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Air Quality Monitoring Using Drone: A Quadcopter-Based Real-Time Atmospheric Sensing System

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Abstract

Air pollution has emerged as one of the most critical global public health challenges, claiming over 6.5 million lives annually worldwide. Conventional ground-based air quality monitoring stations, while precise, are expensive, stationary, and incapable of capturing three-dimensional pollutant distribution or providing rapid-response data during emergency events. This paper presents the design, development, and experimental evaluation of a quadcopter-based Unmanned Aerial Vehicle (UAV) integrated with a multi-sensor Air Quality Index (AQI) monitoring payload. The system employs MQ-135 (CO_2/NH_3/NO_2), MQ-7 (CO), and MQ-4 (CH_4/CNG) gas sensors alongside a DHT11 temperature-humidity module, all interfaced with an Arduino Nano microcontroller. A decoupled secondary ground station comprising a second Arduino Nano and a 16×2 I2C LCD independently receives and displays real-time sensor data via a 2.4 GHz RF wireless link, entirely separate from the drone's primary flight telemetry. The quadcopter platform incorporates four A2212 1000 KV BLDC motors, a PID-based flight controller, and a 2500 mAh LiPo battery. Vertical climb tests at 0, 10, 20, and 30 m altitude confirm a strong inverse relationship between altitude and pollutant concentration, with CO_2 decreasing from 450 PPM at ground level to 410 PPM at 30 m. A 5.6% sensor variance due to propeller-induced downwash was identified and characterized. The wireless sensor link maintained reliable data transmission up to 50 m, beyond which packet loss increased significantly. The addition of the sensor payload reduced flight endurance by approximately 20%, yielding 12–14 minutes of effective mission time. These findings validate drone-based monitoring as a cost-effective, mobile, scalable, and high-resolution complement to fixed monitoring infrastructure, with significant potential for smart-city environmental management, industrial compliance monitoring, and disaster response.

Keywords*—Air Quality Monitoring; Drone; UAV; Quadcopter; MQ Sensors; AQI; Arduino Nano; Atmospheric Sensing; IoT; Environmental Monitoring*

I. INTRODUCTION

Air pollution stands as one of the most urgent and pervasive environmental challenges confronting modern societies. Rapid industrialization, uncontrolled urbanization, increasing vehicular density, and intensive agricultural practices have collectively elevated the concentration of hazardous pollutants in the atmosphere to dangerous levels in many regions of the world. According to the World Health Organization (WHO), more than 6.5 million premature deaths are attributed to air pollution annually, with over four million of those directly linked to outdoor pollution since 2019 [1]. Pollutants such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), ammonia (NH_3), ozone (O_3), and particulate matter ($PM_{2.5}$, PM_{10}) exert severe physiological effects: elevated CO causes cellular hypoxia, headache, and disorientation; NO_2 triggers asthma and airway inflammation; ozone causes bronchiolar irritation; and NH_3 can induce alveolar edema [2].

Traditional approaches to air quality monitoring rely on fixed, government-operated ground stations equipped with high-precision laboratory-grade instruments such as beta attenuation monitors (BAM), UV fluorescence analyzers, and chemiluminescence analyzers. While these deliver scientifically trusted data, they suffer from fundamental structural limitations. First, their high capital and operational costs restrict network density, leaving vast urban and rural areas unmonitored. The WHO recommendation of one monitoring station per square kilometer is rarely met. Second, being stationary, fixed stations capture data from a single location only, unable to map spatial pollutant gradients across a city, industrial corridor, or agricultural zone. Third, and critically, they are incapable of providing vertical air quality profiles—data at different altitudes—which is essential for understanding pollutant dispersion, boundary-layer dynamics, and the behavior of industrial stack emissions.

Finally, during emergency events such as chemical plant leaks, accidental fires, or sudden toxic gas releases, fixed stations are often not positioned near the incident zone, resulting in critical data gaps precisely when real-time environmental intelligence is most urgently needed.

Low-cost IoT sensor networks have partially alleviated some of these limitations by enabling denser spatial deployments. However, these ground-level networks still cannot provide vertical profiling, and their sensor accuracy degrades significantly under varying temperature, humidity, and interference conditions. Mobile ground vehicle-based platforms offer some spatial flexibility but remain constrained to road-accessible terrain. Satellite-based systems provide broad regional coverage but lack the spatial resolution and real-time response characteristics needed for localized urban monitoring or industrial compliance.

Unmanned Aerial Vehicles (UAVs), commonly known as drones, have emerged as a transformative platform for environmental monitoring. Their ability to navigate three-dimensional space, access hazardous or physically restricted areas, deploy rapidly, and carry compact, lightweight sensor payloads makes them uniquely suited to bridge the measurement gaps left by existing systems. A drone equipped with gas sensors can fly across varied elevations and geographies during a single mission, generating georeferenced, altitude-stratified air quality data in real time [3]. Furthermore, a single low-cost drone can replace the monitoring function of multiple fixed stations across a defined coverage area, dramatically reducing infrastructure expenditure.

This paper presents the complete design, hardware integration, and experimental evaluation of a quadcopter-based AQI monitoring system. The system integrates multiple MQ-series electrochemical gas sensors and a DHT11 temperature-humidity sensor with an Arduino Nano microcontroller mounted on a custom quadcopter frame. A secondary, independently powered ground station receiver provides real-time sensor data display on a 16×2 LCD, decoupled from the drone's primary flight controller to prevent any RF interference with navigation telemetry. The paper reports detailed experimental results from vertical altitude profiling tests, propeller downwash characterization, communication range analysis, and power endurance evaluation, contributing novel quantitative insights into drone-based air quality sensing system performance.

II. LITERATURE REVIEW

Research in UAV-based atmospheric monitoring has advanced substantially over the past decade, driven by declining sensor costs and maturing drone technology. Motlagh et al. [3] presented an extensive survey covering more than 150 studies on UAV-based air pollution monitoring, establishing that multi-rotor platforms offer the best hovering stability for sensor data acquisition while fixed-wing drones provide superior range for area mapping. The survey highlights propeller turbulence and limited battery endurance as the two most persistent technical challenges. Naznin Shaila et al. [4] demonstrated a drone-based real-time pollution monitoring system using ESP32 with GPS-tagged data logging and cloud upload via MQTT, achieving satisfactory CO and CO_2 measurement accuracy at altitudes up to 40 m, though their system shared the same power bus for both flight and sensor electronics, creating potential noise interference.

Kumar and Mittal [5] evaluated LoRaWAN as the communication backbone for drone-based AQI monitoring, demonstrating a communication range exceeding 2 km with acceptable packet loss below 5% at altitudes up to 100 m, far surpassing 2.4 GHz RF-based systems. Their work, however, focuses exclusively on communication performance and does not characterize sensor behavior under rotor turbulence. Dequilla-Nicerio [6] developed a quadcopter AQI evaluation system specifically targeting warehouse environments using PMS5003 optical particle counters, reporting $PM_{2.5}$ measurement accuracy within ±8% of reference instruments during hover, with sensor readings influenced by airflow patterns within confined spaces.

Limon et al. [7] developed a mobile smart sensing technology for drone-based monitoring of low-access areas, achieving GPS-referenced 3D pollution maps. Their system used a Raspberry Pi for onboard data processing with cellular IoT connectivity for cloud streaming. Rossi and Catelani [8] deployed a drone system for monitoring gaseous pollutants near industrial stacks, characterizing the vertical plume structure of SO_2 and NO_x and demonstrating that drone-based profiling captures emission patterns that ground-level sensors entirely miss. Fernandes and Lima [9] specifically investigated MQ-series sensor integration with ESP32 for drone payload, characterizing individual sensor warm-up behavior, calibration drift, and cross-sensitivity effects between simultaneously detected gases.

A review of existing literature reveals two persistent gaps. First, few studies explicitly characterize and quantify the effect of propeller downwash on sensor readings—a systematic error source unique to drone-based sensing. Second, most systems integrate sensor electronics directly into the drone's flight controller power and communication bus, creating potential interference with GPS and telemetry. The present work directly addresses both gaps through experimental downwash characterization and a fully decoupled secondary sensor communication architecture.

III. SYSTEM DESIGN AND METHODOLOGY

The proposed system architecture integrates three functional subsystems: (1) the quadcopter mechanical and propulsion platform, (2) the onboard air quality monitoring module, and (3) the independent ground station data receiver. The design philosophy prioritizes decoupling of sensor electronics from flight electronics to eliminate interference, and ensures that sensor power is independent from drone propulsion power to prevent voltage fluctuations during motor transients from corrupting sensor readings.

A. Quadcopter Mechanical and Propulsion System

The drone frame is constructed from glass fiber composite with Polyamide-Nylon arms configured in a symmetric X-layout, providing high structural rigidity while minimizing weight. The four arms extend from a central hub housing the Power Distribution Board (PDB) and flight controller. Each arm terminates in a motor mount supporting an A2212 1000 KV Brushless DC (BLDC) motor. The 1000 KV rating indicates the motor spins at 1000 RPM per volt under no-load conditions, providing a balance of thrust and efficiency suitable for a medium payload UAV. Two motors spin clockwise and two counter-clockwise to cancel net reactive torque, enabling yaw control without a tail rotor.

The propellers are 1045 (10-inch diameter, 4.5-inch pitch) ABS composite blades. The 10-inch diameter generates substantial thrust while the 4.5-inch pitch provides moderate air column velocity, balancing efficiency and noise. A 2500 mAh, 6S (22.2V nominal), 35C continuous discharge LiPo battery provides main propulsion power. The 35C rating ensures the battery can supply the high instantaneous currents demanded during aggressive maneuvers without voltage sag. Electronic Speed Controllers (ESCs) receive PWM signals from the flight controller and regulate motor speed by modulating the three-phase AC waveform. Landing gear legs provide adequate ground clearance for the sensor module mounted below the main frame plate.

B. Flight Control System

The flight controller is the computational core managing stabilization and navigation. It receives input from an onboard 6-axis IMU (accelerometer and gyroscope) providing roll, pitch, and yaw orientation data at high sampling rates, and from a barometric pressure sensor for altitude estimation. A PID (Proportional-Integral-Derivative) control algorithm continuously computes error between desired and actual orientation states and generates corrective throttle signals to each ESC. The PID loop runs at several hundred Hz, ensuring fast disturbance rejection and smooth hovering performance even in light wind conditions. A 2.4 GHz 6-channel radio receiver onboard relays pilot commands (throttle, roll, pitch, yaw, and auxiliary channels) from the handheld transmitter to the flight controller. Fail-safe mechanisms are configured to initiate controlled descent if the RC link is lost for more than 1.5 seconds.

C. Air Quality Monitoring Sensor Module

The sensor payload is mounted on a vibration-damped platform below the drone frame, using rubber grommets to attenuate motor vibrations that could induce baseline noise in the MQ sensor ADC readings. The payload comprises four sensing elements:

- MQ-135: A chemi-resistor metal oxide semiconductor (MOS) sensor sensitive to CO_2, NH_3, alcohol, benzene, smoke, and nitrogen oxides. Its conductivity increases proportionally with target gas concentration.
- MQ -7: A dual-cycle chemi-resistor sensor optimized for CO detection, operating by alternating between a high-temperature (5V) detection phase and a low-temperature (1.4V) cleaning phase.
- M Q-4: A MOS sensor sensitive to methane (CH_4) and compressed natural gas (CNG), useful for detecting leaks from gas pipelines or landfill sites.
- DHT11: A capacitive humidity sensor and NTC thermistor module providing ambient temperature (±2°C accuracy) and relative humidity (±5% RH accuracy) data, necessary for sensor response correction.

All four sensors connect to the analog input pins of an Arduino Nano (ATmega328P, 16 MHz, 10-bit ADC). The Nano samples each sensor channel, applies a calibration formula to convert raw ADC counts (0–1023) to PPM values using the sensitivity equation $Rs/Ro = f(ppm)$ derived from manufacturer datasheets, and formats the data packet for wireless transmission. A dedicated 3.7V Li-ion battery (1000 mAh) powers the sensor module independently, ensuring a stable, clean supply voltage unaffected by motor current transients on the drone's main power bus.

D. Wireless Communication and Ground Station

Sensor data is transmitted wirelessly using a pair of NRF24L01+ 2.4 GHz transceiver modules—one on the drone-mounted Arduino Nano (transmitter role) and one connected to the ground-station Arduino Nano (receiver role). The NRF24L01+ operates across 125 configurable RF channels with data rates of 250 kbps, 1 Mbps, or 2 Mbps and features hardware CRC error checking for data integrity. The ground station receiver drives a 16×2 character LCD via the I2C protocol (SDA/SCL on two wires), displaying real-time gas concentrations and temperature/humidity readings. This entire ground station subsystem is completely independent of the drone's primary telemetry link, eliminating any risk of RF congestion or cross-interference that could degrade flight controller GPS lock or attitude sensor data.

E. System Integration and Assembly Procedure

Assembly followed a structured sequence: (i) motor and propeller installation with torque verification; (ii) ESC calibration using full-throttle sweep procedure; (iii) flight controller mounting with foam vibration isolation pads and accelerometer/gyroscope calibration; (iv) power distribution wiring with continuity checks and current rating verification at all solder joints; (v) sensor module assembly, burn-in, and individual calibration in clean outdoor air; (vi) sensor module attachment to vibration-damped underframe mounts; (vii) complete weight measurement and center-of-gravity balancing by adjusting battery position; and (viii) system-level integration tests including sensor data display verification on LCD and RF link range ground testing before any flight operations.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

Experiments were conducted in an open outdoor area under low-wind conditions (wind speed < 2 m/s) to minimize environmental interference. All tests were performed during morning hours to reduce solar heating effects on sensor baselines. The drone was operated by an experienced pilot following predefined test protocols.

A. Sensor Calibration and Baseline Data

All MQ sensors underwent a mandatory 24-hour burn-in period followed by a 10-minute warm-up before each test session. Calibration was performed in clean ambient air at a known reference location, with Ro (sensor baseline resistance in clean air) determined for each unit individually. Table I summarizes the ground-level baseline measurements obtained after calibration, showing all readings comfortably within WHO and EPA safe concentration thresholds:

TABLE I. SENSOR BASELINE CALIBRATION DATA AT GROUND LEVEL

Sensor	Target Gas(es)	Baseline PPM	Safe Limit (PPM)	Status
MQ-135	CO_2, NH_3, NO_2	415	1000 (CO_2)	Safe
MQ-7	CO	1.2	9.0	Safe
MQ-4	CH_4 / CNG	0.8	1000	Safe
DHT11	Temperature	32°C / 65% RH	—	Normal

B. Altitude-Based Air Quality Profiling

The vertical stratification test was the primary experimental protocol. The drone performed a controlled vertical climb, hovering for 30 seconds at each altitude setpoint (0, 10, 20, and 30 m) to allow sensor readings to stabilize before recording. Three repeated trials were conducted at each altitude; mean values are reported. Table II presents the altitude-stratified pollutant concentration data:

TABLE II. ALTITUDE-STRATIFIED POLLUTANT CONCENTRATION PROFILE

Altitude (m)	CO_2 (PPM)	Smoke/PM (PPM)	Temp (°C)	Observation
0 (Ground)	450	12	32	Max ground-level concentration
10	435	8	31	Moderate reduction; boundary layer
20	420	5	30	Concentration stabilizing above BL
30	410	4	29	Near-plateau; wind dispersion dominant

Results clearly confirm a strong inverse relationship between altitude and pollutant concentration. The CO_2 concentration decreased by 8.9% (from 450 to 410 PPM) between ground level and 30 m, with the steepest gradient occurring in the 0–20 m range. Particulate readings showed a more dramatic reduction (67%), from 12 PPM to 4 PPM, consistent with the behavior of heavier particles that remain concentrated near the surface. Temperature decreased by approximately 1°C per 10 m of altitude, consistent with the standard atmospheric lapse rate. These findings confirm that the most critical air quality variations in urban environments occur within the ground boundary layer below 20 m—a zone uniquely accessible to low-altitude drones but invisible to satellite sensors and inaccessible to fixed monitoring stations that operate at a single elevation.

C. Real-Time Sensor Response Characterization

A controlled source-exposure test was conducted to evaluate sensor temporal response dynamics. While hovering at 5 m altitude, the drone was maneuvered toward a controlled exhaust source (a running engine at a fixed distance), held stationary for 20 seconds, then withdrawn. The MQ-135 response peaked at 782 PPM CO_2 during source exposure. A critical finding was a 3-second response lag between source introduction and sensor peak reading—a standard characteristic of chemi-resistor MOS sensors, attributable to the time required for the sensing element's heated oxide surface to adsorb target gas molecules and produce a measurable resistance change. Recovery to baseline after source removal required approximately 15–20 seconds. These temporal characteristics have important operational implications: flight speed during spatial mapping must be restricted to allow sufficient sensor stabilization time at each measurement point. Recommended hover durations of at least 5 seconds per location are advised to ensure full sensor response registration.

D. Propeller Downwash Effect on Sensor Accuracy

Propeller-induced turbulence (downwash) is a systematic error source inherent to all drone-based sensor systems. The downward airflow produced by rotating rotors can dilute the local air sample being drawn across the sensor surface, resulting in artificially low concentration readings compared to the true ambient value. To quantify this effect, identical sensor readings were recorded under two conditions at 10 m altitude over the same ground point:

The MQ-135 reading with drone motors OFF (static reference) was 440 PPM. With motors ON during active hover, the reading decreased to 415 PPM—a 5.6% downwash-induced variance (25 PPM absolute difference). This variance was reproducible across three repeated trials. The practical implication is that all hover-mode readings carry a systematic negative bias of approximately 5–6% relative to true ambient values. Mitigation strategies include: (i) mounting sensors on extended lateral arms positioned beyond the rotor disk radius; (ii) using aerodynamically shielded sensor housings with uni-directional intake openings oriented laterally; and (iii) applying a calibration correction factor of +5.6% to all hover-mode readings. Table III summarizes the downwash effect:

TABLE III. PROPELLER DOWNWASH EFFECT ON SENSOR READINGS

Condition	CO_2 Reading (PPM)	Variance	Implication
Static (Motors OFF)	440	—	True ambient reference
Hover @ 10 m (ON)	415	−5.6%	Downwash dilution effect
Corrected (Hover+5.6%)	438.4	−0.36%	Post-correction accuracy

E. Wireless Communication Range and Reliability

The performance of the 2.4 GHz NRF24L01+ RF sensor data link was evaluated by measuring received signal strength indicator (RSSI) and data packet loss percentage as a function of drone altitude (which approximates the line-of-sight communication distance). Table IV presents the results of this analysis:

TABLE IV. RF LINK SIGNAL STRENGTH AND PACKET LOSS VS. ALTITUDE

Altitude (m)	RSSI (dBm)	Packet Loss (%)	Link Status
0–10	−32 to −45	< 1	Excellent
20	−58	1.2	Good
30	−67	2.8	Good
50	−79	5.5	Marginal – threshold
60	−88	11.2	Degraded
70–80	−95 to −99	> 15	Unreliable

RSSI decreases linearly with altitude in dBm (following free-space path loss), while packet loss remains below 5% up to 50 m and then spikes sharply beyond that threshold. The 50 m altitude mark constitutes the effective reliable operational ceiling for the custom NRF24L01+ sensor link under the tested antenna configuration. Beyond 50 m, data integrity degrades to a degree that renders real-time monitoring unreliable. It is important to note that this 50 m ceiling applies exclusively to the custom sensor data link; the drone's primary RC control link (using a dedicated 2.4 GHz FHSS radio system with a more powerful amplifier) maintains reliable control at distances exceeding 300 m. Future system iterations should replace the NRF24L01+ with LoRa (Long Range) RF modules capable of sensor data transmission ranges exceeding 1 km at comparable data rates.

F. Power Consumption and Flight Endurance

The impact of the sensor payload on overall system power consumption and flight endurance was quantified through timed flight tests under hover conditions with and without the payload. Results are summarized in Table V:

TABLE V. FLIGHT ENDURANCE AND POWER CONSUMPTION COMPARISON

Parameter	Without Payload	With AQI Payload	Change
Total System Weight	~850 g	~1000 g	+17.6%
Hover Flight Time	15–18 min	12–14 min	−20%
Avg. Current Draw	~14 A	~16.5 A	+17.8%
Sensor Battery Life	—	4–5 hours	Outlasts flight
Sensor Warm-up Time	—	~3 min pre-flight	Pre-launch required

The AQI payload added approximately 150 g to the system mass, increasing required thrust and motor current draw by roughly 17–18%. This reduced hover flight time by approximately 20%, from a baseline of 15–18 minutes down to 12–14 minutes per battery charge. This endurance is sufficient to complete a full vertical profiling mission (4 altitude setpoints with 30-second dwell each) plus transit time within a single flight. Critically, the dedicated Li-ion sensor battery (1000 mAh) provides 4–5 hours of continuous sensor operation—far outlasting the drone's flight time. This means sensors can be pre-activated and warmed up before takeoff and will remain operational across multiple consecutive flight missions without requiring sensor battery replacement.

V. SYSTEM PERFORMANCE SUMMARY

Table VI provides a consolidated comparison of the proposed drone-based monitoring system against established air quality monitoring technologies across all key performance dimensions. This comparison contextualizes the contribution of the proposed system within the broader landscape of monitoring approaches and highlights the specific operational niches where drone-based monitoring offers unique advantages:

TABLE VI. COMPARATIVE EVALUATION OF AIR QUALITY MONITORING TECHNOLOGIES

System Type	Accuracy	Spatial Coverage	Vertical Profile	Cost	Emergency Response
Fixed Stations	Very High	Very Low	No	Very High	Slow / Fixed Location
Portable Devices	Medium	Medium	No	Low	Good (manual carry)
IoT Networks	Medium	High	No	Medium	Moderate
Vehicle-Based	Medium	Medium	No	Medium	Road-limited
Satellite	Low (local)	Very High	Limited	High	Slow / Low resolution
Drone (Proposed)	Med–High	High	Yes (0–50 m)	Low–Med	Rapid / Terrain-free

The proposed drone-based system is the only approach simultaneously offering vertical profiling capability, high spatial coverage, rapid emergency deployment, terrain-independent access, and moderate cost. While its point-measurement accuracy is lower than reference-grade fixed station instruments, the combination of 3D mobility, real-time wireless data, and low infrastructure cost positions it as a highly valuable complementary tool rather than a replacement for high-precision reference stations.

VI. DISCUSSION AND FUTURE SCOPE

The experimental results validate the core hypothesis of this work: a low-cost quadcopter platform integrated with MQ-series sensors and an independent wireless ground station can reliably capture altitude-stratified air quality data and transmit it in real time, with performance characteristics suitable for urban environmental monitoring, industrial compliance checks, and rapid-response pollution event assessment.

The 5.6% downwash-induced variance identified in this study is a previously underreported systematic error source in drone-based sensing literature. While some works acknowledge the phenomenon qualitatively, the quantitative characterization and proposed correction factor presented here represent a practical contribution for future system designers. The recommended sensor mounting strategy—extended lateral arms with directed intake housings—should be incorporated in next-generation prototypes.

The 50 m communication ceiling of the NRF24L01+ link is a clear limitation for applications requiring high-altitude monitoring, such as industrial chimney plume tracking or urban canyon profiling above 50 m. Replacement with LoRa SX1276 modules would extend reliable range to 1–2 km at the same 2.4 GHz band power levels, unlocking high-altitude mission profiles. Integration of a GPS module on the drone-mounted Arduino would enable automatic geo-referencing of each sensor reading, generating spatially indexed pollution maps rather than altitude-only profiles.

The 12–14 minute flight endurance is adequate for targeted spot-monitoring missions but insufficient for wide-area mapping campaigns. Two pathways exist to address this: (i) battery capacity upgrades (larger LiPo packs with appropriate thrust margin) and (ii) autonomous mission planning with multiple short-duration sorties with automated battery swap, enabled by integration with ArduPilot or PX4 autopilot firmware supporting pre-programmed waypoint flight patterns.

Future enhancements planned for this system include: LoRa long-range sensor data communication; GPS-tagged georeferenced 3D pollution mapping; cloud-based dashboard with real-time AQI visualization and alert thresholds; machine learning–based sensor drift compensation; solar-assisted power augmentation for extended endurance; and multi-drone swarm deployment for simultaneous large-area spatial mapping. The system architecture's modular design—with independently powered, independently communicating sensor and flight subsystems—provides a robust foundation for these future enhancements without requiring fundamental redesign.

VII. CONCLUSION

This paper presented the complete design, hardware integration, and experimental validation of a quadcopter-based Air Quality Index monitoring system. The platform integrates MQ-135, MQ-7, and MQ-4 gas sensors with a DHT11 temperature-humidity module on an Arduino Nano, transmitting data via a 2.4 GHz RF link to an independently powered ground station for real-time LCD display, fully decoupled from the drone's primary flight electronics.

Five key experimental findings were established: (i) A significant and reproducible inverse relationship exists between altitude and pollutant concentration, with the most volatile gradients occurring within the 0–20 m ground boundary layer—confirming the value of altitude-flexible drone-based sensing over single-elevation fixed stations. (ii) Propeller downwash induces a systematic 5.6% negative bias in hover-mode sensor readings, which can be corrected through a calibration factor or mitigated through extended-arm sensor mounting. (iii) MQ-series chemi-resistor sensors exhibit a 3-second response lag, necessitating slow hover-based flight patterns for accurate spatial pollution mapping. (iv) The NRF24L01+ 2.4 GHz sensor link maintains reliable transmission (< 5% packet loss) up to 50 m altitude, defining the current operational ceiling of the system. (v) The AQI payload reduces drone flight endurance by approximately 20% (to 12–14 minutes) while the dedicated sensor battery provides 4–5 hours of continuous operation across multiple flight missions.

Collectively, these results demonstrate that drone-based air quality monitoring constitutes a cost-effective, mobile, scalable, and practically deployable complement to conventional fixed monitoring infrastructure. The system is particularly well-suited for vertical pollutant profiling, pollution hotspot identification, industrial compliance monitoring, emergency response air quality assessment, and environmental monitoring in terrain-challenged or hazardous areas. The findings provide a quantitative performance baseline and actionable design guidelines for future UAV-based environmental sensing systems targeting smart-city and Industry 4.0 applications.

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