Atmospheric CO_2 Level Measurement and Discomfort Index Calculation with the use of Low-Cost Drones

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ABSTRACT

Unmanned Aerial Vehicle (UAV) platforms are emerging as an essential tool for various studies in environmental engineering. The quadcopters drones have immense potential for sensor interfacing and stable data acquisition. These UAVs can perform critical activities like volcanic eruption monitoring, stack emission monitoring, urban air quality monitoring, identification of pollution levels in 3D space, etc. Carbon dioxide (CO_2) and the Discomfort Index (DI) are essential indicators of air quality and climate comfort. Hence, it is critical to monitor them with extreme accuracy. This study demonstrates a novel application of CO_2 profiling using low-cost drones at varied altitudes. The drone-aided vertical CO_2 profiling was carried out at 60 m AGL (Above Ground Level) during summer and winter, in Nagpur city of India. This study retrieved some exciting data on the DI. It was found that CO_2 concentration in the range of 20-70 m AGL was lower than the surface level. The derived DI was maximum at the height range of 40-50 m. Inversion was observed in the range of 30-40 m. A positive correlation between CO_2 and temperature was observed in both seasons. The lightweight commercial drones are capable of tethering sensor modules to get accurate results in less cost and effort. This type of novel tethered sensor technique could be applicable in weather forecasting, landfill surface monitoring, volcanic eruption monitoring, and other probable applications with few drone flight limits.

Keywords-vertical profiling; CO2 profile; sensors; discomfort index; NDIR

I. INTRODUCTION

Gas detection and precise monitoring are crucial in the environmental, mining, metrological, and agriculture sectors [1]. At present, there are many studies available on gas sensing technologies. The rapid changes in sensor technology from analog to digital sensors have promoted various levels of sensing from ppm (parts per million) to ppb (parts per billion) level [2]. The rise of Green House Gas (GHG) emissions globally (Figure 1) is caused by fossil fuel burning and, consequently, the increase in CO_2 levels worldwide. The concentrations of CO_2 emissions were highest in the year 2018, and after the COVID-19 pandemic, the level has not reduced significantly [3]. The major reason behind these elevated levels of GHGs is the utilization of fossil fuels in non-organized sectors. These sectors mainly include concrete and energy-based industries. Power generation accounts for more than 50% of CO_2 emissions in India.

Changes in the CO_2 level affect the photosynthesis of plants. The negative ecological consequences of an increase in CO_2 levels are depicted in [4, 5]. Many research studies have analyzed and interpreted climate change and surface CO_2 level changes to understand the future predictions of global warming and temperature change on this planet. The profiling of CO_2 at multiple altitudes is a novel attempt at environmental engineering.

The health burden of a city or town has always been challenging. The dispersion of CO_2 gas at various heights is critical concerning urban health. The dispersion of CO_2 gas at elevated heights is a critical indicator for urban health and the population in the area. The issues arising from atmospheric temperatures, like seasonal heat sensation and frequent changes in ambient temperature, are observed in various densely populated cities of the country. The existing AAQMS (Ambient Air Quality Monitoring Stations) provide data for air quality (AQ) and CO_2 levels [5-6]. These stations provide the data for a 1 km radius at ground level and are installed in limited locations. Hence, it becomes difficult to study accurate CO_2 levels in the AGL range in urban settings. The DI of the city is often calculated using data from a single or a few weather stations. In this DI calculation process, the data for the AGL range of CO_2, temperature and humidity are not considered. The degree of exposure due to multiple air pollutants at different heights can be accurately identified based on the measured data of pollutants at various AGL heights. Most air-quality drones are equipped with low-cost sensors. The sensors are attached to low-cost quadcopters without considering the aerodynamics of the drone. In such cases, the results may have errors.

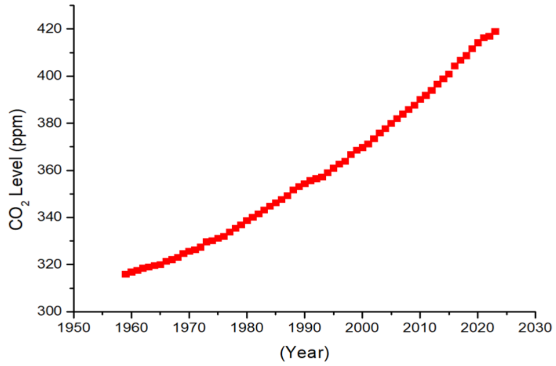

Fig. 1. Global CO_2 level.

The measurement of CO_2 was first initiated in 1958 [7, 8]. After that, numerous measurement methods have been designed for vertical and horizontal profiling of air pollutants. In GHG and DI modelling predictions for meteorological applications, the data of CO_2, temperature, and humidity play a significant role. But the methods of CO_2 measurement, like tethered balloons or radiosonde, are not only costly and time-consuming, they are also complex in nature and difficult to implement practically [9, 10]. During the '80s, helicopters were employed for aerial surveys in residential and industrial settings. But with the introduction of Unmanned Aerial Vehicles (UAVs) for aerial surveys, monitoring gaseous concentrations became easier. Multirotor UAVs are categorized with regard to the number of rotors and their thrust (quadcopters, hexacopters, and octocopters), fixed wings, single rotor helicopter, fixed-wing hybrid VTOL, etc. Some early research was conducted with UAVs to understand the vertical profile in the environment. In these research explorations, UAVs with fixed-wing planes were employed, and sensor mounting experiments were conducted. Due to the capacity of these UAVs to fly 1000 m AGL for more than 45 min, they were found to be very effective in meteorological applications. These UAVs had some drawbacks such as complexity in aerial operations, instability, maneuverability, slow speed of operation, stationary flights, etc., hence the sensor reading may get disturbed due to the non-holding/hovering position in the air. Table I [11, 12] depicts the comparison between fixed wind UAVs and multi-rotor UAVs.

TABLE I. FIXED-WING VS MULTI-ROTOR UAVS

Factors affecting environmental monitoring	**Fixed wing platform**	**Multi-rotor UAV platform**
Flight time	~ 50 min	~ 20 min
Altitude	High (~30,000 ft)	Low (~1,500– 11,150 ft)
Hovering and stability in 3D space	Low (can't hover at a fixed point)	High (in cm) using RTK
Sensor location	At tail/nose/ onboard	Below frame/body
Take off / landing type	Horizontal (needs launching platform)	Vertical (does not need launching platform)
Take off area	Larger with takeoff strips	Very small with no takeoff strip
Learning curve and datasets	Larger and more complex datasets	Smaller and easier datasets

As shown in Figure 2, many researchers mounted the sensor onboard or kept the left side at the nose or below the frame of the drone [13, 14]. However, such experiments considered the downwash by the propellers. These drawbacks forced us to think of other simple options for monitoring CO_2 and other environmental pollutants like particulate matter, SO_x, NO_x, and CO.

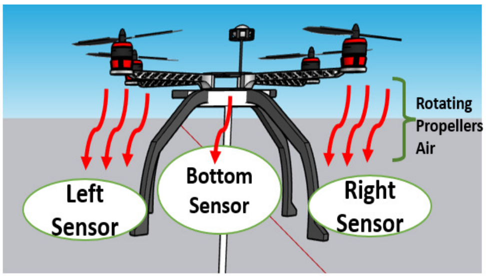

Fig. 2. Positions used for sensor mounting.

A. *The Role of DI*

The DI is a parameter that indicates the human heat sensation in numerous climatic conditions. It is defined by:

$$DI = T\text{-}(0.55\text{-}0.0055 \times RH)\ (T\text{-}14.5) \qquad (1)$$

The existence of high-rise buildings, vegetation, and thermal discomfort sensation directly impact the DI. Therefore, the DI was first calculated using multiple altitude levels. Some studies reveal the direct impact of changes in surface temperature on the human body and comfort. "Stedman Heat Index" is the best example of quantifying the stress imposed on humans due to atmospheric moisture and temperature [15]. The current study investigates the concentration of ambient CO_2 levels along with temperature and humidity [16]. The specific objectives of this experimental work were to examine the feasibility of UAVs (quadcopters) for environmental parameter monitoring purposes compared to the traditional available methods. Then the design of a standard protocol for drone-aided gas monitoring is discussed [16-18]. The calibration of the CO_2 sensor was targeted before tethering it near the drone [14]. Possible aerodynamic drag experiments were performed to attach the sensor module at multiple locations near the drone. The seasonal data were collected using the designed protocol.

II. MATERIALS AND METHODS

A. *Design of the Sensor Module*

DJI Phantom 4 Pro, a quad-copter-based commercial model, was the UAV used in this study. This model is widely accepted and used for various research applications in air quality [18, 19]. The quadcopter with weight carrying capacity of 300 g for 20 min was sufficient for this application. The fundamental reason for the selection of this model was its excellent hovering altitude stability in aerial settings. A Non-Dispersive Infrared Detector (NDIR) sensor was employed for monitoring the levels of CO_2, temperature, relative humidity, and time logs in the memory card. This sensor has a detection range of 0-9999 ppm. The resolution of this instrument is 1 ppm. To hang below the drone, the sensor module weight was brought down below 200 g. For that purpose, a separate DC-DC step-down circuit was attached with the data logger to make it battery operated, as depicted in Figure 3.

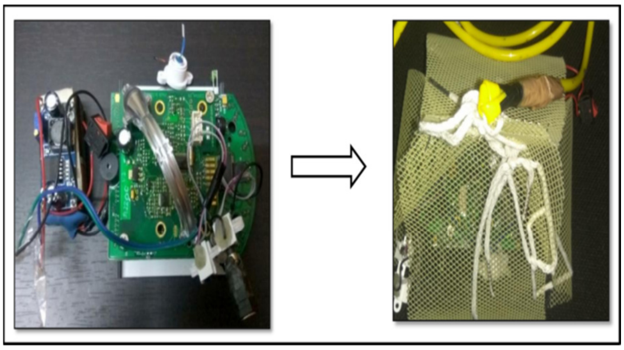

Fig. 3. The sensor module.

B. *Calibration of the CO_2 Sensor Module*

For calibration of the CO_2 module, the CO_2 sensor was kept in the specially designed acrylic test chamber demonstrated in Figure 4. The closed test chamber has an arrangement of providing multiple gas standard spikes, a high-speed fan and dilation assembly for the internal environment. Initially, two sensors were kept in the test chamber. One was used in the drone and the other was the calibrated reference CO_2 sensor. Multiple known gas concentrations were spiked through the inlet of the test chamber and the concentration was recorded manually at an interval of 60 s [2]. Measurements of CO_2 were recorded for 60 min for each sensor. The calibration step was repeated in a monthly basis to assure a relation coefficient as near as possible to 1 [3].

Fig. 4. Calibration chamber.

C. *Site Selection*

The sensor module was cross verified with the other calibrated Testo 440 CO_2 sensor ± (50 ppm) in the specially designed gas chamber unit. A customized sampling methodology was developed to avoid propellers' aerodynamic drag and thrust on sensors during data collection at multiple heights [20, 21]. To make it more interference-free from air flow, the sensor was hung with a fiber mesh. To assure errorless measurement, the readings of CO_2 sensor with and without the mesh were cross checked and found to be the same. To keep the sensor steady, a PVC pipe was employed. The position was identified using an anemometer and multiple aerodynamic studies in simulation software. The drone flight presented in this study took place at the CSIR-NEERI Nagpur campus. The coordinates for the location were 21.1238570 latitude and 79.0701430 longitude. This location was surrounded by a green zone and located in the central area of Nagpur city, Maharashtra, India. The study was carried out from December to May. Flights were taken, in a weekly basis, in the morning, afternoon, and evening hours from a predetermined location. The wind condition was normal during each flight. The area of the CSIR-NEERI campus is 100 acres. Figure 5 depicts the study location of the experimental work.

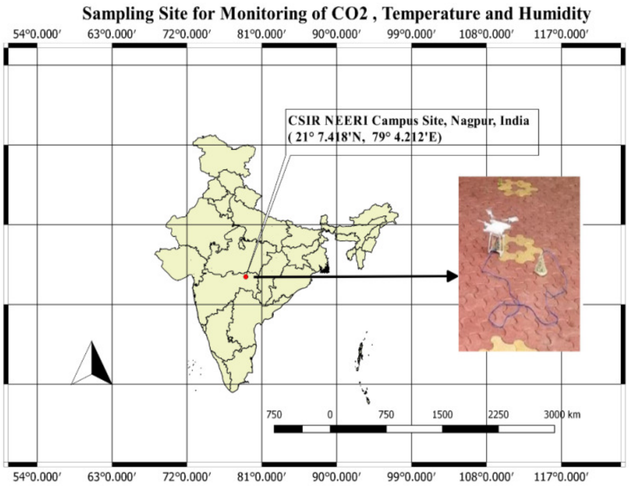

Fig. 5. Sitemap of the study area.

III. RESULTS

A. Sampling Protocol and Flight Path

The customized sampling protocol has been designed to measure gas concentrations at multiple heights. In most of the previous studies, it has been observed that the sensor array was mounted on the drone or in the vicinity of the landing gears of the quadcopter. This assembly is always made by neglecting the effect of downwash and thrust of the propellers. Apart from the propeller shape and size, the downwash effect deviates the sensor values during hovering and in-flight operations. Therefore, a novel sampling protocol has been designed as per the user's applications at the sampling site and pollutant matrix. As given in Figure 6, the protocol can be used at AGL meteorological data collection in open ground, green zones, and landfill sites with calm wind conditions.

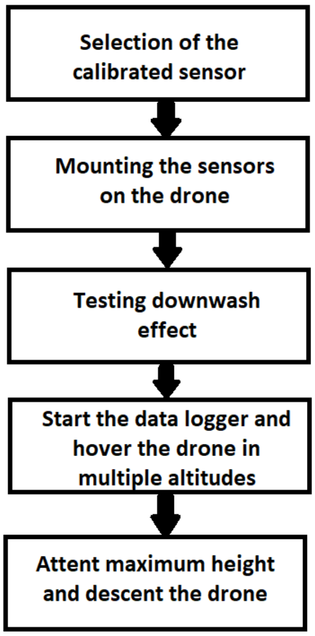

Fig. 6. Drone-assisted sampling protocol.

The trajectory of the flight path was pre-identified. Therefore, the drone throttled upward from a fixed location and hovered at 5.0 m intervals. The drone was hovering at a location for 1.5 min at the sampling frequency as suggested by the DGCA guidelines. Figure 7 denotes the sensor's path and propeller impact analysis. It helps to minimize the dispersion effect in the horizontal plane. In the case of preferring a simple vertical path, there are chances of air dilution due to propellers. It can be observed in Figure 7(a) that maximum area was covered during vertical profiling. This path does not disturb the composition of the air due to shift in the horizontal position by 5 m. During the ascending flight, 1 min interval data were stored in a memory card, and after attending 60.0 m height, the descending data were collected and stored in a memory card. The flight path was plotted in MS-office toolbox and surfer software. It has been observed that the rotating propellers of the drone create a downwash effect in hovering instances. Hence CFD (Computational Fluid Dynamics) simulation of an axial flow of drone propellers was conducted to study the downwash effect using the rotating region method. The simplified model of a rotating quadcopter was employed and simulated in air chamber. Airflow of 5000 mm × 5000 mm was employed in the chamber. This study aimed to find the region where the air affects minimally the sensor. As displayed in Figure 7(b), it could be observed that the quadcopter rotated at the height of 2625 mm with a maximum of 10,000 RPM. It was found that the region below 137.5 mm had the minimal impact of the propellers. Hence, the tethered distance was adjusted to 3048 mm away from the drone to avoid the impact of wind on CO_2 sensor. Tethering the sensor module away from the drone is a very simple technique that can be useful in many applications such as surface emissions monitoring, methane emission from municipal solid waste and landfill sites, and even volcanic eruptions monitoring.

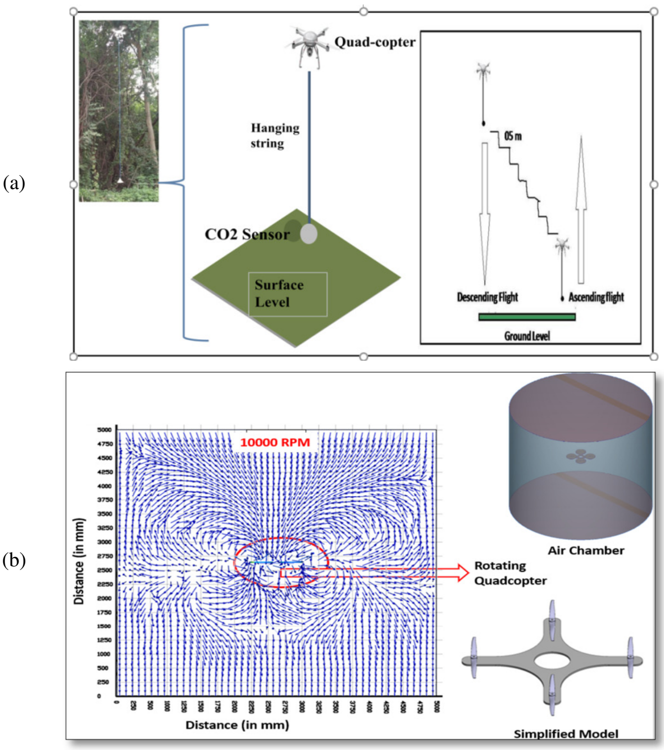

Fig. 7. (a) Flight path adopted during data collection, (b) propellers' impact on sensor analysis.

B. Calibration of the Sensor Module

Figures 8-9 show the promising calibration results of the CO_2 sensor with the calibrated CO_2 meter. The R^2 value between the two sensors was 0.97929. The close chamber tests were repeatedly performed before each flight. This result shows that the mounted sensor module was accurate in the 3D space after mounting to the drone.

C. Seasonal Data Collection

The main objective was to formulate a sampling method for CO_2 detection using commercially available low-cost drones with accurate time-series data collection. The experimental design was made for two different seasons (winter and summer) over urban locations and experiments separately for morning and evening hours. The idea was to check the difference (if any) in the daily pattern of vertical profiling.

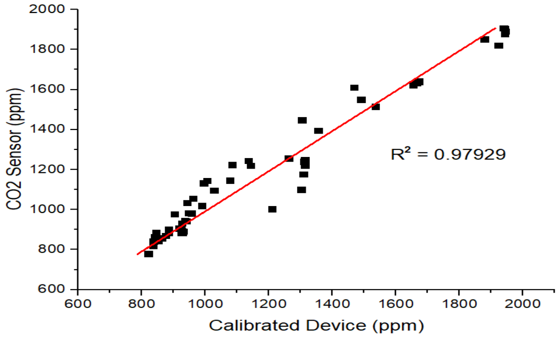

Fig. 8. Closed chamber test.

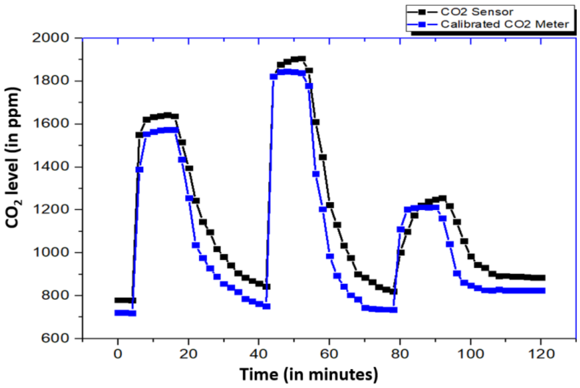

Fig. 9. Time series plot.

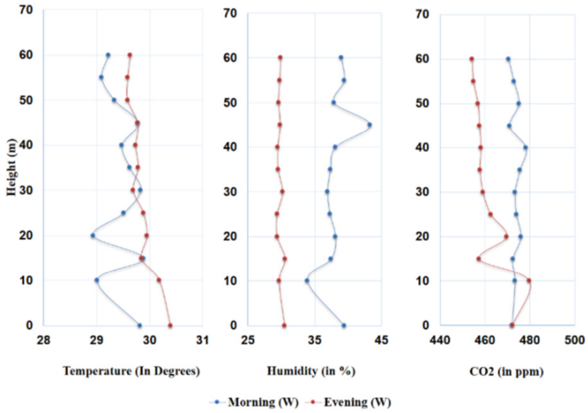

Fig. 10. Altitude-wise temperature, humidity, and CO_2 levels during morning and evening-winter.

IV. DISCUSSION

During wintertime, the vertical profiling of CO_2, temperature and relative humidity was performed during the morning and evening hours. Temperature and CO_2 levels were negatively correlated (-0.2) and the relative humidity remained constant. During the morning, the inverse scenario prevails, the chances of pollutants being trapped under the inversion layer are higher. That is why the concentration of CO_2 at 40-60 m AGL is found to be more in the morning than in the evening. The vertical profiling shows that the trend is opposite in the evening hours. The observations from the result are that temperature and CO_2 are positively correlated (+0.9), whereas relative humidity shows no significant relation with CO_2. During the evening, no exact inversion scenario occurs.

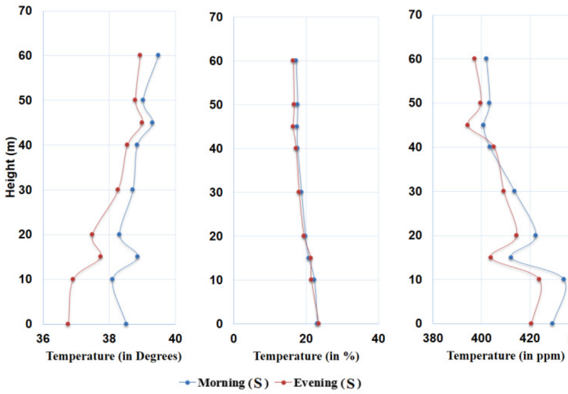

Fig. 11. Altitude-wise temperature, humidity, and CO_2 levels during morning and evening-summer.

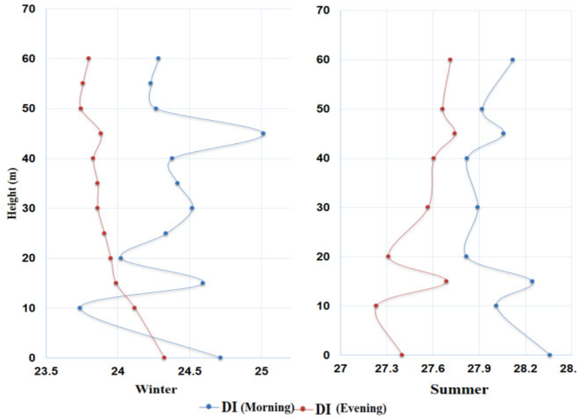

Fig. 12. Winter and summer DI.

During summertime, the vertical profile of CO_2, temperature, and relative humidity shows that during the morning, temperature and CO_2 are negatively correlated, and relative humidity remains constant. During the morning time the inverse scenario increases. The chances of pollutants being trapped under the inversion layer are more, which is why the concentration of CO_2 at 40-60m AGL is found to be more than that of the evening. The vertical profiling of CO_2, temperature, and relative humidity shows the opposite trend during the evening hours. Temperature and CO_2 are positively correlated, whereas relative humidity shows no significant relation with CO_2 and remains constant and the inverse scenario occurs. The derived DI is maximum at 40-50 m height., DI during summertime mornings is maximum at the height of 0-10 m.

This methodology of pollutant data collection is feasible at the non-accessible locations of landfill sites, ecologically sensitive locations, volcanic eruptions, etc. According to the protocol, the user must keep the sensor away from the drone. Therefore, there are minimum chances of interfering with the propellers and their effect on the sensors. Similarly, the drone can be protected during each survey, and users can change the sensor module each time as per their requirement for monitoring. The telescopic arm or pulley system can be attached to the drone to maintain the center of gravity of the drone. The proposed method is helpful in collecting the gaseous samples on varied heights and assures sample collection without any disturbance. The researchers optimized the process after experimentation and developed the SOP (Standard Operating Procedure). During this study it was observed that this experiment could not be carried out below 10 m/s wind velocity. The SOPs will be different for VOCs and particulate matter-based surveys.

V. CONCLUSIONS

The temperature and humidity profile of the atmospheric layer governs its stability. In addition, the concentration of some greenhouse gases (GHGs), like CO_2, varies with time and season as the atmospheric dynamics change. As the atmosphere warms due to the increased presence of GHGs (e.g. CO_2), its ability to carry moisture increases. This reflects increased stress on the human body. The DI gradually increases in tune with increased temperature and humidity. The CO_2 concentration decreases slowly from 20 m height in urban settings. Every area has buildings of varying heights, which impact the accumulation of pollutants. These pollutants have different concentrations in different height ranges. The heat reflection was monitored in 20 m AGL in urban settings. It was found that the drone flight should be below 5 m/s to avoid pendulum movement. In case of high-temperature locations like volcanic eruptions, MSW sites, etc., precautions and safety measures for the protection of sensors should be employed.

Extraction of this information from the atmosphere is a challenging and costly affair. The proposed methodology of vertical profiling will reduce error and provide accurate pollutant concentration data in 3D space. The current project's efforts have been made to materialize and validate a novel method for vertical profiling and information dissemination through sensor modules. In this regard, one derived parameter, DI, is formulated and studied over the urban setup during two seasons (winter and summer). The methodology employed in this study was found to be cost-effective and precise. This methodology can be applied autonomously in various environmental emission monitoring sectors like open cast mining emission monitoring, municipal solid waste gas emission analysis, and other surface-level harmful gas analyses. More research is required in the method development for drone-aided particulate matter monitoring.

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