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Sensor Based Air Pollutants Monitoring Using Unmanned Aerial Vehicle in Raipur City

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ABSTRACT. Sensor based air quality monitoring systems has an ability to provide real-time data with higher resolution. In the current study, small and portable sensor-based air quality monitoring system coupled with an unmanned aerial vehicle (UAV) platform has been used. Air pollutants such as particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2), carbon monoxide (CO), and sulphur dioxide (SO_2) are vertically monitored at eight different locations spread across four zones (i.e., industrial, transportation, residential, and public-place zone) in Raipur city. Vertical variation of pollutants at 5, 10, 15, and 20 m from ground level are monitored and analysed. Data has been analysed for the above five pollution causing parameters and it is observed that there is decreasing trend in the concentration has been observed to be winter > post-monsoon > monsoon season as reported in the previous studies for Raipur city. This type of monitoring system is cost effective as it requires UAV, sensors, mobile, and less skilled person for operation when compared to above mentioned monitoring systems in India. There are certain limitations of the study which includes less flying endurance of the UAV used with additional payload, observation of air pollutant concentration at lower altitude, and restrictions imposed on flying UAV at any location by the local authority due to COVID-19.

Keywords: UAV, PM_{10}, $PM_{2.5}$, NO_2, CO, SO_2, vertical monitoring

1. Introduction

Air quality is affected by quantity of pollutant emissions, frequency, type of physical and chemical changes in the atmosphere. Both natural and anthropogenic pollutants are found in the air for a variety of reasons. Human induced pollutants are found in high quantities in heavily urbanized areas, where population density is often high, and also having negative impact on human health. Pollution levels are mostly caused by low stack emissions (Chlebowska-Styś et al., 2017), primarily from road transport and household and municipal garbage, as well as from individual building (Jeong et al., 2008; Zhao et al., 2017).

To reduce emissions from these sources, scientists and authorities have developed an effective management system. Although, affluent countries have homogeneous and measurable sources, they have problems in hotspot areas, which are controlled by location-specific air quality control plans. Furthermore, atmospheric contamination associated with hardship are further complicated and critical in developing countries, where sources are diverse, unidentified, and uncontrolled. Previous research informed that ambient air pollutant levels in Indian metropolitan cities have been consistently infringing the World Health Organization (WHO) and National Ambient Air Quality Standards (NAAQS) guidelines in the past few years (Gulia et al., 2017; Kumar et al., 2017). These investigations found a lot of spatial and temporal variations. For the development of an effective administration strategy, these huge spatiotemporal fluctuations in air pollution levels need reliable and prompt measurement.

Air quality monitoring is currently conducted in Raipur using both traditional manual stations and real-time continuous ambient air quality monitoring stations (CAAQMS). Every six months, the monitor/analyzer of the CAAQMS is calibrated to assure the superiority of the generated data. Such stations are permanently installed and produce air quality data for a particular area at a very high cost. Hence, it is necessary to develop a new monitoring method that is both precise and cost-effective so it can be adopted by other rapidly rising cities or smart cities of India.

In interpretation of the above-mentioned criteria, the current research is an effort to investigate the viability of a small portable air quality monitoring system. The current study looked at several air quality monitoring methodologies as well as their benefits and drawbacks. Deshmukh et al. (2013) used the gravitimetric analysis for size segregation of particulate matter samples. Deepaka and Jaya (2018) used low volume sampler for monitoring partticulate matters. Guttikunda et al. (2019) and Jaiswal et al. (2019) performed the manual monitoring for observation of air pollutants. There are a diverse range of air pollution monitoring technologies available, ranging from tradi-

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Table 1. Zone Wise Air Pollutant Monitoring Locations

Zone	Description (Nomenclature)	Latitude (N)	Longitude (E)
Industrial	Urla (I1)	21°18'34.488"	81°37'09.868"
Residential	Avanti Vihar house roof (R1)	21°14'33.828"	81°40'09.624"
	Avanti Vihar road (R2)	21°14'34.130"	81°40'09.454"
	Residence near AIIMS (R7)	21°15'20.304"	81°34'59.736"
	Sarona (R8)	21°14'50.564"	81°34'20.953"
Public Place	Agrasen Chowk (PP1)	21°14'46.920"	81°37'35.110"
Transportation	Pachpedi Naka Bridge (T3)	21°13'12.360"	81°38'56.929"
	Pachpedi Naka Road (T4)	21°13'12.676"	81°38'59.647"
	Raipur Chowk bridge (T5)	21°13'52.694"	81°36'05.626"
	Raipura Chowk Road (T6)	21°13'52.467"	81°36'04.827"
	Tatibandh Chowk (T7)	21°15'32.299"	81°34'02.661"

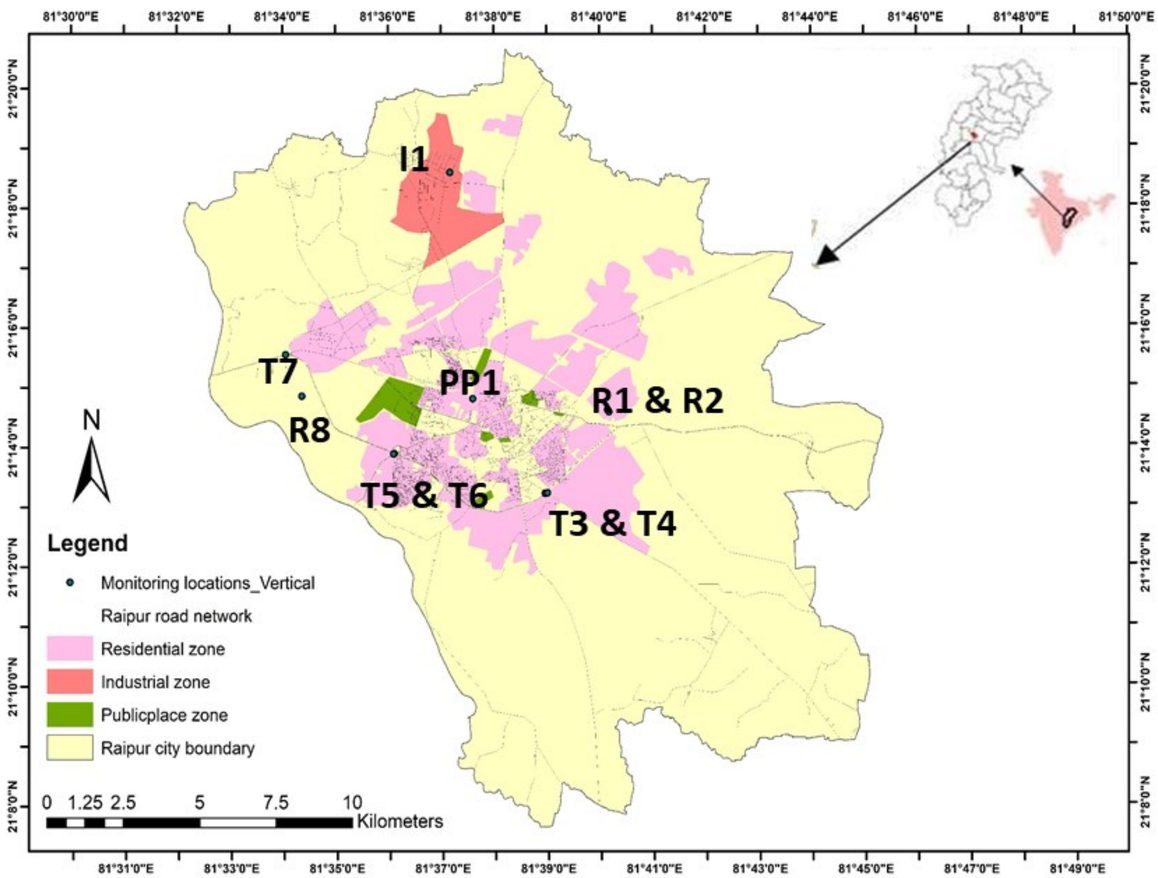

Figure 1. Study area showing monitoring locations at different zones.

tional to advanced. Traditional air pollution monitoring systems are mainly comprised of composite devices that are well-known. To assure data quality and precision, this equipment employs composite measuring techniques as well as a variety of other technologies. However, these instruments are expensive requires high current intake, have large volume, and are bulky. Advanced methods such as light detection and ranging, satellite remote sensing, aircrafts, and unmanned aerial vehicles (UAVs) can track emissions in three dimensions, although satellite remote sensing systems are not extensively employed due to their high cost and limited resolution. Another limitation of the satellite approach is the unreliability of the data obtained. Aircraft/helicopters are only considered when a vast region needs to be covered in a short amount of time with a high observation height (Lambey and Prasad, 2021). The cost and absence of low-altitude observations are disadvantages of this technique. UAVs are more efficient in terms of 3D monitoring than fixed wing aircraft, have higher sampling resolution, are less expensive, and can be operated from the ground.

Previously, numerous studies have been done on air quality monitoring using an UAV but they all have some limitations, which mainly include the study of single pollutant only in vertical direction without access to the real time data (Mueller et al., 2015; Li et al., 2019; Liu et al., 2020). Several studies (Moltchanov et al., 2015; EioNet, 2018; Singla et al., 2018; Li et al., 2020) suggested that low-cost sensors could be a good alternative for air quality monitoring in cities with significant spatiotemporal fluctuations and budget restrictions. The initial investment and yearly operational costs of a wireless sensor-based air quality monitoring system are often regarded to be approximate five times lower than those of a traditional monitoring systems. It can also be used to build a city-wide exposure assessment map with fewer ambiguity using interpolation (Kanaroglou et al., 2005). The majority of the sensors use metal oxide or electrochemical technology. The electrochemical theory is used in gas sensors, while the light scattering approach is used in particulate matter sensors. The sensors are calibrated in the manufacturing plant and in the field with a fixed concentration and with a standard device (Moltchanov et al., 2015; Borrego et al., 2018; Zimmerman et al., 2018). However, this technology has a number of drawbacks, including short life span, data management cost which at times exceed the sensor cost (White et al., 2012). The performance can degrade as time goes on sensor drift or simply ageing, or due to calibration fails if significant pollutant distribution or environmental changes occur during the effective implementation in relation to calibrating time (Castell et al., 2017; Hagan et al., 2018; Masey et al., 2018; De Vito et al., 2020). It can only operate within a certain humidity and temperature range, and it may be susceptible to influence from other gases.

In the current study, small and portable sensor-based air quality monitoring system coupled with UAV platform has been used. Air pollutants such as particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2), carbon monoxide (CO), and surfur dioxide (SO_2) are monitored at eight different locations for Raipur city. Vertical variation of pollutants at 5, 10, 15, and 20 m from ground level are monitored and analyzed. The current study is an advancement to the previous studies in many ways. Firstly, it includes vertical monitoring of pollutants which has been not done previously. Secondly, monitoring of concentration of various pollutants using a single monitoring system. Thirdly, the transmission of real time data to the user.

2. Methods

2.1. Study Area

Raipur, the state capital of Chhattisgarh, is situated on the Mahanadi River's western bank. Raipur is located between 21°11′22″ to 21°20′02″ N and 81°32′20″ to 81°41′50″ E, as shown in Figure 1. The city's elevated landscape varies between 219 and 322 meters. It features a level surface with a few high areas that have a general northwest slope. Raipur has a tropical climate with both wet and dry seasons. The average yearly temperature is around 27 °C. In April and May, temperatures may exceed 45 °C. The annual precipitation averages around 1330 mm. Summer (March ~ May), monsoon (June ~ September), post-monsoon (October ~ November), and winter (December ~ February) are the four seasons of Raipur. It has population of over one million people, according to the 2011 census. The city is mainly comprised of arid barren soil, while the central part comprised of many water bodies.

2.2. Methodology

The overall methodology adopted in this study is illustrated in Figure 2. The whole study area has been divided mainly into four zones namely transportation zone, public place zone, industrial zone and residential zone. Pollutant monitoring in vertical direction using UAV has been done at eight locations which are distributed all over the city and falls under the above mentioned zones. The zones are made on the basis of different activites that take place in the individual zones causing the air pollution. The pollutants such as $PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2 has been observed because these are the major pollutants that are highly responsible for poor air quality. Table 1 shows zone wise air pollutant monitoring locations in the study area along with its description and nomenclature used. Monitoring and recording of pollutant concentration has been performed for two times a day from October 2021 to December 2021 on daily basis for all locations as given in Table 1. Monitoring of pollutants in vertical direction has been done at 5, 10, 15, and 20 m above ground level. Later the data is seasonally analyzed. During vertical measurements using UAV, additional battery is always carried to avoid interruption in data monitoring. Due to COVID-19 situation, it has been permitted by the local authority to fly drone with restricted time and height. This restriction on time and height is one of the limitations of this work. Gas sensors are used in the study as discussed in the following section 2.3 and the details of sensors used in the study are described and presented in Table 2. The sensor system has been placed at the bottom of the UAV as shown in Figure 3a. While Figure 3b shows monitoring of the pollutants in industrial area at an altitude of 5 m above ground level.

2.3. Ground Control and Communication

The UAV is employed as a portable surveillance device that can fly autonomously and semi-autonomously (guided) while maintaining its stability within the payload limit it can sustain. The pollution monitoring system has been integrated with the UAV which transmits the monitored data to ground control station (GCS). The monitoring system uses a GSM module to transmit real-time data to the ground station. The data is sent via Message Queuing Telemetry Transport (MQTT) protocol. The GCS includes the remote-control device to manage the UAV at different elevations and cell phone device with data card for receiving and saving the real time pollution data from monitoring system.

2.4. Data Collection

Pollution monitoring has been done as shown in Figure 2 and the time for the monitoring has been decided according to the peak traffic hours in each zone. The monitoring time for this study is between 9:00 am ~ 12:00 noon in the morning session and 4:00 ~ 6:00 pm in the evening session. UAV used in the

Table 2. Sensors Used in the Present Study

Pollutant	Method of Measurement	Sensor				
		Type	Dimension (l × b × h) (in mm) / Weight (in gm)	Resolution	Accuracy	Range
$PM_{2.5}$ and PM_{10}	Light Scattering[a]	Plantower PMS7003	48 × 37 × 12 / 27	1 μg/m^3	-	0.3 ~ 10 μm
CO	Solid-State Sensor[b]	MQ7 Gas Sensor	17.5 (diameter) × 22.5 / 5	-	-	20 ~ 2000 ppm
NO_2	Electrochemical Sensor[c]	NO2-B43F Sensor	32.3 (diameter) × 20 / 13	12 ppb	-	0 ~ 20 ppm
SO_2	Electrochemical Sensor[d]	SPEC DGS-SO2	44.5 × 20.8 × 8.9 / 50	50 ppb	15% of the reading	0 ~ 20 ppm
Reference Instruments Used in this Study						
$PM_{2.5}$ and PM_{10}	Beta Ray Attenuation[e]	BAM 1020 Continuous Particulate Monitor	310 × 430 × 400/ 19000	-	-	-
NO_2	Oxidationcatalyst and Chemiluminescence[f]	Horiba APNA 370	430 × 450 × 310/ 20000	5 ppb	-	0 ~ 10 ppm
SO_2	UV Fluorescence[g]	Horiba APSA 370	220 × 430 × 550/ 19000	-	-	0 ~ 10 ppm

Note: l: length, b: breadth, h: height
[a] https://download.kamami.pl/p564008-PMS7003%20series%20data%20manua_English_V2.5.pdf (accessed March 29, 2022)
[b] http://www.ventor.co.in/Datasheet/MQ-7.pdf (accessed March 29, 2022)
[c] http://www.alphasense.com/WEB1213/wp-content/uploads/2018/12/NO2B43F.pdf (accessed March 29, 2022)
[d] https://www.spec-sensors.com/wp-content/uploads/2017/01/DGS-SO2-968-038.pdf (accessed March 29, 2022)
[e] https://metone.com/wp-content/uploads/2019/10/BAM-1020-1.pdf (accessed March 29, 2022)
[f] https://www.horiba.com/int/products/detail/action/show/Product/apna-370cu-2-204/ (accessed March 29, 2022)
[g] https://www.horiba.com/int/process-and environmental/products/detail/action/show/Product/apsa-370-452/ (accessed March 29, 2022)

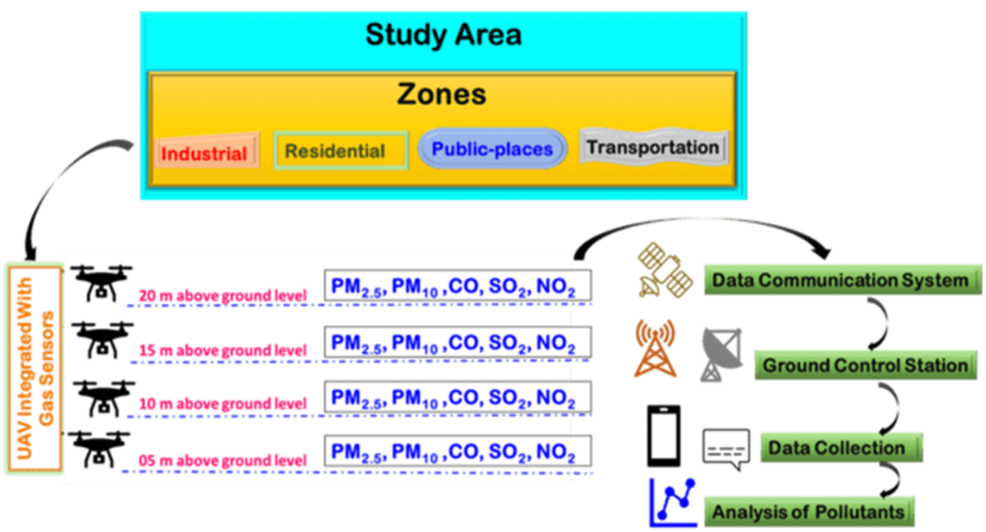

Figure 2. Methodology adopted in the current study.

current study is DJI Phantom 3 Professional. The height of the UAV from the ground level has been set as a parameter flight control/fly path in the software before operation. The same flying height is being observed through the display of the UAV's remote control. All the monitoring has been done in the normal climatic conditions i.e., in very low to low wind speed conditions in which there will not be much effect/negligible effect of wind speed.

Real time data has been obtained from the wireless sensor-based air pollutants monitoring system. The obtained data has been compared with the air quality data prescribed by Central Pollution Control Board (CPCB) which is an environmental authority of the central government. Bar-chart has been used to present the real time data of study area and its comparison with the CPCB data (24 hours average) and also with previous studies (Deshmukh et al., 2013; Jaiswal et al., 2019) for Raipur city.

2.5. Sensors Used in the Study

Thermal, mass, electrochemical, potentiometric, amperometric, conductometric, and optical sensors are the most common gas sensors, which are classified based on their operational principles (Janata, 2009; Liu et al., 2012). Alphasense B43F sensor for nitrogen dioxide, SPEC sensor for sulphur dioxide, Plantower PMS7003 sensor for particulate matter ($PM_{2.5}$ and PM_{10}), and MQ7 sensor for carbon monoxide measurement has been used to develop the current sensing payload. Table 2 shows the characteristics of all sensors used in the present study.

Alphasense and SPEC sensors are amperometric electrochemical cells that provide a current proportionate to the partial volume of the gas being measured. MQ7 sensor, on the other hand, is a semiconductor sensor in which gas molecules interact directly with the sensor material. The sensing material must have a large, exposed surface for interacting with gas molecules, as well as appropriate active sites for binding these molecules and the ability to successfully convert these binding events into detectable signals. The monitoring system uses a GSM module to transmit real-time data to the ground station. The data is sent via the MQTT protocol. Because of its ease of use and programming, as well as its faster data transfer speed and reduced power consumption, the Arduino microcontroller has been chosen. The Arduino can power all the gas sensors at the same time. The monitoring device is operated using lithium polymer battery. The sensor system is housed in a waterproof enclosure to protect the sensors from the outdoor environment, particularly excessive humidity and temperature fluctuations. The gadget works well in temperatures ranging from 0 to 50 degrees Celsius, relative humidity levels of 10 to 95 percent, and high levels of ambient dust. The data transfer frequency is 1 minute. Units (Pennanen et al., 1997) of NO_2 and SO_2 has been changed from ppm to μg/m^3 and for CO, from ppm to mg/m^3 for better comparison of results with CPCB measurements.

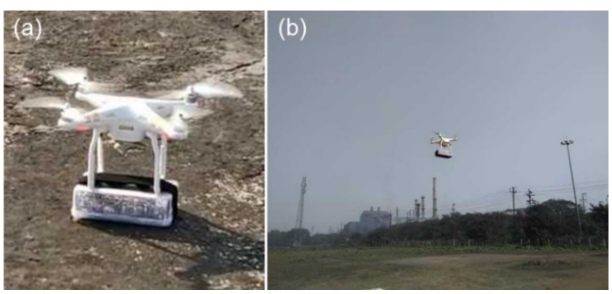

Figure 3. Placement of the air quality (a) monitoring system on the UAV and (b) monitoring of air pollutants in industrial zone at 5 m above ground level.

Table 3. Rotor Effect on Air Quality

Pollutant	Concentration (propellers off)	Concentration (propellers on)	Difference (%)
$PM_{2.5}$	65.93	58.88	11.29
PM_{10}	75.20	71.00	5.74
NO_2	39.34	36.24	8.20
CO	11.25	10.83	3.80
SO_2	12.25	12.22	0.24

The quality of the sensor has been evaluated using the collocation method. The sensors have been operated with the standard fixed instruments at same place for same time period for measurement. After comparison with the fixed instrument data, the data accuracy of the sensor has been improved by modifying the settings of the sensor. In the present, study, measurement of SO_2 has been done using Horiba APSA 370 which is based on ultraviolet fluorescent (UVF) method. Measurement of NO_2 has been done using Horiba APNA 370 (chemiluminescence approach based) device and Particulate matter concentration has been monitored using Met One Instruments BAM 1020 (based on beta attenuation method) device. All the above-mentioned devices are considered as standard instruments to referrer in this study.

2.6. Influence of UAV Propeller Speed on Air Quality

The sensor-based monitoring system has been integrated on UAV platform and then rested on a flat and clean surface. The power has been turned on for the on-board sensor system and the UAV to ensure that they are operational. The sensor was being warmed up for 30 minutes before measurement. To observe the effect of propeller rotation on the air quality (Guan et al., 2021), two tests have been performed on ground level. For test 1, the measurements have been recorded continuously for 10 minutes without operation of the propeller. Later, in test 2, the UAV propeller has been switched on and kept on the maximum speed before take-off. Again, the measurements have been obtained for 10 minutes.

Before the use of UAV integrated with sensor system, the effect of the air speed generated from propellers on the measurement of the air quality sensor needed to be verified. Two experiment tests have been carried out to quantify the rotor effect. The obtained measurements have been averaged and shown in Table 3.

3. Results and Discussions

Air pollutants are released by natural events such as volcanic eruptions, wind soil erosion, forest fires, sandstorms, and plant pollen dispersal; however, pollutants are primarily released by anthropogenic activities, particularly industrial manufacture and motor vehicle operation in an urban region. In an industrial zone, the major source of pollution is from the industrial emissions and the movement of heavy. Whereas, in residential zone, the major sources are burning of coal and wood, construction activities and the transport activities. While in public-place and transportation zone, the major sources are the movement of vehicles and their emissions. During winter days, all these pollutants get accumulated near to ground surface and affects both living being and environment when compared to other seasons. The living being is affected in terms of breathing issues while the environment gets affected in terms of global warming and acid rains.

Zone wise monitoring locations are presented in Figure 1. Vertical fluctuations of PM_{10}, $PM_{2.5}$, NO_2, CO, and SO_2 levels in different seasons has been observed at 5, 10, 15, and 20 m above ground level is being presented in the following sections. The sensor's concentration data has been extracted and analyzed. For each of the stations, good data acquisition has been observed and presented.

The presence of higher particulate matter concentration in public place may be due to the ongoing construction work of buildings, maintenance of roads, wood burning, etc. While at

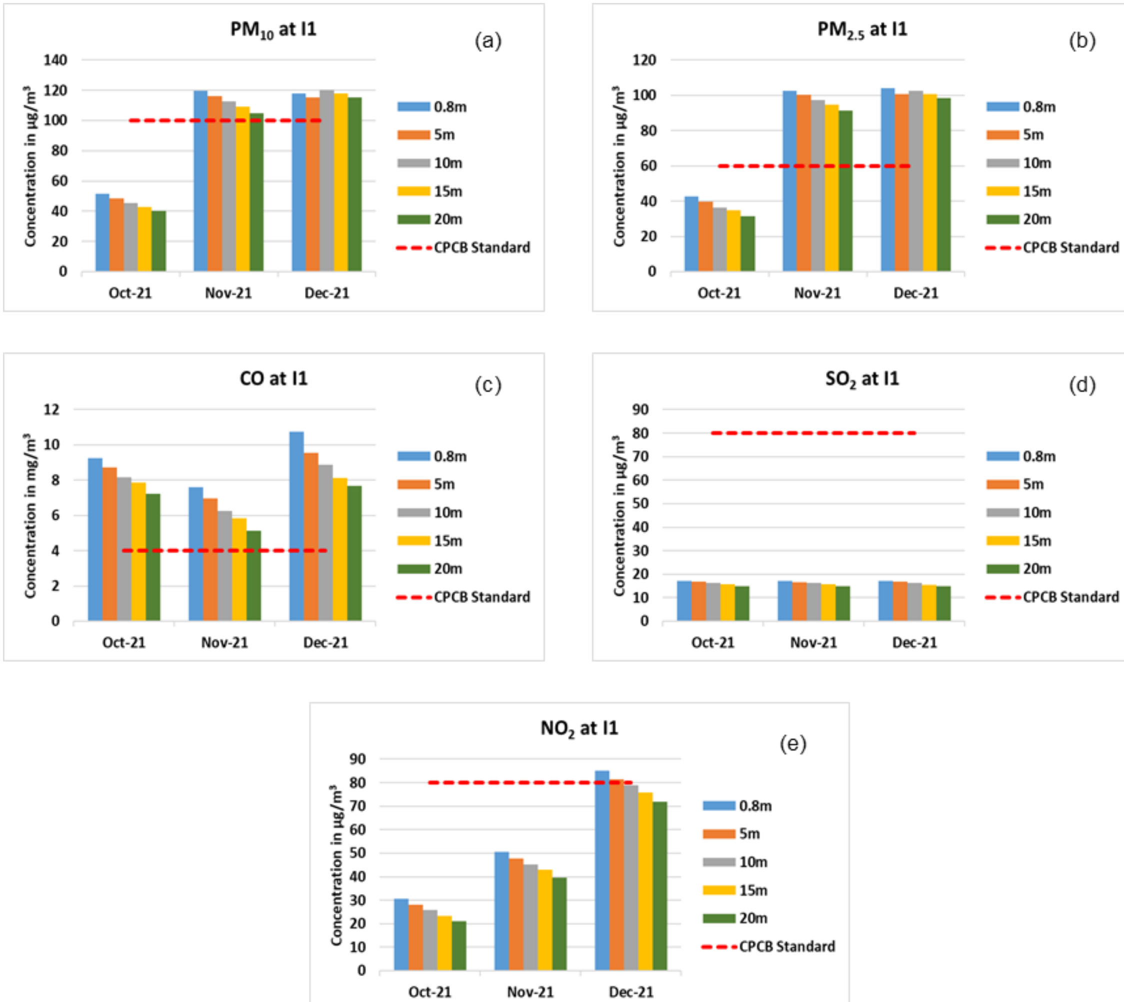

Figure 4. Vertical variation air pollutant concentration in industrial zone for (a) PM_{10}, (b) $PM_{2.5}$, (c) CO, (d) SO_2, and (e) NO_2.

transportation zone, the higher $PM_{2.5}$ and PM_{10} concentration is due to the smoke emitted from the vehicles. Higher concentration during post-monsoon and winter season is due to stable atmosphere with low temperature where the particulate matters accumulate more near the ground. Cold temperature traps the pollution near ground through process of temperature inversion. In this process, layer of warm air lies over colder air making a shield so that the pollutant cannot move upwards. Hence, causing an increase in pollutant concentration near ground surface. The main reason for higher level of CO concentration in transportation zone is due to emission produced from vehicular movements and diesel-based construction equipment. Higher level of CO occurs in area having high traffic density. Other reason of higher CO concentration is burning of coal at industries. The industries surrounding the study area are mainly comprises of iron industries which requires coal as a fuel for the industrial processes. Also, the coal is transported to the industries using diesel generated vehicle. Both these factors are responsible for the increase in CO concentration. The cause of residential zone and public-place zone to be the hotspot for SO_2 concentration is the decaying of building materials and paints of the existing buildings, emission from the vehicles and coal burning. The concentration in post-monsoon has been found to be greater than the concentration in winter season. This is due to more industrial operations during monsoon season. The increase in industral operation was due to the earlier lockdown in the area (March ~ May 2021) due to COVID-19. To increase the working and the production, almost all industries were running with full capcity during monsoon causing pollutant emission from the chimneys. The major causes of higher NO_2 concentration hotspot for NO_2 is burning of fossil (coal, gas, and oil), emissions from vehicles are the major causes of higher NO_2 concentration in industrial and public-place zone. Whereas in the residential area, the NO_2 is increased due to use of kerosene or wood-based appliances such as room heater, stove, and water heaters.

3.1. Vertical Variation for Industrial Zone

3.1.1. PM_{10} and $PM_{2.5}$ Concentration

In industrial zone, UAV has been used to obtain the concentration of $PM_{2.5}$ and PM_{10} concentration at an elevation of 5, 10, 15, and 20 m above ground level. The observations have been taken for period of three months (October ~ December). It has been observed that the concentration of $PM_{2.5}$ and PM_{10} has decreased gradually with increase in elevation in October and November. While in December, it has been observed that there was increase in concentration of particulate matters with increase in elevation. Highest concentration of $PM_{2.5}$ has been observed to be 60 µg/m^3 in December at 0.8 m while highest PM_{10} concentration has been found to be 120.34 µg/m^3 in December at 10 m above ground level. For the months of November and December, the observed concentration of $PM_{2.5}$ and PM_{10} has been found to be higher than CPCB standards (60 and 100 µg/m^3, respectively). This is due to the accumulation of the pollutants in winter season. During winter, due to temperature inversion, the pollutant concentration remains near ground level causing the increase in the pollution and affects the surrounding. Figures 4a and 4b show the variation of concentration of PM_{10} and $PM_{2.5}$ with reference to the elevation.

3.1.2. CO Concentration

In industrial zone, CO has been found to be higher at I1 than the prescribed limits of CPCB in all elevation levels. The maximum concentration of CO has been found to 10.75 mg/m^3 in December month at 0.8 m AGL while the lowest value is 5.13 mg/m^3 in November at an elevation of 20 m AGL in the month of November. This may be due to the combustion from heavy vehicles moving in industrial area. The concentration has a gradual decrease with increase in elevation. CO concentration has been observed to be higher than CPCB prescribed limit (4 mg/m^3) in all three months. Figure 4c shows the variation of CO concentration with elevation in industrial zone.

3.1.3. SO_2 Concentration

At location I1 in industrial area, decreasing trend of concentration of SO_2 with increase in elevation has been observed for all three months. The observation location is surrounded by sponge iron industries and small power plants combined with movement of heavy vehicles causes the higher concentration of SO_2. Highest concentration value is found to be 17.27 µg/m^3 at 0.8 m in December while the lowest value 14.79 µg/m^3 in November at an elevation of 20 m. Both maximum and minimum concentrations were below the CPCB limiting values (80 µg/m^3). Figure 4d shows the variation of SO_2 with elevation in industrial zone.

3.1.4. NO_2 Concentration

In industrial zone, nitrogen dioxide (NO_2) has been found to be higher at I1 than the prescribed limits of CPCB (80 µg/m^3). at an elevation of 0.8 and 5 m AGL during month of December. In all three months, NO_2 concentration was observed to be higher at 0.8 m above ground. This is due to the combustion from heavy motor vehicles moving in industrial area. The concentration has a gradual decrease with increase in elevation. Figure 4e shows the variation of NO_2 concentration with Elevation in industrial zone.

3.2. Vertical Variation for Residential Zone

3.2.1. PM_{10} and $PM_{2.5}$ Concentration

In residential zone, at three locations (i.e., R1 & R2, R7, and R8), the vertical variation of $PM_{2.5}$ and PM_{10} concentration has been observed. It has been observed that the concentration of $PM_{2.5}$ and PM_{10} has decreased gradually with increase in elevation in October and December. While there was increase in concentration of $PM_{2.5}$ and PM_{10} at R1 and after that its decreases with increase in elevation. At location (R1 & R2), the maximum concentration of $PM_{2.5}$ has been found to be 105.15 µg/m^3 in December month at 0.8 m AGL while the lowest value is 45.37 µg/m^3 at an elevation of 20 m AGL in the month of October. The maximum concentration of PM_{10} has been found to be 117.28 µg/m^3 in December month at 0.8 m AGL while the lowest value is 53.47 µg/m^3 at an elevation of 20 m AGL in the month of October. At location R7 and R8, it has been observed that concentration of $PM_{2.5}$ and PM_{10} has decreased gradually with increase in elevation for all three months. At R7, the maximum concentration of $PM_{2.5}$ and PM_{10} has been found to be 102.48 and 114.98 µg/m^3 in December month at 0.8 m AGL while the lowest value is 22.95 and 30.47 µg/m^3 at an elevation of 20 m AGL in the month of October. Similarly, at location R8, the maximum concentration of $PM_{2.5}$ and PM_{10} has been found to be 102.28 and 112.56 µg/m^3 in December month at 0.8 m AGL while the lowest value is 30.18 and 36.36 µg/m^3 at an elevation of 20 m AGL in the month of October. Figures 5a and 6d show the variation of concentration of PM_{10} and $PM_{2.5}$ with reference to the elevation at location (R1 & R2). Figures 5b and 6e show the variation of concentration of PM_{10} and $PM_{2.5}$ with reference to the elevation at R7 and Figures 5c and 6f for R8, respectively. The PM_{10} concentration has been found to be higher than CPCB limit (100 µg/m^3) at all three locations in December 2021. At the same time as the $PM_{2.5}$ concentration has found to be higher than CPCB limit (60 µg/m^3) at location (R1 & R2) during November 2021 and December 2021. While at other locations, $PM_{2.5}$ concentration has found to be higher than CPCB limit in December 2021 only.

3.2.2. CO Concentration

In residential zone, at location (R1 & R2) maximum concentration of CO has been found to be 15.45 mg/m^3 in December month at 0.8 m AGL while the lowest value is 5.24 mg/m^3 at an elevation of 20 m AGL in the month of November. Both maximum and minimum concentration values are higher than CPCB standard values. In this location due to continuous movement of vehicles may be reason for high concentration of CO. Figure 5g shows the variation of CO concentration with Elevation at R1 & R2 location. At location R7 of residential zone, CO concentration is found to be almost similar in October and November. There was increase in concentration in month of December. R7 is located around 300 m inside from the main road of the city but due to combustion from vehicles and burning of coal in household during winter is the main cause of increased CO concentration. For all three months, CO concentration showed decreasing pattern with increase in elevation although concentration limits were higher than CPCB standard limit (4

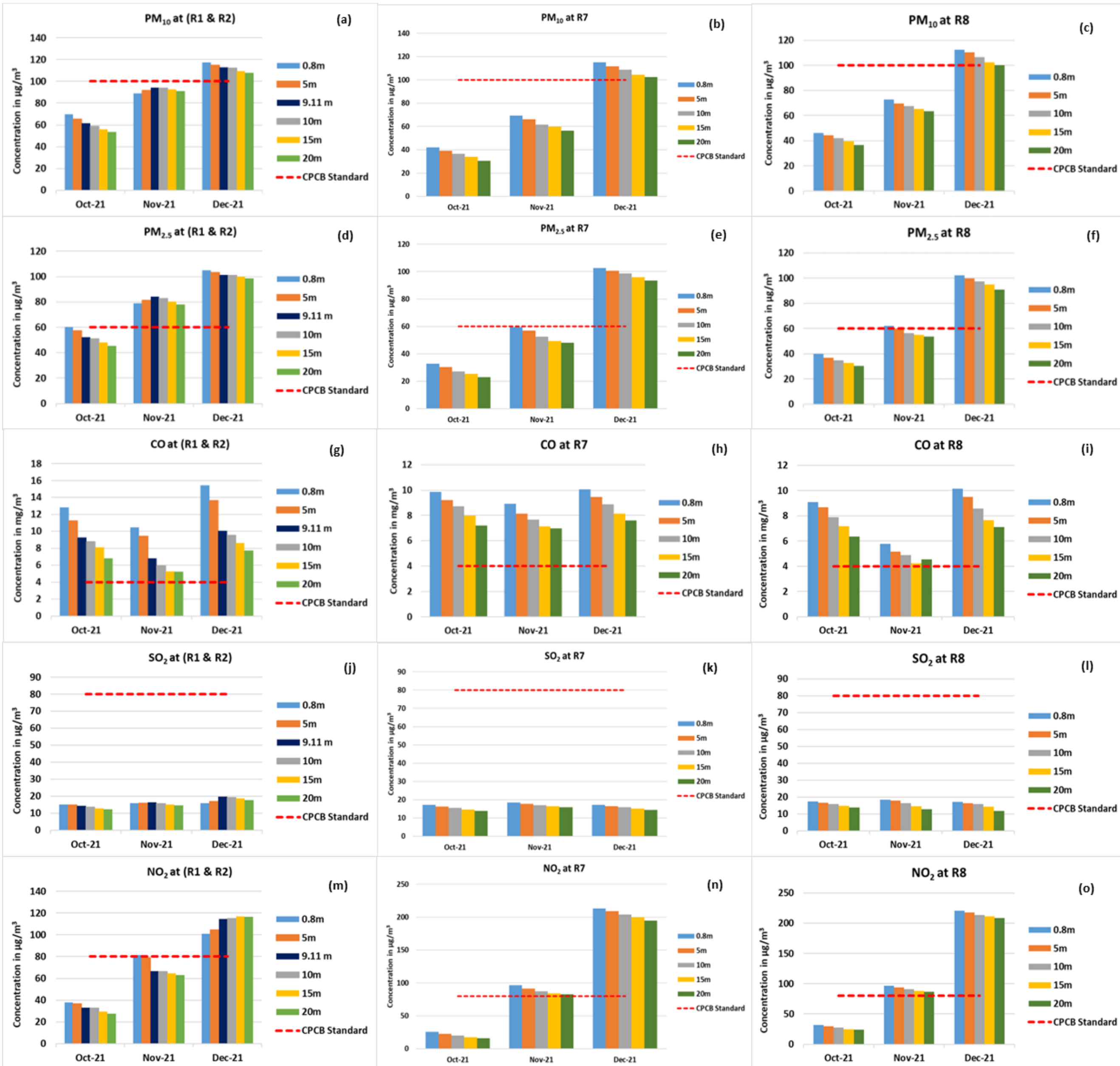

Figure 5. Vertical variation of air pollutant concentration in residential zone: (a) PM_{10} for location (R1 & R2); (b) PM_{10} for location R7, (c) PM_{10} for location R8, (d) $PM_{2.5}$ for location (R1 & R2), (e) $PM_{2.5}$ for location R7, (f) $PM_{2.5}$ for location R8, (g) CO for location (R1 & R2), (h) CO for location R7, (i) CO for location R8, (j) SO_2 for location (R1 & R2), (k) SO_2 for location R7, (l) SO_2 for location R8, (m) NO_2 for location (R1 & R2), (n) NO_2 for location R7, and (o) NO_2 for location R8.

mg/m^3). The maximum value was found to be 10.07 mg/m^3 during December at 0.8 m while the minimum value was 6.96 mg/m^3 at an elevation of 20 m AGL in November. Figure 5h shows the variation of CO concentration with elevation at R7. At location R8 of residential zone, pattern of CO concentration is found to be almost similar in all three months. The maximum value was found to be 10.15 mg/m^3 during December at 0.8 m while the minimum value was 4.23 mg/m^3 at an elevation of 15 m AGL in November. Figure 5i shows the variation of CO concentration with elevation at R8.

3.2.3. SO_2 Concentration

In residential zone, at location (R1 & R2), SO_2 concentration has been observed to be having decreasing trend with increase in elevation for October month. While in November and December, SO_2 concentration has found to be higher at elevation of 9.11 m AGL. This was due to the movement of off-road vehicles and heavy vehicles in this area. The maximum concentration of SO_2 has been found to be 19.77 µg/m^3 in December month at 9.11 m AGL while the lowest value is 12.35 µg/m^3 at elevation of 20 m AGL in the month of October. Figure 5j shows

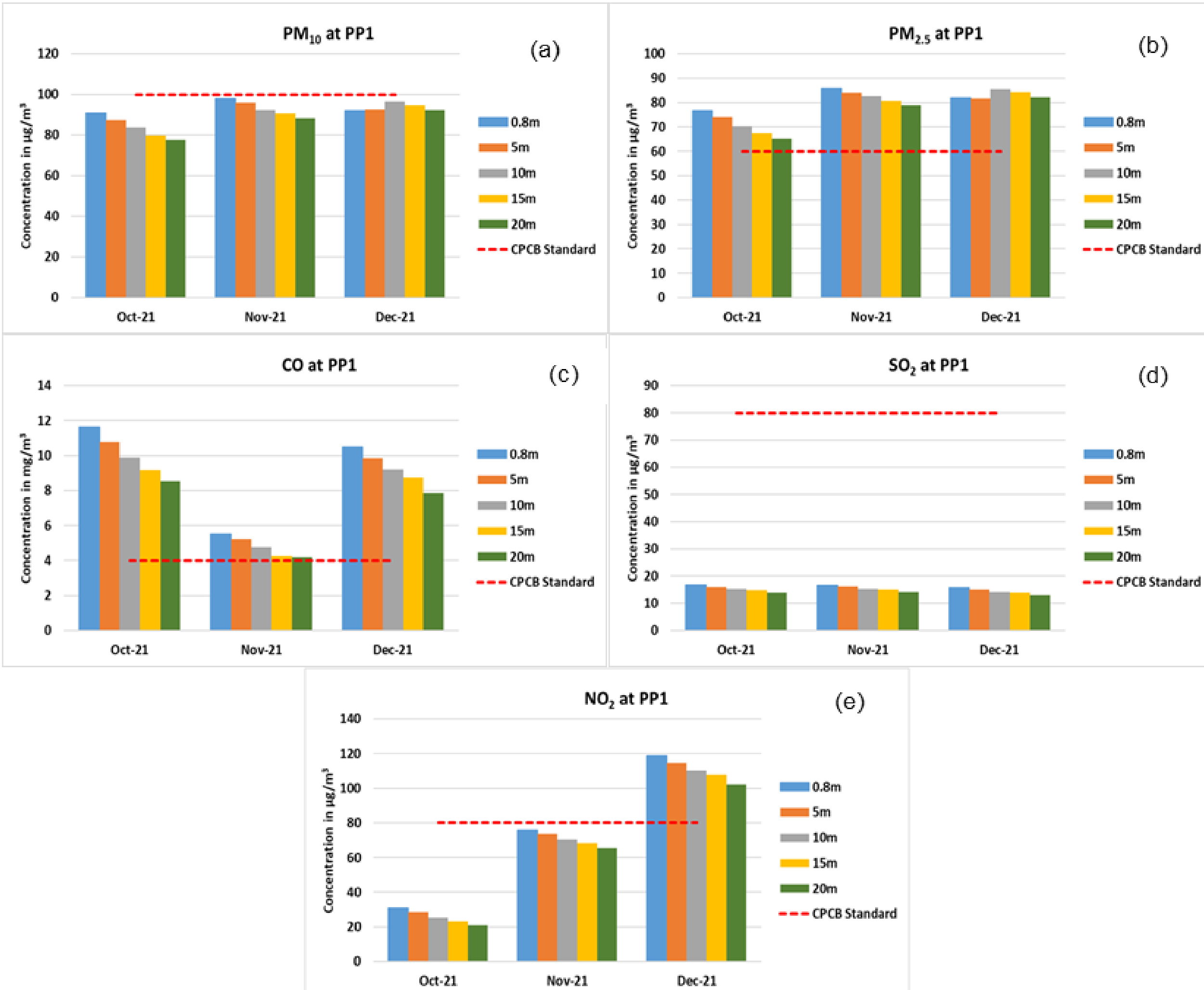

Figure 6. Vertical variation air pollutant concentration in public-place zone for (a) PM_{10}, (b)$PM_{2.5}$, (c) CO, (d) SO_2, and (e) NO_2.

the variation of SO_2 concentration with elevation at R1 & R2 location. At location R7 of residential zone, SO_2 concentration is found to be almost similar in October and November. There was increase in concentration in month of December. R7 is located around 300 m inside from the major road of the city but due to continuous construction work many heavy vehicles have been passing the location which causes the increase SO_2 concentration. The other cause may be the accumulation of pollutant in the month of November and December due to stable environment and low mixing height. For all three months, SO_2 concentration showed decreasing pattern with increase in elevation although concentration limits were lower than CPCB standard limit (80 µg/m^3). The maximum value was found to be 18.41 µg/m^3 during November at 0.8 m while the minimum value was 13.94 µg/m^3 at an elevation of 20 m AGL in October. Figure 5k shows the variation of SO_2 concentration with elevation at R7. At location R8 of residential zone, pattern of SO_2 concentration is found to be almost similar to the R7. The maximum value was found to be 18.50 µg/m^3 during November at 0.8 m while the minimum value was 11.67 µg/m^3 at an elevation of 20 m AGL in December. Figure 5l shows the variation of SO_2 concentration with elevation at R8.

3.2.4. NO_2 Concentration

In residential zone, at location (R1 & R2) maximum concentration of NO_2 has been found to be 116.87 µg/m^3 in December month at 15 m AGL while the lowest value is 27.49 µg/m^3 at elevation of 20 m AGL in the month of October. Both maximum and minimum concentration values are higher than CPCB standard values. In this location due to continuous movement of vehicles may be reason for high concentration of NO_2. Figure 5m shows the variation of NO_2 concentration with elevation at R1 & R2 location. At location R7 of residential zone, in month of November and December, NO_2 concentration has been higher than the CPCB limits (80 µg/m^3). R7 is located around 300 m inside from the main road of the city but due to combustion from diesel-based vehicles is the main cause of increased NO_2 concentration. For all three months, NO_2 concentration showed decreasing pattern with increase in elevation although concentration limits were higher than CPCB standard limit (80 μg/m^3). The maximum value was found to be 213.18 μg/m^3 during December at 0.8 m while the minimum value was 16.11 μg/m^3 at an elevation of 20 m AGL in October. Figure 5n shows the variation of NO_2 concentration with elevation at R7. At location R8 of residential zone, pattern of NO_2 concentration is found to be almost similar to R7. The maximum value was found to be 220.54 μg/m^3 during December at 0.8 m while the minimum value was 24.11 μg/m^3 at an elevation of 20 m AGL in October. Figure 5o shows the variation of NO_2 concentration with elevation at R8.

3.3. Vertical Variation in Public-Place Zone

3.3.1. PM_{10} and $PM_{2.5}$ Concentration

In public place zone, at PP1 UAV has been flown for observation of vertical profile of concentration of $PM_{2.5}$ and PM_{10}. It has been observed that the concentration of $PM_{2.5}$ and PM_{10} has decreased gradually with increase in elevation in October and November. While in December, it has been observed that there was increase in concentration of particulate matters with increase in elevation. This is due to the agglomeration of the pollutants in winter season. Highest concentration of $PM_{2.5}$ and PM_{10} has been observed to be 85.75 and 97.94 μg/m^3 in November at 0.8 m while lowest $PM_{2.5}$ and PM_{10} concentration has been found to be 65.23 and 77.54 μg/m^3 in October at 20 m above ground level. Figures 6a and 6b shows the variation of concentration of PM_{10} and $PM_{2.5}$ w.r.t the elevation. The PM_{10} concentration has been found to be lower than CPCB limit (100 μg/m^3) at for all three months. At the same time as the $PM_{2.5}$ concentration has found to be higher than CPCB limit (60 μg/m^3) for all three months.

3.3.2. CO Concentration

In public place zone, at PP1 UAV has been flown for observation of vertical profile of concentration of CO. It has been observed that the concentration of CO has decreased gradually with increase in elevation in October, November and December. In October, it has been observed that there was higher concentration level of CO at 0.8 m AGL. This is due to more vehicular movement and Dusshera festival. The maximum value was found to be 11.64 mg/m^3 during October at 0.8 m while the minimum value was 4.19 mg/m^3 at an elevation of 20 m AGL in November. The CO concentration has been found to be higher than CPCB standard (4 mg/m^3) for all three months. Figure 6c shows the variation of concentration of CO w.r.t the elevation.

3.3.3. SO_2 Concentration

For public place zone, similar trend of SO_2 concentration has been observed as found in I1 and R7. Highest SO_2 concentration has been found to be 16.72 μg/m^3 at PP1 in October at 0.8 m AGL while the lowest concentration of 12.99 μg/m^3 has been found to at 20 m AGL in December. Figure 6d depicts the variation of SO_2 concentration in public place zone. The concentration of SO_2 has been observed to be less than CPCB standard (80 μg/m^3) for all three months.

3.3.4. NO_2 Concentration

For public place zone, similar trend has been observed as found in I1 and R7. Highest NO_2 concentration has been found to be 118.71 μg/m^3 at PP1 in November at 0.8 m AGL while the lowest concentration of 21.10 μg/m^3 has been found to at 20 m AGL in October. During month of December 2021, NO_2 concentration has been found to be higher than the CPCB prescribed limit (80 μg/m^3). Figure 6e depicts the variation of SO_2 concentration in public place.

3.4. Vertical Variation in Transportation Zone

3.4.1. PM_{10} and $PM_{2.5}$ Concentration

In transportation zone, at three locations (i.e., T3 & T4, T5 & T6, and T7), UAV has been flown for determining vertical variation of concentration of $PM_{2.5}$ and PM_{10}. At location (T3 & T4), it has been observed that particulate matter concentration has been gradually decreasing with increase in elevation in the month of October. However, in the post monsoon (November) and winter (December), the $PM_{2.5}$ and PM_{10} concentration starts increasing with the increase in elevation. The main cause of this type of phenomenon is the stable surrounding environment and low mixing height during winter season. At location (T3 & T4), the maximum concentration of $PM_{2.5}$ has been found to be 125.67 μg/m^3 in December month at 10 m AGL while the lowest value is 66.74 μg/m^3 at an elevation of 20 m AGL in the month of October. The maximum concentration of PM_{10} has been found to be 142.61 μg/m^3 in December month at 10 m AGL while the lowest value is 79.68 μg/m^3 at an elevation of 20 m AGL in the month of October. Figures 7a and 7d show the variation of con- centration of PM_{10} and $PM_{2.5}$ with reference to the elevation at (T3 & T4). At location (T5 & T6), higher concentration of particulate matter has been observed during December at elevation of 0.8 and 5 m above ground level after which there was decrease in concentration with increase in elevation values. For October and November, the concentration decreases as elevation increases. At (T5 & T6), the maximum concentration of $PM_{2.5}$ and PM_{10} has been found to be 136.44 and 152.74 μg/m^3 in December month at 0.8 m AGL while the lowest value is 50.87 and 60.15 μg/m^{3}at an elevation of 20 m AGL in the month of October. Figures 7b and 7e show the variation of concentration of PM_{10} and $PM_{2.5}$ with reference to the elevation at (T5 & T6). At location T7, it has been observed that the concentration of $PM_{2.5}$ and PM_{10} has decreased gradually with increase in elevation in October and November. While in December, it has been observed that there was increase in concentration of particulate matters with increase in elevation. The main reason of increase in concentration is the ongoing construction of roads and bridges in this location as this location serves as the junction of national highway and state highway. Similarly, at location T7, the maximum concentration of $PM_{2.5}$ and PM_{10} has been found to be 134.98 and 156.74 μg/m^3 in December month at 0.8 m AGL while the lowest value is 58.64 and 73.37 μg/m^3 at an elevation of 20 m AGL in the month of October. Figures 7c and 7f show the variation of concentration of PM_{10} and $PM_{2.5}$ with reference to the elevation at T7. The PM_{10} concentration has been found to be higher than CPCB lim-

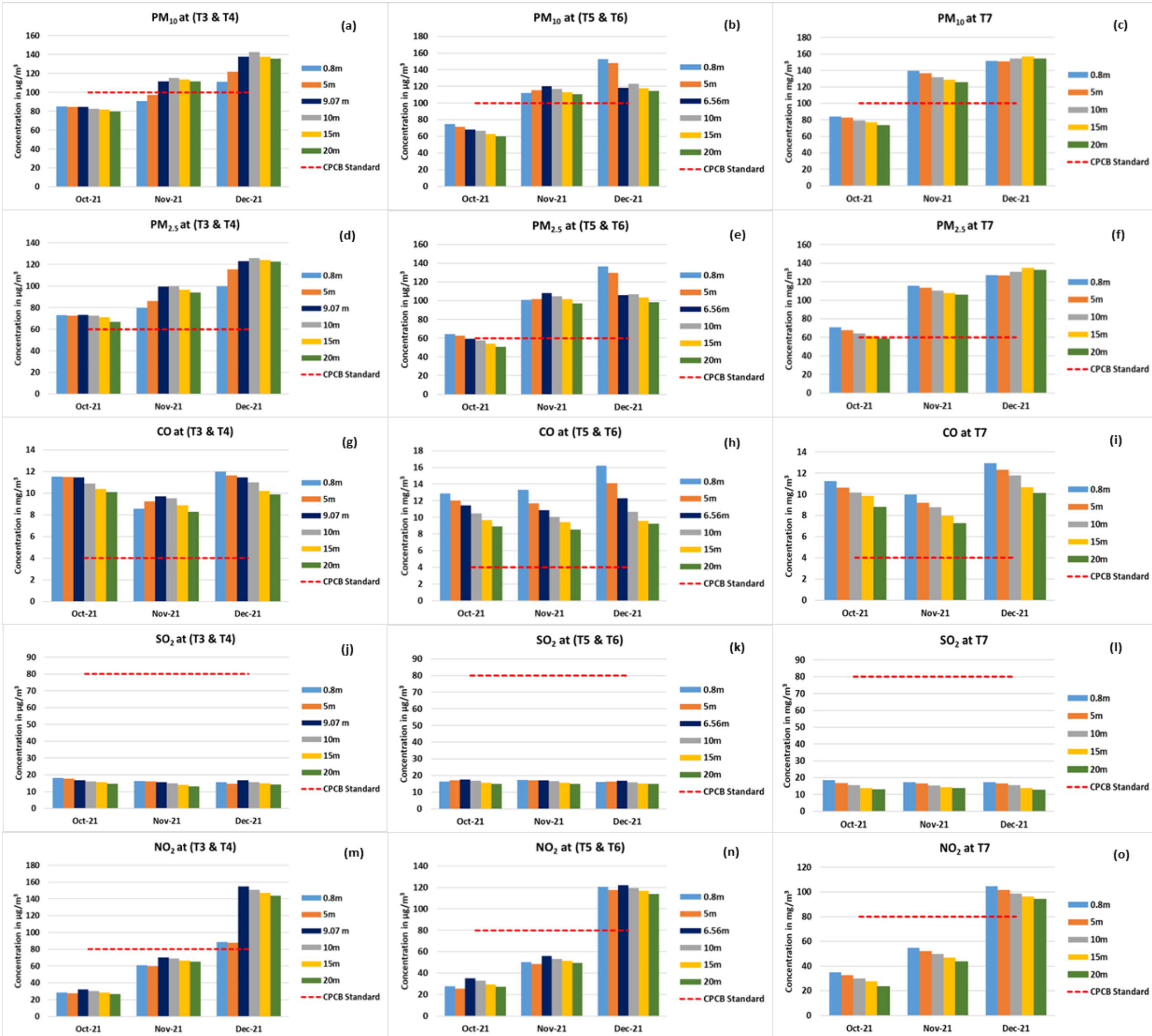

Figure 7. Vertical variation of air pollutant concentration in transportation zone: (a) PM_{10} for location (T3 & T4), (b) PM_{10} for location (T5 & T6), (c) PM_{10} for location T7, (d) $PM_{2.5}$ for location (T3 & T4), (e) $PM_{2.5}$ for location (T5 & T6), (f) $PM_{2.5}$ for location T7, (g) CO for location (T3 & T4), (h) CO for location (T5 & T6), (i) CO for location T7, (j) SO_2 for location (T3 & T4), (k) SO_2 for location (T5 & T6), (l) SO_2 for location T7, (m) NO_2 for location (T3 & T4), (n) NO_2 for location (T5 & T6), and (o) NO_2 for location T7.

it (100 µg/m^3) during November 2021 and December 2021. At the same time as the $PM_{2.5}$ concentration has found to be higher than CPCB limit (60 µg/m^3) for all three months.

3.4.2. CO Concentration

In transportation zone, vertical variation of concentration of CO at three locations (i.e., T3 & T4, T5 & T6, and T7) has been observed. At location (T3 & T4), it has been observed that carbon monoxide concentration has been gradually decreasing with increase in elevation in the month of October and December. However, in November month, there has been increase in concentration at an elevation of 9.07 m when compared to other elevation. The maximum value was found to be 11.98 mg/m^3 during December at 0.8 m while the minimum value was 8.26 mg/m^3 at an elevation of 20 m AGL in November. Figure 7g shows the variation of concentration of CO with reference to the elevation at T3 & T4. At location T5 & T6, the CO concentration decreased with increase of elevation for all three months of observation. This location is situated at intersection of national highway (NH-56) and state highway. It is also the main pathway to the one of the pilgrimage sites of Raipur city. Hence, a dense traffic volume is always observed here which causes higher concentration of CO. The maximum value was found to be 16.23 mg/m^3 during December at 0.8 m while the minimum value was 8.54 mg/m^3 at an elevation of 20 m AGL in November. Figure 7h shows the variation of concentration of CO with reference to the elevation (T5 & T6). At location T7, it has been observed that the concentration of CO has decreased gradually with increase in elevation in October, November, and December. The main reason of increase in concentration of CO is the location which serves as the junction of national highway and state highway. Hence heavy traffic movement is always found here. The maximum value was found to be 12.93 mg/m^3 during December at 0.8 m while the minimum value was 7.25 mg/m^3 at an elevation of 20 m AGL in November. Figure 7i shows the variation of concentration CO with reference to the elevation at T7. In all three months, CO concentration has been observed to be higher than CPCB prescribed limit (4 mg/m^3).

3.4.3. SO_2 Concentration

At location (T3 & T4), in transportation zone, it has been observed that SO_2 concentration has been gradually decreasing with increase in elevation in the month of October, November and December. The maximum value was found to be 18.12 µg/m^3 during October at 0.8 m while the minimum value was 13.01 µg/m^3 at an elevation of 20 m AGL in November. Although the location is occupied with heavy traffic during daytime but the SO_2 concentration observed has been below the CPCB prescribed limits (80 µg/m^3). Figure 7j shows the variation of concentration of SO_2 with reference to the elevation. At location (T5 & T6), the SO_2 concentration decreased with increase of elevation for all three months of observation. The maximum value was found to be 17.47 mg/m^3 during October at 6.56 m while the minimum value was 14.88 mg/m^3 at an elevation of 20 m AGL in December. The maximum value has been obtained at the bridge situated at observed location where high-density traffic is available day time. Figure 7k shows the variation of concentration of SO_2 with reference to the elevation (T5 & T6). At location T7, it has been observed that the concentration of SO_2 has decreased gradually with increase in elevation in October, November, and December. The main reason of increase in concentration of SO_2 is the fuel combustion from heavy traffic and off-road equipment's used for construction of bridges and roads. The maximum value was found to be 18.45 µg/m^3 during October at 0.8 m while the minimum value was 12.61 µg/m^3 at an elevation of 20 m AGL in December. Figure 7l shows the variation of concentration SO_2 with reference to the elevation T7.

3.4.4. NO_2 Concentration

At location (T3 & T4), it has been observed that nitrogen dioxide concentration has been fluctuating with change in elevation for all three months. But in December month, the concentration has been higher than CPCB standards at all elevations. The maximum value was found to be 154.95 µg/m^3 during December at 9.07 m while the minimum value was 26.74 µg/m^3 at an elevation of 20 m AGL in October. Figure 7m shows the variation of concentration of NO_2 with reference to the elevation. At location (T5 & T6), pattern of the NO_2 concentration was same as (T3 & T4) for all three months of observation. This location is situated at highway; hence, a dense traffic volume is always observed here which causes higher concentration of NO_2. The maximum value was found to be 122.15 µg/m^3 during December at 6.56 m while the minimum value was 25.65 µg/m^3 at an elevation of 5 m AGL in October. Figure 7n shows the variation of concentration of CO with reference to the elevation. At location T7, it has been observed that the concentration of NO_2 has decreased gradually with increase in elevation in October, November, and December. The main reason of increase in concentration of NO_2 is the location which serves as the junction of national highway and state highway. Hence heavy traffic movement is always found here. The maximum value was found to be 104.67 µg/m^3 during December at 0.8 m while the minimum value was 23.47 µg/m^3 at an elevation of 20 m AGL in October. Figure 7o shows the variation of concentration NO_2 with reference to the elevation. For the month of December 2021, in all the locations, NO_2 concentration showed concentration limits were higher than CPCB standard limit (80 µg/m^3).

4. Conclusions

The analysis and prevention of air pollution largely depend on the horizontal and particularly vertical monitoring of atmospheric contaminants. Additionally, it is a helpful addition to the present monitoring strategy, which primarily dependent on ground monitoring stations. UAV provides an innovative way to detect vertical air pollution. In this study, an air quality monitoring system integrated with an UAV has been proposed. This system can detect pollution at horizontal as well as at vertical direction and has been utilized to measure $PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2 at various altitudes. Vertical monitoring of the air pollutants has been done for the first time in the study area using an UAV. The principal finding of this study includes firstly the efficiency of the small portable sensors for monitoring air quality parameters. Secondly, it has been observed that there is decreasing trend in the concentration has been observed to be winter > post-monsoon > monsoon season as reported in the previous studies for Raipur city. Thirdly, the data compares well with the authorized instruments in terms of representation of any area (low to high concentration). The effect of the air speed generated from propellers on the measurement of the air quality sensor needed has also been verified. The hotspots for particulate matter ($PM_{2.5}$ and PM_{10}) throughout the monsoon, post-monsoon, and winter seasons have been identified as being in the transportation and public-place zone. Only the transportation zone has high CO concentrations throughout the monsoon, post-monsoon, and winter seasons. In the case of SO_2, it has been discovered that the public-place is a hotspot throughout all seasons. Similar to this, during the monsoon, post-monsoon, and winter seasons, residential and industrial zones have been hotspots for NO_2. According to the observed data, the transportation zone has been more adversely impacted by air pollutants than the other zones. In case of vertical monitoring, the maximum concentration has been observed near the ground and then starts to decrease with increase in altitude. The study demonstrates that sensor-based monitoring system can be a cost-effective when compared with authorized/reference monitoring instruments for assessing urban air quality.

The monitoring of air pollutants in both horizontal and vertical direction using portable sensors integrated to UAV is viable but there are also some limitations to this study. The limitations mainly includes (a) UAV used in the study has less flying endurance with additional payload which should be replaced with an UAV having higher flying time capacity; (b) UAV should be flown at higher level to study the behavior of pollutant concentration with increase in altitude; (c) restrictions imposed on flying UAV at any location by the local authority due to COVID-19 and also due to new regulations formed by Directorate General of Civil Aviation (DGCA) which is the government aviation authority.

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