# A Review of the application of unmanned aerial vehicles in air pollution monitoring

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**Abstract.** At present, air pollution in China remains severe, posing significant threats to public health and imposing heavy economic and healthcare burdens. China has become the country with the highest number of newly diagnosed and fatal cases of lung cancer globally, underscoring the urgent need to address air pollution. In recent years, unmanned aerial vehicle (UAV) technology has developed rapidly, characterized by low cost and high flexibility. UAVs can serve as platforms for carrying air pollution monitoring sensors, offering advantages such as timeliness and adaptability when integrated with air quality monitoring efforts. This paper reviews practical experimental cases involving UAVs in air pollution monitoring, summarizing the various methods and target pollutants monitored using UAVs. It further analyzes the characteristics demonstrated by UAVs in these monitoring experiments. Compared with traditional air pollution monitoring methods, UAV-based monitoring exhibits advantages including lower cost, greater flexibility, and higher spatial and temporal resolution. Some studies have also explored the use of UAVs for pollution source tracing and dust suppression, demonstrating their broader potential in air pollution control. Finally, the paper offers prospects for the future development of UAV-based air pollution monitoring technologies.

**Keywords:** Unmanned Aerial Vehicle (UAV), air pollution monitoring, air pollutants, pollution source tracing

## 1. Introduction

Over the past four decades since the launch of China's Reform and Opening-Up policy, the country has experienced rapid economic development and urbanization. The explosive growth of industry and the number of motor vehicles, coupled with the earlier lack of stringent regulation on atmospheric pollutant emissions, has led to a marked deterioration in air quality. As a result, some cities have faced periods of severe air pollution [1], while the overall decline in air quality has had a profound impact on urban residents' health. In 2021, the number of newly diagnosed lung cancer cases in China reached 934,704, an increase of 659,952 cases compared with 1990. In 2022, the global number of new lung cancer cases stood at 2.4807 million, with 1.8175 million deaths. Among these, China reported 1.0606 million new cases and 733,300 deaths, ranking first globally in both incidence and mortality [2].

In recent years, the Chinese government has made significant efforts to improve air quality and safeguard public health. However, research in China on air pollution control and the relationship between air pollution and health began relatively late. Existing World Health Organization (WHO) reports on air pollution and epidemiology are largely based on data collected from fixed monitoring stations. Due to the limited number of these stations, the data they provide may not accurately reflect the overall air quality across entire urban areas. Consequently, the Global Air Quality Guidelines developed based on such data are inadequate for capturing the intra-urban variations in air quality [3]. This highlights the urgent need for more advanced and scientific monitoring methods to obtain real-time data on urban air pollution, thereby supporting both environmental governance and research on the epidemiological impacts of air pollution.

In recent years, the development of unmanned aerial vehicle (UAV) technology has introduced new methods and opportunities for air pollution monitoring. In December 2023, China's Central Economic Work Conference identified the low-altitude economy as a strategically emerging industry prioritized for development [4]. Today, China's UAV technology has advanced rapidly and now occupies a strategic position in the global low-altitude economic market. In 2023, the direct output value of China's low-altitude economy reached 505.95 billion yuan. According to forecasts by the Guangdong-Hong Kong-Macao Greater Bay Area Digital Economy Research Institute, the contribution of the low-altitude economy to China's national economy is expected to reach between 3 and 5 trillion yuan by 2025 [5]. Based on these projections, UAVs are anticipated to become increasingly integrated into various aspects of daily life and production in China. Against this backdrop, the use of UAVs

for monitoring urban air pollutants presents a promising approach to overcoming the limitations of traditional monitoring methods—such as low spatial coverage and insufficient spatiotemporal resolution. UAVs may also be employed for pollution source tracing, thereby enabling timely interventions to mitigate air pollution while simultaneously collecting spatiotemporal data to support related scientific research. This study reviews and synthesizes recent literature on UAV-based air pollution monitoring, with the aim of providing useful insights for future research in this field.

## 2. Literature search strategy and inclusion/exclusion criteria

Literature was retrieved from several academic databases, including CNKI (China National Knowledge Infrastructure), Web of Science, The Engineering Index, and SpringerLink. The Chinese search keywords used were "无人机" (unmanned aerial vehicle) and "大气污染" (air pollution), while the English search terms were "UAV-based" and "air pollution." The search was limited to publications from the year 2015 to 2025.

The inclusion criteria, based on the research content and methodologies of the retrieved literature, were as follows: ① The air pollution monitoring equipment—whether electronic nose sensors or remote sensing sensors—must be mounted on a UAV platform; ② The literature must contain concrete experimental data or practical applications.

The exclusion criteria were as follows: ① The publication is a conference abstract, review article, or research report; ② The literature focuses solely on system design, platform development, or software programming, without conducting actual air pollution monitoring experiments; ③ The full text is not accessible, or the publication date is earlier than 2015.

## 3. Results

A total of 13 relevant studies were included based on the established inclusion and exclusion criteria. The details of the included literature are presented in Table 1.

**Table 1.** Summary of included literature

| No. | Author | Title | Location | Pollutant Type | Overview of Method | Key Findings | Limitations |
|---|---|---|---|---|---|---|---|
| 1 | Lin Sainan [6] | Study on UAV-Based Air Pollution Testing Methods and Distribution Characteristics in Street Canyons | Guangzhou | Particulate matter, ozone, sulfur oxides, nitrogen oxides | UAV equipped with sensors used to measure pollutants at pedestrian height in street canyons with different height-to-width ratios | Proposed a UAV-based method for monitoring air pollution in street canyon areas | Limited variety of canyon types selected |
| 2 | Luo Jinglan [7] | Comparative Analysis of Ozone Pollution in Meishan Based on UAV Vertical Observation | Meishan | Ozone | UAV conducted vertical and horizontal measurements (up to 50 m height, 20 m width) at different times to calculate mean values | Mapped spatial-temporal distribution of ozone in parts of Meishan | Did not analyze meteorological influences; no comparison with fixed monitoring data |
| 3 | Guo Wei [8] | Vertical Distribution Characteristics of $O_3$ Under Different Pollution Conditions Based on UAV Observations | Datong, Taiyuan, Linfen | Ozone | UAVs ascended from 10 m to 500 m in three cities to collect vertical ozone data | Revealed vertical distribution and variation of ozone in three cities | No comparison with data from fixed monitoring stations |
| 4 | Liu Xin [9] | Study and Application of Dust Dispersion Patterns in Anjialing Open-Pit Coal Mine Based on UAV Monitoring Technology | Anjialing Coal Mine, Pingshuo | Particulate matter | UAV collected dust data at multiple heights; compared with fixed monitoring data and tested UAV for dust suppression | Established seasonal dust concentration models; demonstrated consistency with fixed station data; simulated UAV dust control feasibility | |
| 5 | Bi Daojin [10] | Study of a Dust Storm Event in the Taklamakan Desert Using UAV Vertical Observations | Tazhong & Minfeng, Taklamakan Desert | Particulate matter | UAV equipped with wind and atmospheric sensors to collect vertical data on common particulates | Developed models of concentration vs. height, humidity, temperature, wind speed; analyzed sensor performance under different atmospheric conditions | No comparison with traditional monitoring data |
| 6 | He Zhenbang [11] | Reliability Study of UAV-Based Low-Altitude Remote Sensing System for Sudden Highway Environmental Pollution Dispersion | A highway (unspecified) | | UAV used for atmospheric image capture; optical imaging combined with clustering analysis to estimate pollution probability and affected area; mathematical modeling and simulation used to verify system reliability | Provided UAV system failure rate and reliability data; concluded high system reliability | Did not analyze effects of meteorological conditions |
| 7 | Xie Lihua [12] | UAV-Based Air Pollution Source Localization Technology and Experimental Study | Campus (unspecified) | Ethanol | UAV equipped with sensors to detect specific pollutants; used Gaussian plume model to trace source | UAV successfully hovered at source location under both obstructed and unobstructed conditions | Limited study scope and pollutant types |

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| 8 | Yi Jianwen [13] | Study on Vertical Distribution of VOCs in a Petrochemical Industrial Park in Guangdong Based on UAV Monitoring | Heshan | Volatile Organic Compounds (VOCs) | UAV-mounted sensors used to monitor and sample VOCs in a petrochemical park | Identified types, proportions, and vertical distribution characteristics of VOCs in the park | Lacked comparison with fixed monitoring data |
| 9 | Wei Shuncheng [14] | UAV-Based Emergency Monitoring and Source Tracing of Air Pollution | Hangzhou | Particulate matter, sulfur dioxide | UAV conducted vertical measurements at selected points; pollutant concentration data used to locate pollution sources | Obtained vertical pollutant distribution and estimated pollution source locations | Few measurement sites; source tracing relied on algorithms rather than real-time UAV tracking; possible accuracy limitations |
| 10 | Tommaso Francesco Villal [15] | Development and Validation of a UAV Based System for Air Pollution Measurements | Brisbane, Aerospace Automation Research Center | $CO_2$, CO, $NO_2$, NO | Compared sensor data with UAV propellers off vs. hovering; validated UAV reliability in pollutant monitoring | Demonstrated feasibility of integrating sensors into UAVs; highlighted need for real-world application testing | Indoor simulation only; limited applicability to outdoor conditions |
| 11 | Yu Heyao [16] | Improving Fugitive Dust Emission Inventory from Construction Sector Using UAV Images Recognition | Pearl River Delta | Particulate matter | Combined UAV imagery with deep learning models to assess construction emissions | Generated emission inventory via UAV data and manual validation; confirmed UAV feasibility and broad applicability | Limited study area; no comparison with traditional monitoring methods |
| 12 | Peng Rena [17] | A UAV-based method for efficiently measuring the spatial pattern of multiple air pollutants in street canyons | Guangzhou | Particulate matter, ozone, sulfur oxides, nitrogen oxides | UAV used in both indoor incense burning and optimized outdoor street layouts for low-altitude sampling | Collected multi-pollutant data within a 24-minute UAV flight | Did not analyze impact of atmospheric conditions |
| 13 | Aravindaguru [18] | Environmental Drones for Autonomous Air Pollution Investigation, Detection, and Remediation | Coimbatore, Hosur, Ooty, Karur (India) | Particulate matter, ozone, $NO_2$, $SO_2$, $CO_2$ | UAV equipped with multiple sensors to monitor pollutant concentrations at various sites; conducted propeller interference tests | Confirmed UAV effectiveness for monitoring multiple pollutants | Did not analyze atmospheric interference or compare with fixed monitoring data |

## 3.1. Air pollutants

The types of air pollutants monitored using UAV-based technologies primarily include inhalable particulate matter, ozone, carbon oxides, sulfur oxides, nitrogen oxides, and volatile organic compounds (VOCs). Among the 13 reviewed studies, 5 focused on multiple types of air pollutants, 7 examined a single pollutant, and 1 did not specify the pollutant type under investigation. Specifically, 7 studies collected concentration data on inhalable particulate matter ($PM_{2.5}$, $PM_5$, and $PM_{10}$); 4 studies focused on ozone ($O_3$); 5 studies used UAVs to monitor carbon oxides, sulfur oxides, and nitrogen oxides (e.g., CO, $SO_2$, $NO_2$); and 2 studies involved the monitoring of VOC concentrations. One of the VOC-related studies used ethanol, both indoors and outdoors on a university campus, as a representative volatile compound to simulate other types of air pollutants.

## 3.2. Data acquisition methods

In UAV-based air pollution monitoring, data are obtained either through remote sensing using UAV-mounted visible light imaging systems or via onboard atmospheric sensors that directly measure pollutant concentrations. Among the 13 reviewed studies, 2 employed UAVs to capture remote sensing imagery of the target areas and analyzed these images to infer pollution levels. The remaining 11 studies utilized UAVs equipped with specific sensors corresponding to the target pollutants to directly collect concentration data.

Among the 13 included studies, 6 employed fixed-point or fixed-altitude data collection methods. For example, Aravindaguru et al. selected five sampling sites to collect concentration data for particulate matter, nitrogen dioxide, sulfur dioxide, and other pollutants. Five studies conducted vertical measurements to obtain pollutant concentration profiles at different altitudes. For instance, Wei's study selected seven monitoring sites where UAVs collected particulate matter and sulfur dioxide concentrations at altitudes of 50 m, 100 m, 150 m, 200 m, 250 m, 300 m, 350 m, 400 m, 450 m, and 500 m above each site. Additionally, two studies utilized UAV remote sensing methods to assess pollution levels over specified spatial areas.

Regarding application scenarios, among the 13 included studies, 4 not only employed UAVs to collect pollutant concentration data but also attempted to trace pollution sources by combining UAV measurements with diffusion models. For example, Xie's study successfully conducted localized UAV-based air pollution source tracing using programmed control and electronic nose sensors, effectively avoiding obstacles along the flight path and accurately identifying the pollution source with minimal deviation. Liu's study went beyond analyzing pollution source dispersion to experimentally demonstrate the feasibility of UAV-based spraying for dust suppression.

## 3.3. Reliability and accuracy analysis

All the reviewed studies obtained specific concentration data of the targeted air pollutants within their respective experimental environments. Among them, three studies solely relied on pollutant concentration data collected by UAV-mounted sensors without comparing these data to those from fixed monitoring stations to assess the accuracy and reliability of the UAV measurements. Conversely, nine studies not only utilized UAVs to collect pollution data but also employed conventional pollutant monitoring methods to obtain comparative datasets for analysis. For example, in Guo's experiment, UAV data collected while hovering at 10 meters above ground level were compared with ground-based monitoring station data, demonstrating a reliability of over 93% for UAV-measured ozone concentrations near the surface. Similarly, He's study concluded a 93% reliability rate for UAV-based pollutant concentration measurements. Yi's research combined UAV-collected pollutant data with air samples gathered by portable instruments, which were subsequently analyzed in the laboratory to validate the reliability of UAV data. Multiple studies, based on such comparative experiments, concluded that UAV-based investigation of air pollution is both feasible and broadly applicable.

## 3.4. Error analysis

Among the seven studies that conducted comparative experiments, three performed detailed error analyses between data collected by fixed monitoring instruments and those obtained via UAVs. In Liu's study, based on mathematical and physical principles, three sets of calculation formulas were proposed to quantify the influence of UAV rotor downwash on collected pollutant concentration data, incorporating gradient transport, turbulence statistics, and similarity theory. Villa's study focused on analyzing discrepancies between air pollution data collected at the same location by UAVs when hovering versus when stationary. Utilizing the collected data, several violin plots were generated, showing that pollutant concentrations were higher when the UAV's propellers were off and the sensor was within the plume. However, the UAV-induced downwash effect was mainly confined within three meters of the measurement point, and airflow effects on measurement data were considered negligible. Aravindaguru's study fixed the UAV atop a tower to collect pollutant concentration data, then flew the UAV in the same position to gather comparable data. The differences between the two measurements for $PM_{2.5}$ and $PM_{10}$ concentrations were 9% and 8.3%, respectively. After adjusting the propellers, these discrepancies were reduced to 6.2% and 6.6%, respectively.

## 4. Discussion

### 4.1. Traditional air pollution monitoring

#### 4.1.1. Limitations of traditional air pollution monitoring

Within a given regional scope, several discrete monitoring points are selected based on specific criteria. At each point, manual or automatic air pollution monitoring instruments are installed, and observation towers or lidar stations are established to conduct

ground-level atmospheric monitoring and sampling. This represents the most traditional and widely used approach for air pollution monitoring. Various types of monitoring instruments are low-cost, allowing flexible adjustment of deployment density and coverage according to monitoring needs. These instruments can detect multiple types of air pollutants and are lightweight and portable, facilitating redeployment or retrieval after use. However, these instruments typically monitor pollution only near the ground surface and cannot capture data in the vertical dimension. Observation towers, with moderate costs, enable long-term, stable horizontal and vertical monitoring of multiple pollutants within a limited spatial range. Nonetheless, their monitoring height is relatively low, and coverage areas are limited. Lidar stations, which are more expensive, can monitor pollution over higher and broader atmospheric ranges; however, their monitoring suffers from ground-level blind spots [19], and they can detect fewer pollutant types compared to the other two platforms. The data obtained from such monitoring stations have high temporal continuity, which facilitates analysis and forecasting of pollution trends. However, significant limitations exist: First, spatial limitations are evident. For example, in 2021, the spatial representativeness of national control points for PM2.5 in the Yangtze River Delta region covered only 63.23% of the total area [20]. Under this context, whether data collected at monitoring stations can accurately reflect pollution levels in the unmonitored areas remains an unresolved issue. Second, monitoring height is clearly restricted. Although lidar systems can monitor vertical ranges extending several kilometers, their limitations have resulted in a relatively minor role in air pollution monitoring. Observation towers typically monitor within 500 meters [21], and portable monitoring instruments usually capture data only within several meters above ground level.

Satellite remote sensing-based atmospheric monitoring is an advanced technique developed alongside the maturation of satellite remote sensing technology. It employs sensors mounted on satellite platforms to detect and retrieve concentrations of airborne pollutants such as particulate matter and ozone within the Earth's atmosphere, thereby providing relevant air pollution data. Notable satellites equipped with atmospheric pollution monitoring capabilities include China's Fengyun-4 (FY-4) and Gaofen-5, the United States' CALIPSO, and Japan's Himawari-8, among others. Regarding cost, satellite platforms are extremely expensive, with Earth observation satellites costing hundreds of millions of US dollars. In terms of observational capabilities, the Gaofen-5 satellite has a spatial resolution of 30 meters; however, due to spatial coverage constraints, the effective resolution of its data in practical applications is often lower than this nominal value. Furthermore, Shen et al. (2019) compared ozone concentration data from the Ozone Monitoring Instrument (OMI), aboard the US Aura satellite, with ground-based monitoring station data and concluded that satellite observations have limited sensitivity within the atmospheric boundary layer.

## 4.2. UAV-based atmospheric pollution monitoring methods

From the UAV atmospheric pollution monitoring experiments recorded in the literature summarized in Table 1, it is evident that UAV-based monitoring platforms possess numerous advantages compared to traditional atmospheric pollution monitoring platforms. Unlike monitoring towers and ground-based lidar stations, UAVs equipped with sensors offer the flexibility to select monitoring areas as needed and enable vertical observations at heights far exceeding those of monitoring towers. Furthermore, within their effective operational altitude range, UAVs have no observational blind spots. For example, DJI's FLYCART 30 UAV model can reach a maximum altitude of 6,000 meters above sea level and carry a maximum payload of 30 kilograms. These specifications demonstrate that UAV platforms can simultaneously carry multiple monitoring sensors, allowing extensive horizontal and vertical atmospheric pollution observations over large areas and various altitudes.

Compared with ground-based monitoring instruments, UAV monitoring platforms not only offer greater flexibility in the deployment of detection devices but also provide a significantly wider monitoring altitude range. In contrast to satellite remote sensing platforms, UAV platforms incur substantially lower costs; the research, manufacturing, and launch cost of a single satellite is sufficient to deploy a large number of UAV monitoring units capable of covering an observational range comparable to that of the satellite. Moreover, UAV-derived data typically exhibit higher spatial resolution than satellite data. Additionally, satellites cannot maintain a constant relative position over the target observation area, so no matter how frequent their observations, they cannot match the temporal resolution achievable by UAV platforms. This leads to UAV monitoring data exhibiting richer and more accurate spatiotemporal correlations of atmospheric pollution compared to satellite data.

## 4.3. Development directions of UAV-based air pollution monitoring

Utilizing UAVs for air pollution monitoring inevitably faces challenges such as vast monitoring areas, complex urban structures, variable weather conditions, and the handling of massive data volumes. Therefore, UAV-based air pollution monitoring technology must be integrated with other advanced technologies to more effectively accomplish these tasks.

①Integration with advanced UAV technologies: Due to the particular demands of air pollution monitoring, UAVs selected as sensor carriers should prioritize features such as high maximum flight altitude, strong endurance, large payload capacity, and a long rotor-to-center distance. These characteristics enable a single UAV to collect data from multiple points and carry various

pollution monitoring sensors simultaneously for multi-pollutant data acquisition. Furthermore, a longer rotor-to-center distance helps to minimize the interference caused by rotor downwash on the measurement data.

②Integration with advanced Global Navigation Satellite System (GNSS) technology: The combination of UAVs with high-precision positioning technology can enhance the spatial accuracy of collected pollution data, thereby enabling the acquisition of pollution data at specific points and the establishment of pollutant concentration–location models. Such data not only aid in pollution source tracing but also enrich relevant research databases, supporting diverse atmospheric pollution studies [23].

③Integration with Artificial Intelligence (AI) technologies: Large-scale, multi-point, multi-temporal air pollution monitoring generates vast spatiotemporal datasets that constitute a subset of big data. AI technologies, including deep learning and data processing, can accelerate the processing and analysis of UAV-collected pollution monitoring data across wide areas and multiple targets [24]. This integration significantly enhances pollution source tracing and decision-making based on the collected data [25].

④ Integration with other UAV-related industries: As a multifunctional carrier, a UAV can simultaneously carry multiple devices to perform various tasks. Air pollution monitoring can be implemented as one of many functionalities on a single UAV platform. For example, the DJI FLYCART 30, primarily designated as a transport UAV, could perform pollution monitoring during urban logistics operations. This cross-industry integration, once realized, would substantially reduce deployment costs for large-scale UAV-based air pollution monitoring [26].

## 5. Conclusion

The application of unmanned aerial vehicles (UAVs) in air pollution monitoring is feasible, as the pollutant concentration data they collect can accurately reflect the air quality at sampling locations and are comparable to data obtained through traditional methods. Compared with conventional air pollution monitoring techniques, UAV-based monitoring using sensors mounted on UAVs demonstrates significant advantages: ①Low cost: The combined cost of UAVs and sensors is substantially lower than that of fixed monitoring stations and satellite remote sensing technologies. ②High flexibility: Unlike traditional monitoring stations fixed at specific ground locations and handheld instruments limited by height, UAVs can perform large-scale horizontal monitoring and conduct vertical measurements at multiple altitudes at the same location. ③High accuracy: When equipped with remote sensing sensors, UAVs provide monitoring accuracy superior to that of remote sensing satellites. ④ Additional capabilities: UAVs also offer potential for pollution source tracing, pollution reduction, and integration with other UAV functionalities.

At the same time, there remain many promising directions for further research and development in UAV-based air pollution monitoring technology, such as improving the UAV platform's endurance and operational range, enhancing the accuracy and flexibility of associated sensors, and enabling the coordinated operation of multiple UAVs for comprehensive pollution monitoring. It is believed that continued advancements in UAV air pollution monitoring will bring new opportunities and transformative changes to air quality research and management.

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