the indoor and outdoor air that surrounds living organisms and directly influences human health, ecological systems and overall environmental sustainability. Ambient air pollution is a complex mixture of particulate matter and gaseous pollutants, including nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and various volatile organic compounds (VOCs)1. Particulate matter consists of microscopic solid and liquid particles suspended in the atmosphere. Which classified as PM_{10} and $PM_{2.5}$. Major sources of ambient air pollution include vehicular emissions, industrial activities, construction operations, agricultural practices, and residential fuel combustion2. Natural events such as dust storms, wildfires, and volcanic eruptions also contribute to atmospheric pollution although their impacts are often episodic and localized. Human activities are the dominant drivers of deteriorating ambient air quality. Rapid urbanization and industrial growth have increased energy demand, traffic density, and construction-related emissions3. Agricultural practices such as crop residue burning, livestock rearing, and pesticide application further intensify pollution loads. Residential combustion of biomass fuels, coal, and wood also contributes significantly to local air pollution, particularly in developing regions. Poor ambient air quality poses severe risks to human health and the environment. Exposure to particulate matter, nitrogen dioxide, sulphur dioxide, and ozone has been linked to respiratory diseases such as asthma, bronchitis, and chronic obstructive pulmonary disease. Long-term exposure increases the likelihood of cardiovascular disorders, neurological impairments, and premature mortality4.

Factor Affecting air quality are Major human-induced contributors include industrial emissions, vehicular exhaust, thermal power generation, agricultural activities, and residential fuel combustion. These sources emit a range of pollutants, including particulate matter, nitrogen oxides, sulphur dioxide, carbon monoxide, and volatile organic compounds, which collectively deteriorate atmospheric quality. Air pollution is generally categorized into two main types on the basis of the pollutants formation i.e. primary and secondary pollution. Primary pollutants are Particulate Matter (PM) Tiny solid or liquid particles suspended in the air, SO_2, NO_x, Volatile Organic Compounds. Secondary Pollutants are nitric acid (HNO_3), sulfuric acid6. House quality also influence on Ambient Air Quality. Different constructions and layout of house affect ambient air quality7,8.

Varanasi (Uttar Pradesh) is globally celebrated as a sacred city and a vibrant center of culture, religion, and learning earning its fame as India's spiritual capital. Stretching along the western bank of the holy Ganges, Varanasi is strategically located between 25°31' and 25°20' North latitude and 83°0' and 83°6' East longitude, situated at roughly 80 meters above sea level. The city's unique blend of ancient traditions and bustling modernity makes it a living symbol of India's enduring cultural and spiritual legacy. The following areas of Varanasi city selected for research sampling. S1 to S2 such as S1: Rare Area- Lanka & Bhojubeer, S2: Busy Area- Godauliya & Lahurabeer. Rapid urbanization, population growth, and industrialization have significantly increased the release of air pollutants into the atmosphere. Vehicular emissions from cars, buses, trucks, and motorcycles release large amounts of carbon monoxide, nitrogen oxides, hydrocarbons, and particulate matter, particularly in congested urban areas9,10. Construction activities generate dust and fine particulate matter, further degrading air quality. Domestic activities, including the burning of wood, coal, or biomass for cooking and heating, also produce smoke and particulate matter that affect both indoor and ambient air11. Even waste management practices, such as burning solid waste and plastics, release toxic gases and fine particles into the environment.

Indoor air pollution is often more severe than outdoor pollution, given that individuals spend a significant proportion of their time indoors. Indoor air quality is affected by particulate matter, combustion products from cooking, and volatile organic compounds released from household materials12. Climate variability is likely to intensify air pollution impacts in India by altering meteorological conditions that control pollutant dispersion. Densely populated regions such as the Indo-Gangetic Plain are particularly sensitive, with projected increases in average $PM_{2.5}$ concentrations under future climate scenarios13. Ambient air quality conditions across five major functional zones of Varanasi and compared the observed concentrations with the limits prescribed by the Central Pollution Control Board (CPCB). The seasonal variability, daily peak concentrations, and dominant pollution sources in Varanasi using field measurements and continuous monitoring station data. The central urban locations such as Godowlia and Dashashwamedh Ghat as pollution hotspots, particularly during winter months, while comparatively lower pollution levels were recorded at peripheral locations such as Banaras Hindu University (BHU) and Sarnath.

Developed city-specific Air Quality Health Index (AQHI) frameworks to better capture localized air pollution-related health risks, using data from Delhi and Varanasi14. The public transport vehicles recorded the highest concentrations of volatile organic compounds, while restaurants and hospitality spaces showed elevated particulate matter levels due to poor ventilation. Indoor air pollution as a major contributor to chronic respiratory diseases, particularly chronic obstructive pulmonary disease16. Continuous monitoring of sulphur dioxide, nitrogen dioxide, and particulate matter (PM_{10}) in Gorakhpur from 2018 to 2022 and assessed air quality using the Indian Air Quality Index framework17.

Method of analysis

Instruments:

Instruments are employed for monitoring ambient air quality, including Ambient Air Quality Monitors (AAQM), High Volume Air Samplers (HVAS), Respirable Dust Samplers (RDS), Continuous Ambient Air Quality Monitoring Systems (CAAQMS), gas analyzers, particulate matter monitors for $PM_{2.5}$ and PM_{10}, multi-gas detectors, and advanced devices such as the GrayWolf DirectSense™ IAQ monitoring system. These instruments are widely used to assess concentrations of gaseous pollutants, particulate matter, temperature, humidity, and other environmental parameters in both indoor and outdoor environments18,19.

Monitoring Schedule

Air: In the present study, SPM and RSPM were monitored 48 hourly at 8 hourly intervals in a week and SO_2 and NO_x were monitored 48 hourly at 4 hourly intervals in a week, using respirable dust sampler (RDS) and high volume sampler. At each location, monitoring was carried out twice a week for the year July, 2023 to June, 2024 to cover all the five seasons winter (December to January), Summer (April to June), monsoon (July to September), autumn (October to November) and spring (February to March). Air pollutants were monitored according to the schedule.

GrayWolf Sensing instrument is used in this study. This is a fully integrated system for measuring indoor air quality, toxic gases, airspeed and other parameters. A Pocket PC running WolfSense™ PPC application software takes readings of air quality, toxic gas, airspeed, moisture or other parameters from a probe connected through the serial port20. WolfSense PC also assists in the creation of reports, incorporating the data and notes that have been collected. In the DirectSense™ IAQ PPC kit, the probe (model IQ-410) has four sensors, which provide up to nine measurements21: Temperature (°F, °C), Relative Humidity (%RH), Carbon Monoxide (ppm CO), and Carbon Dioxide (ppm CO_2) are the primary measurements. Dew Point Temperature, Absolute Humidity, Wet Bulb Temperature, Humidity Ratio and Specific Humidity are derived from the Temperature and Relative Humidity sensor readings22. For the measurement of these pollutants for indoor, the instruments were positioned in the center of the living room, bed room and kitchen at a height of 1 m from the ground, it was also kept at least 1 m away from potential sources of air pollutants. For outdoor measurements, sampling was made 5m away from the boundary of the house. The instruments were kept 1m above the ground level, and 1m away from the outdoor source of air pollutant.

This study was conducted during the winter of September 2023- November 2024. Concentrations of indoor Carbon Monoxide (ppm CO), Carbon Dioxide (ppm CO2), Temperature (0F/0C), Dew point temperature, absolute humidity, wet bulb temperature and relative humidity (%RH) were measured in the living room where people spent outdoor. Measurements were carried out 5m away from the house. Indoor and outdoor concentration levels of all these pollutants were alternatively measured for a period of 12h (6.00 am to 18.00pm) in a day.

Result & Discussion

- **Ambient Air pollution in S1 Road side location**

Ambient air pollution in Lanka and Bhojubeer raod side location lanes is characterized by high PM2.5 and PM10 levels, along with nitrogen oxides and carbon monoxide. There are present less amount of greenery which affect ambient air quality. Details of air components are presented in table 1.

Table 1: S1 Roadside Location (Lanka & Bhojubeer: Rare Area)

Ambient Air components in µg/m3												
Month	COx			SO2			NOx			SPM		
	Min	Max	Avg.	Min	Max	Avg.	Min	Max	Avg.	Min	Max	Avg.
Jan	52	157	104.5	5	5	5	31	41.4	36.2	26.5	105	65.7
Feb	48	147	97.5	5	5	5	23.2	41.2	32.2	39.9	294	166.9
Mar	42	136.5	89.2	6.3	23.1	14.7	19.4	47.8	33.6	23.1	273	148.9
Apr	35	130	82.5	5.8	25	15.4	18.4	41	29.7	31	260	145.5
May	31.5	160	95.7	3.6	26.5	14.9	17.3	45.7	31.5	63	210	136.5
June	21	105	63	6.3	23.1	14.7	17	41.5	29.2	22.1	221.2	121.6
July	10	63	36.5	2.3	23.1	12.7	17.3	41.5	29.4	12.2	157.5	84.8
Aug	15.7	73.5	44.6	4.2	21.3	12.7	15.2	37.3	26.2	13.3	197.5	105.4
Sep	26.2	84	55.1	4.2	22.5	13.1	17.3	45.4	31.3	5.9	210	107.9
Oct	36.7	115.5	76.1	6.3	25.2	15.7	18.4	46.7	32.5	21.3	262.5	141.9
Nov	47.2	147	97.1	7.35	26.2	16.8	19.4	49.9	34.6	30.7	294.5	162.6
Dec	63	168	115.5	8.4	28.3	18.3	21.5	54.1	37.8	27.8	325.5	176.2

The table 1 roadside air-quality data show consistently higher concentrations during winter and post-monsoon months, with COx and SPM peaking from October to February. This reflects greater traffic congestion, lower atmospheric dispersion, and increased combustion activities in cooler months23. Summer and monsoon months (June–August) record comparatively lower pollutant levels due to rainfall washout and improved ventilation. SPM levels remain the most critical concern, frequently exceeding typical urban standards, indicating heavy resuspension of road dust and vehicular emissions.

- **Ambient Air pollution in S2 Road side location:**

Ambient air pollution in Godauliya and Lahurabeer (S2) Road Side location areas is marked by elevated PM2.5, PM10, nitrogen oxides, and carbon monoxide. Intense pedestrian movement, continuous vehicular congestion, street vendors, construction dust, and restricted air circulation lead to pollutant accumulation, significantly deteriorating local air quality and public health. Details of air components are presented in table 2.

Table 2: S2 Roadside location (Godauliya & Lahurabeer: Busy Area)

Ambient Air components in µg/m3												
Month	COx			SO2			NOx			SPM		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
Jan	71.6	214.9	143.3	7.1	28.7	17.9	24.3	67.3	45.9	143.3	430	286.6
Feb	64.4	200.6	132.5	7.1	28.6	17.2	22.9	64.6	41.8	128.9	401	264.9
Mar	57.3	186.3	121.8	8.6	31.5	19.7	22.9	61.6	43.8	114.6	372	245.1
Apr	50.1	178.1	114.8	10.4	34.4	21.2	21.4	60.1	41.5	100.3	359	258.7
May	42.9	171.9	107.1	11.4	35.8	23.6	20.4	58.7	39.9	85.9	343	222.7
June	28.6	143.3	86.9	8.6	31.5	20.7	18.6	52.9	36.7	57.3	301	200.3
July	14.3	85.9	78.4	5.7	28.6	12.7	15.7	45.8	22.6	42.9	215	126.9
Aug	21.5	100.3	60.3	5.7	28.6	12.7	17.6	47.2	22.3	50.1	201	125.9
Sep	35.8	114.6	75.2	7.1	30.1	12.7	20.4	57.2	38.6	71.6	287	180.8
Oct	50.1	157.6	109.1	8.6	34.4	21.2	21.4	60.1	38.7	107.5	359	131.0
Nov	64.	200.	132.5	10	35.8	14.9	22.9	64.4	32.7	128.9	401	196.9
Dec	85.9	229.3	157.6	11.4	38.7	25.1	25.7	70.2	48.9	157.6	445	301.6

Table 2 shows that ambient air quality at this busy roadside location shows consistently high pollutant loads, with winter months generally recording the highest averages for COx, NOx and SPM, indicating poor dispersion under stable atmospheric conditions. COx averages often exceed 120 µg/m³, while NOx and SO_2 remain comparatively lower but still elevated, reflecting dominant vehicular emissions. SPM levels are particularly concerning, with several months showing very high average values, suggesting significant respirable particulate pollution. Summer and monsoon months display somewhat reduced concentrations, likely due to better dispersion and wet deposition, yet levels remain indicative of sustained, traffic-related air quality stress24.

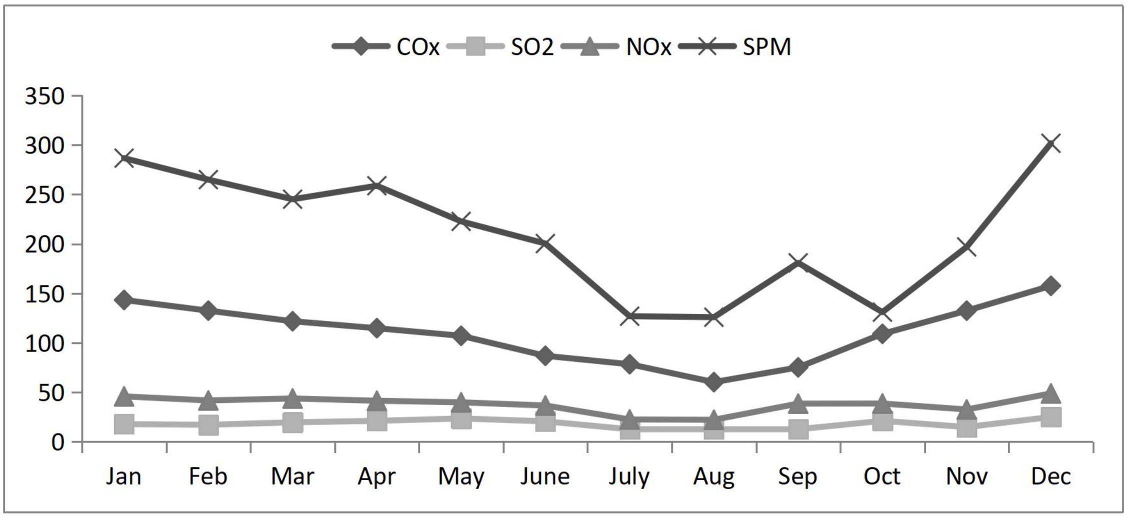

Fig. 2: S2 Roadside location (Godauliya & Lahurabeer: Busy Area)

Indoor ambient quality for S1 (Narrow lane area in low category houses) for high polluted area:
This is high polluted zone in this category of house which reflects significantly from surrounding outdoor emissions and limited ventilation. Elevated levels of COx, SO_2, NOx, and SPM likely accumulate indoors, posing health risks such as respiratory discomfort, eye irritation, and reduced overall indoor environmental quality. Details of observation given in table 3.

Table 3: Indoor ambient quality for S1 Narrow lane area in low category houses for high polluted area (living (Liv.) &kitchen(Kit.) room in µg/m3)

Month	COx			SO2			NOx			SPM		
	Liv.	Kit.	Avg	Liv.	Kit.	Avg	Liv.	Kit.	Avg	Liv.	Kit.	Avg
Jan	88	90	89	9.75	10	9.8	28.65	29	28.82	156	160	158
Feb	82.15	84	83.1	9.75	10	9.8	27.68	28	27.84	144.3	148	146.1
Mar	76.3	78	77.1	10.92	11.2	11.1	32.55	33	32.77	132.6	136	134.3
Apr	72.4	74	73.2	12.09	12.4	12.2	31.77	32.2	31.98	124.8	128	126.4
May	68.5	70	69.2	12.87	13.2	13.1	29.43	29.8	29.62	101.4	104	102.7
June	56.8	58	57.4	15.6	16	15.1	25.14	25.4	25.27	89.7	92	90.85
July	37.3	38	37.6	9.36	9.6	9.4	26.31	26.6	26.46	74.1	76	75.05
Aug	43.15	44	43.5	9.75	10	9.85	24.75	25	24.88	64.35	66	65.18
Sep	58.75	60	59.3	10.14	10.4	10.2	22.61	22.8	22.71	97.5	100	98.75
Oct	64.6	66	65.3	11.31	11.6	11.4	24.36	24.6	24.48	117	120	118.5
Nov	82.15	84	83.1	12.09	12.4	12.2	34.11	34.6	34.36	144.3	148	146.1
Dec	95.8	98	96.9	13.65	14	13.8	35.67	36.2	35.94	163.8	168	165.9

The table 3 reveals that levels of ambient air gases peak in winter months, with COx up to 85 µg/m³ and SPM to 165 µg/m³, while summer shows minimums around 9-35 µg/m³ across pollutants. Overall, kitchen concentrations often exceed living rooms, indicating cooking-related emissions, with annual means decreasing from winter highs25.

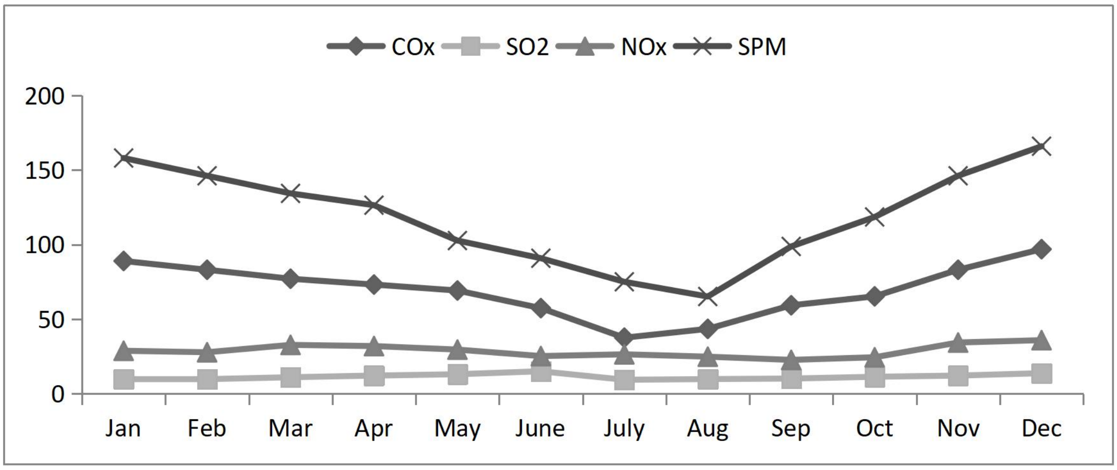

Fig. 3: Indoor ambient quality for S1 Narrow lane area in low category houses for high polluted area (living (Liv.) &kitchen(Kit.) room in µg/m3)

Indoor ambient quality for S1 (Narrow lane area in advanced category houses) for high polluted area:

Indoor ambient quality in S1 narrow lane advanced-category houses within high-polluted areas reveals seasonal pollutant patterns. Details of data presented in table 4.

Table 4: Indoor ambient quality for S1 (Narrow lane) Advanced category dwellers in high polluted area. (kitchen(Kit.) & living (Liv.) room in µg/m3)

Month	COx			SO2			NOx			SPM		
	Liv.	Kit.	Avg	Liv.	Kit.	Avg	Liv.	Kit.	Avg	Liv.	Kit.	Avg
Jan	79	81	80	8.6	8.9	8.8	27.1	27.4	27.3	138	142	140
Feb	73.8	75.7	74.8	8.6	8.9	8.8	26.2	26.5	26.4	127.7	131.4	129.5
Mar	68.7	70.4	69.5	9.7	9.9	9.8	30.5	31	30.8	117.3	120.7	119

Apr	65.2	66.8	66	10.7	11	10.9	29.8	30.3	30.1	110.4	113.6	112
May	61.8	63.3	62.5	11.4	11.7	11.6	27.8	28.1	28	89.7	92.3	91
June	51.4	52.6	52	13.8	14.2	14	24	24.2	24.1	79.4	81.7	80.5
July	34.2	34.9	34.5	8.3	8.5	8.4	25	25.3	25.2	65.6	67.5	66.5
Aug	39.3	40.2	40	8.6	8.9	8.8	23.6	23.9	23.8	56.9	58.6	57.8
Sep	53.1	54.4	53.8	9	9.2	9.1	21.7	21.9	21.8	86.3	88.8	87.5
Oct	58.3	59.7	59	10	10.3	10.2	23.3	23.5	23.4	103.5	105	105
Nov	73.8	75.7	74.8	10.7	11	10.9	31.9	32.4	32.2	127.7	131.4	129.5
Dec	79	81	80	12.1	12.4	12.3	33.3	33.8	33.6	144.9	149.1	147

Table 4 examines shows that annual averages: COx 54 µg/m³, SO2 11 µg/m³, NOx 13 µg/m³, SPM 109 µg/m³; kitchens higher by ~2 µg/m³. Winter peaks show COx ~70 µg/m³, SPM 136 µg/m³; summer troughs COx 33 µg/m³, SPM 70 µg/m³. Elevated high-pollution site levels exceed prior low26.

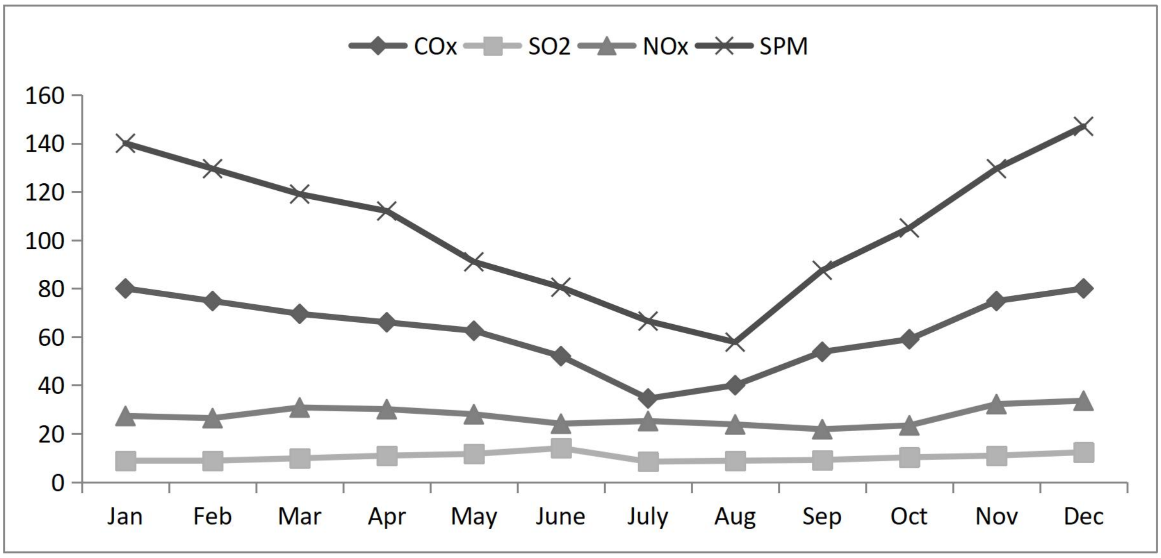

Fig. 4: Indoor ambient quality for S1 (Narrow lane) Advanced category dwellers in high polluted area. (kitchen(Kit.) & living (Liv.) room in µg/m3)

Indoor ambient quality for S1 (Road side location in advanced category houses) for high polluted area:

Indoor ambient quality in S1 Road side location in advanced-category houses within high-polluted areas reveals seasonal pollutant patterns. Details of data presented in table 5.

Table 5: Indoor ambient quality for S1 (Road side location) Advanced category in high polluted area. [kitchen (Kit.) & living (Liv.) in µg/m3]

Month	COx			SO2			NOx			SPM		
	Liv.	Kit.	Avg	Liv.	Kit.	Avg	Liv.	Kit.	Avg	Liv.	Kit.	Avg
Jan	76.8	79.1	77.9	3.6	3.7	3.7	20.7	21.4	21	46.9	48.5	47.7
Feb	71.7	74	72.8	3.6	3.7	3.7	17.9	18.5	18.2	119.2	123.1	121.2
Mar	65.8	67.8	66.8	10.5	10.8	10.7	18.9	19.4	19.1	106.4	109.8	108.1
Apr	61	62.9	62	11	11.4	11.2	16.1	16.6	16.4	103.9	107.4	105.7
May	70.4	72.6	71.5	10.7	11	10.9	17.4	17.9	17.6	97.5	100.7	99.1
June	47	48.5	47.8	10.5	10.8	10.7	15.7	16.2	15.9	86.9	89.7	88.3
July	28.1	28.9	28.5	9.1	9.4	9.2	15.9	16.3	16.1	60.6	62.6	61.6
Aug	33.9	34.9	34.4	9.1	9.4	9.2	13.6	14	13.8	75.3	77.8	76.6
Sep	41.4	42.7	42	9.4	9.7	9.6	17.2	17.7	17.4	77.2	79.6	78.4
Oct	56.4	58.1	57.2	11.2	11.6	11.4	18.1	18.6	18.4	101.4	104.7	103
Nov	71.4	73.7	72.6	12	12.4	12.2	19.6	20.2	19.9	116.2	119.9	118
Dec	84.6	87.3	85.9	13.1	13.5	13.3	21.9	22.5	22.2	125.9	130	128

This table 5 show that SPM is the most prevalent pollutant, reaching its highest levels during winter months. COx levels also peak in winter, while SO_2 and NOx remain relatively low. Pollutant levels are consistently slightly higher in the kitchen than the living area27.

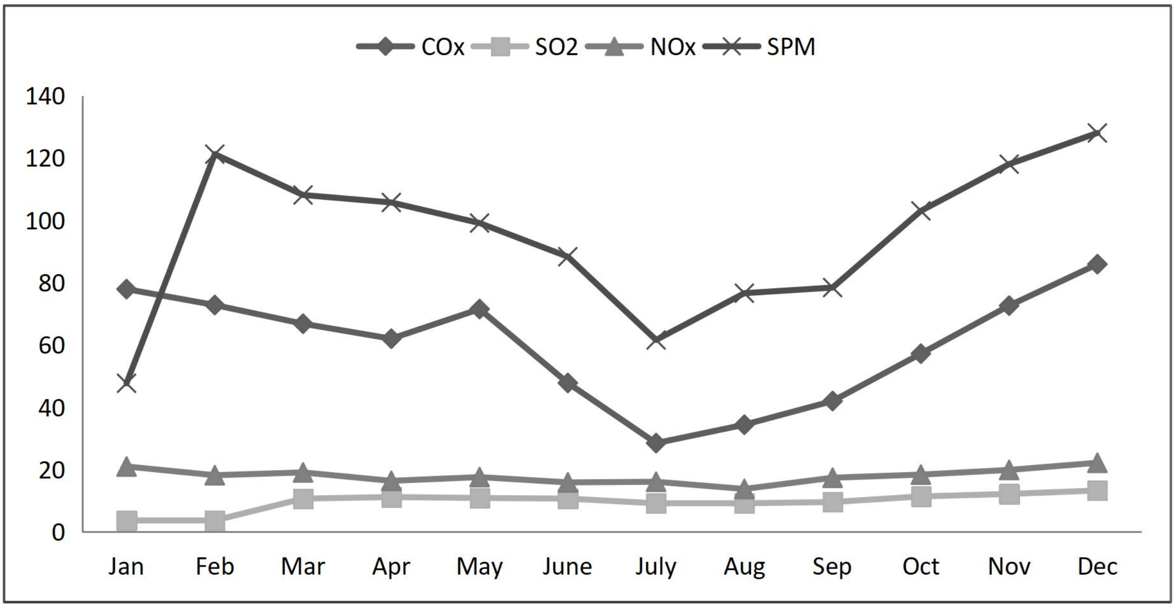

Fig. 5: : Indoor ambient quality for S1 (Road side location) Advanced category in high polluted area. [kitchen (Kit.) & living (Liv.) in µg/m3]

Indoor ambient quality for S2 (Narrow lane location in low category houses) for high polluted area:
Indoor ambient quality in S2 Narrow lane location in low-category houses within high-polluted areas reveals seasonal pollutant patterns. Details of data presented in table 6.

Table 6: Indoor ambient quality for S2 (Narrow lane area in low category houses for high polluted) [kitchen (Kit.) & living (Liv.) in µg/m3]

Month	**COx**			**SO2**			**NOx**			**SPM**		
	Liv.	Kit.	Avg	Liv.	Kit.	Avg	Liv.	Kit.	Avg	Liv.	Kit.	Avg
Jan	114.9	116.3	115.6	8	8.1	8.1	27.8	28.6	28.2	223.9	226.6	225.2
Feb	106.5	107.7	107.1	8	8.1	8.1	26.7	27	26.9	207.1	209.6	208.3
Mar	98.1	99.3	98.7	8.6	8.7	8.6	24.8	25.1	25	189.7	192	190.8
Apr	92.5	93.6	93	8	8.1	8.1	23.1	23.3	23.2	155.2	157.1	156.1
May	86.9	87.9	87.4	4.5	4.6	4.5	25.7	26	25.9	160.6	162.5	161.6
June	70.2	71	70.6	9.2	9.3	9.2	25.6	25.8	25.7	123.5	125	124.2
July	42.1	42.6	42.4	13.4	13.5	13.4	18.8	19	18.9	102.9	104.2	103.6
Aug	45.6	46.1	45.9	13.4	13.5	13.4	33.5	33.9	33.7	106.6	107.9	107.2
Sep	48.6	49.1	48.9	14.4	14.5	14.4	26.5	26.7	26.6	138.4	140.1	139.2
Oct	42.6	43.1	42.9	12.9	13	12.9	22.6	22.9	22.8	100.7	101.9	101.3
Nov	39.7	40.1	39.9	6.7	6.8	6.8	17.2	17.4	17.3	131.6	133.2	132.4
Dec	95.9	97	96.5	11.2	11.4	11.3	19.2	19.4	19.3	149.7	151.5	150.6

The table 6 show that SPM is the most prevalent pollutant, reaching its highest levels during winter months. COx levels also peak in winter, while SO_2 and NOx remain relatively low. Pollutant levels are consistently slightly higher in the kitchen than the living area28,29.

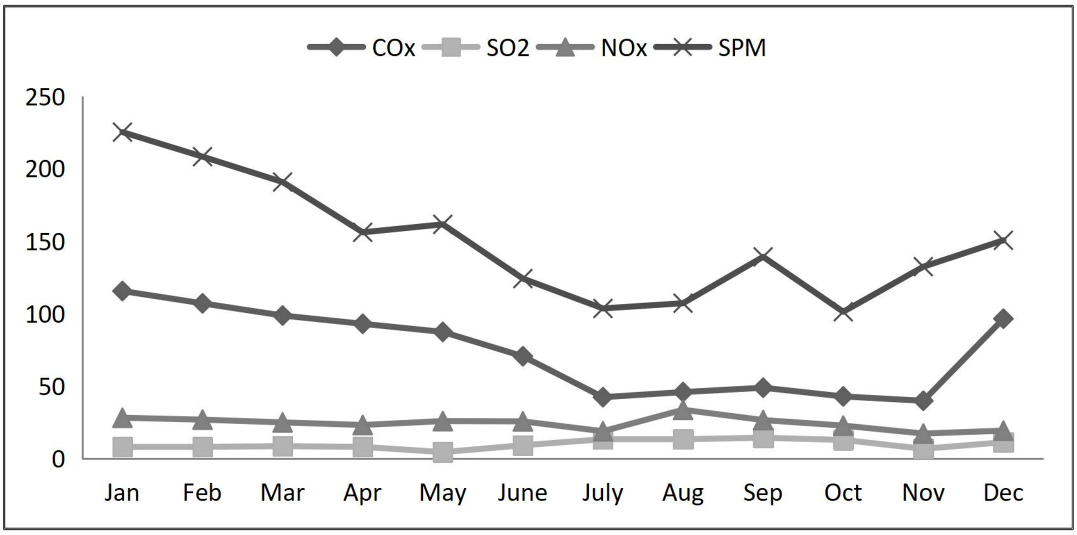

Fig. 6: Indoor ambient quality for S2 (Narrow lane area in low category houses for high polluted) [kitchen (Kit.) & living (Liv.) in µg/m3]

Indoor ambient quality for S2 (Narrow lane location in advanced category houses) for high polluted area:
Indoor ambient quality in S2 Narrow lane location in advanced-category houses within high-polluted areas reveals seasonal pollutantpatterns. Details of data presented in table 7.

Table 7: Indoor ambient quality for S2 (Narrow lane location in advanced category) for high polluted area [kitchen(Kit.) & living (Liv.) in µg/m3]

Month	COx			SO2			NOx			SPM		
	Liv.	Kit.	Avg	Liv.	Kit.	Avg	Liv.	Kit.	Avg	Liv.	Kit.	Avg
Jan	114.7	117.9	116.3	7.2	7.5	7.3	27.1	28.1	27.6	199.8	208.6	204.2
Feb	104.4	107.6	106	7.2	7.5	7.3	26.2	27.1	26.6	184.8	192.9	188.9
Mar	94.2	97.4	95.8	7.7	8	7.8	24.5	25.3	24.9	169.3	176.7	173
Apr	87.4	90.6	89	7.1	7.4	7.2	22.9	23.7	23.3	138.6	144.6	141.6
May	80.5	83.7	82.1	4	4.2	4.1	25.3	26.2	25.8	143.3	149.6	146.4
June	60.1	63.3	61.7	8.2	8.6	8.4	25.1	26	25.6	110.2	115.1	112.7
July	25.9	29.1	27.5	11.9	12.5	12.2	19.1	19.7	19.4	91.9	95.9	93.9
Aug	30.1	33.3	31.7	11.9	12.5	12.2	32.2	33.4	32.8	95.2	99.3	97.2
Sep	33.8	37	35.4	12.8	13.4	13.1	25.9	26.9	26.4	123.6	129	126.3
Oct	26.5	29.7	28.1	11.5	12	11.8	22.5	23.3	22.9	89.9	93.8	91.8
Nov	22.9	26.1	24.5	6	6.3	6.2	17.7	18.2	17.9	117.5	122.6	120
Dec	91.5	94.7	93.1	10	10.5	10.2	19.4	20.1	19.8	133.6	139.4	136.5

Table 7 shows that winter peaks dominate, especially SPM, while monsoon yields lows due to cleansing rains. Kitchens show marginally higher COx/SO2 from cooking, living rooms elevated SPM from external sources30,31.

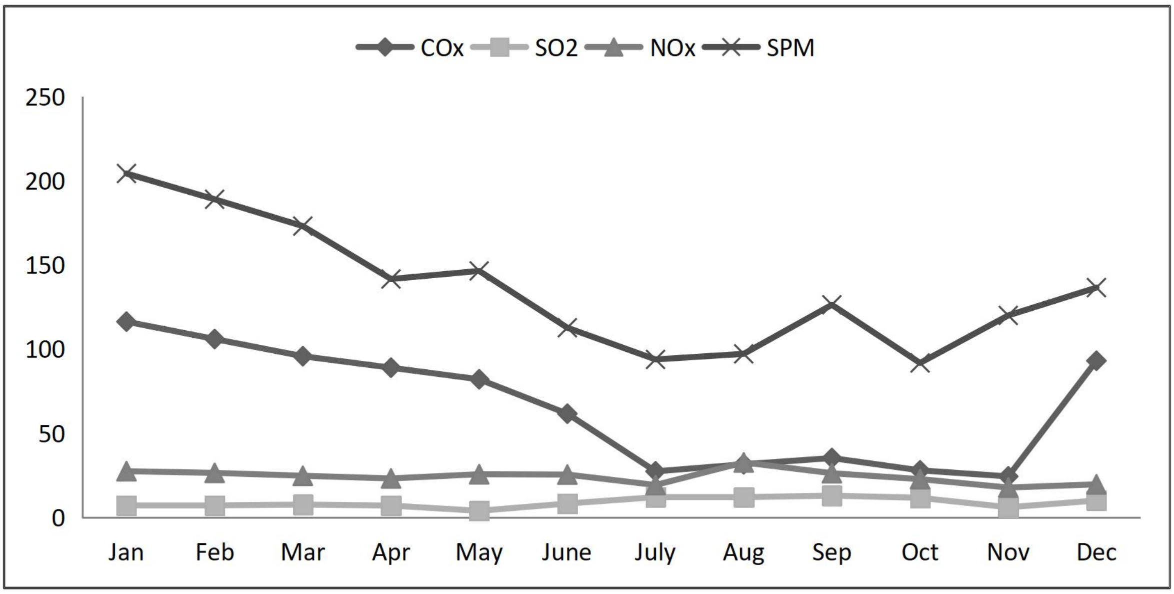

Fig. 7: Indoor ambient quality for S2 (Narrow lane location in advanced category) for high polluted area [kitchen(Kit.) & living (Liv.) in µg/m3]

Indoor ambient quality for S2 (Road side location in advanced category houses) for high polluted area:
Indoor ambient quality in S2 Road side location in advanced-category houses within high-polluted areas reveals seasonal pollutant patterns. Details of data presented in table 8.

Table 8: Indoor ambient quality for S2 (Road side location in advanced category) for high polluted area [kitchen(Kit.) & living (Liv.) in µg/m3]

Month	COx			SO2			NOx			SPM		
	Liv.	Kit.	Avg	Liv.	Kit.	Avg	Liv.	Kit.	Avg	Liv.	Kit.	Avg
Jan	110.2	114	112.1	13.8	14.2	14	45.8	47.2	46.5	220.2	228	224.1
Feb	101.8	105.3	103.6	13.2	13.7	13.5	42.6	43.9	43.3	203.7	210.6	207.2
Mar	93.6	96.8	95.2	15.1	15.7	15.4	44.2	45.5	44.9	188.4	194.7	191.6
Apr	88.3	91.3	89.8	16.3	16.9	16.6	42.4	43.7	43.1	198.9	205.8	202.4
May	82.3	85.1	83.7	18.1	18.7	18.4	41.2	42.3	41.8	171.3	177	174.2
June	66.8	69.1	67.9	15.9	16.5	16.2	38.7	39.7	39.2	154	159.2	156.6
July	60.3	62.3	61.3	9.8	10.1	9.9	27.8	28.3	28.1	97.5	100.8	99.2
Aug	46.4	48	47.2	9.8	10.1	9.9	27.5	28.0	27.8	96.8	100.1	98.5
Sep	57.8	59.8	58.8	9.8	10.1	9.9	40.2	41.3	40.8	138.9	143.7	141.3
Oct	83.9	86.7	85.3	16.3	16.9	16.6	40.2	41.4	40.8	100.7	104.1	102.4
Nov	101.8	105.3	103.6	11.4	11.8	11.6	35.6	36.5	36.1	151.4	156.5	153.9
Dec	121.2	125.3	123.3	19.3	20.5	19.9	48.1	49.7	48.9	231.8	239.7	235.8

The table 36 shows that kitchens display elevated COx/SO_2 from combustion, while SPM surges roadside-influenced in living spaces. Extreme winter peaks plummet in monsoon, confirming inversion trapping and rain scavenging. High levels signal urgent need for source control and filtration in traffic-exposed advanced housing32-34.

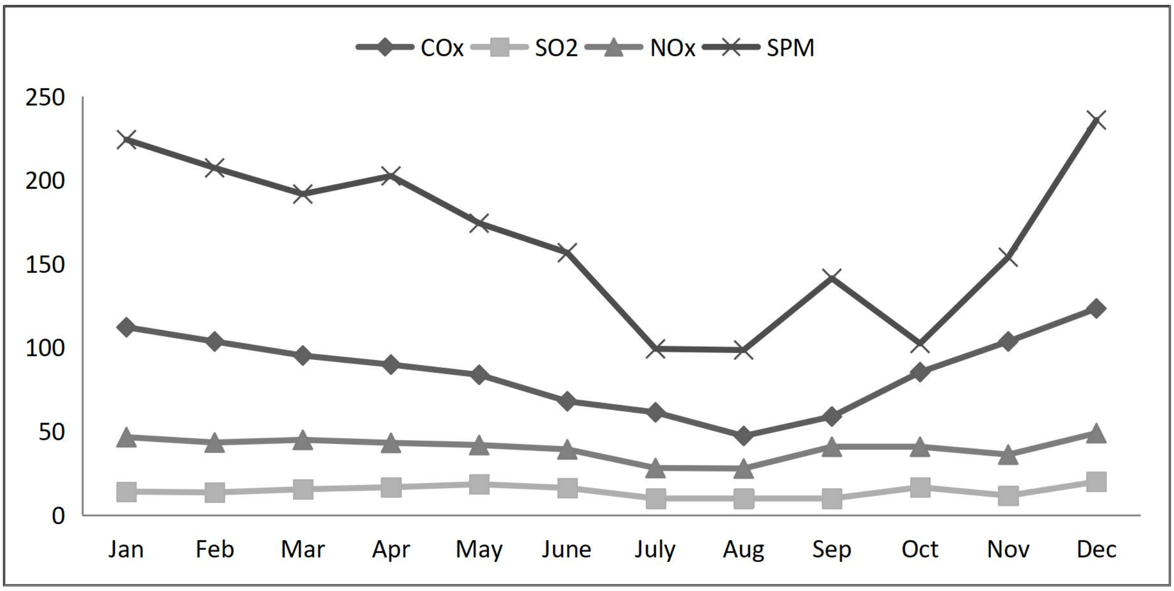

Fig. 8: Indoor ambient quality for S2 (Road side location in advanced category) for high polluted area [kitchen(Kit.) & living (Liv.) in µg/m3]

Conclusion:

The present study highlights the significant influence of traffic density, housing characteristics, and seasonal variations on both ambient and indoor air quality. Among the monitored pollutants, suspended particulate matter (SPM) was found to be the most dominant contaminant in both roadside and residential environments. Pollutant concentrations were consistently higher at busy roadside locations compared to less congested areas, indicating the major contribution of vehicular emissions, road dust, and other anthropogenic activities to air pollution.

Indoor air quality was strongly affected by outdoor pollution levels, particularly in houses located near busy roads and narrow lanes. Low-category houses generally exhibited higher pollutant concentrations than advanced-category houses due to poorer ventilation and greater infiltration of outdoor pollutants. Kitchens showed slightly elevated levels of gaseous pollutants, reflecting the additional impact of cooking activities on indoor air quality.

Seasonal trends revealed that winter months recorded the highest concentrations of COx, SO_2, NOx, and SPM, whereas monsoon months showed comparatively lower levels because of rainfall-induced pollutant removal and improved atmospheric dispersion. The study demonstrates that both ambient and indoor air pollution pose potential health risks to residents, especially in highly polluted urban areas. Therefore, effective traffic management, reduction of vehicular emissions, improvement in housing ventilation, and implementation of air quality control measures are essential to protect public health and improve environmental quality.

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