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MDPI

Review

Drone-Assisted Particulate Matter Measurement in Air Monitoring: A Patent Review

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Abstract: Air pollution is caused by the presence of polluting elements. Ozone (O_3), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and particulate matter (PM) are the most controlled gasses because they can be released into the atmosphere naturally or as a result of human activity, which affects air quality and causes disease and premature death in exposed people. Depending on the substance being measured, ambient air monitors have different types of air quality sensors. In recent years, there has been a growing interest in designing drones as mobile sensors for monitoring air pollution. Therefore, the objective of this paper is to provide a comprehensive patent review to gain insight into the proprietary technologies currently used in drones used to monitor outdoor air pollution. Patent searches were conducted using three different patent search engines: Google Patents, WIPO's Patentscope, and the United States Patent and Trademark Office (USPTO). The analysis of each patent consists of extracting data that supply information regarding the type of drone, sensor, or equipment for measuring PM, the lack or presence of a cyclone separator, and the ability to process the turbulence generated by the drone's propellers. A total of 1473 patent documents were retrieved using the search engine. However, only 13 met the inclusion criteria, including patent documents reporting drone designs for outdoor air pollution monitoring. Therefore, was found that most patents fall under class G01N (measurement; testing) according to the International Patents Classification, where the most common sensors and devices are infrared or visible light cameras, cleaning devices, and GPS tracking devices. The most common tasks performed by drones are air pollution monitoring, assessment, and control. These categories cover different aspects of the air pollution management cycle and are essential to effectively address this environmental problem.

Keywords: air quality monitoring; environmental drones; particulate matter sensor; ambient air monitor; air pollution assessment; UAV for environmental monitoring; aircraft-based air monitoring

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Citation: Altamira-Colado, E.; Cuevas-González, D.; Reyna, M.A.; García-Vázquez, J.P.; Avitia, R.L.; Osornio-Vargas, A.R. Drone-Assisted Particulate Matter Measurement in Air Monitoring: A Patent Review. *Atmosphere* **2024**, *15*, 515. https://doi.org/10.3390/atmos15050515

Academic Editors: Adrianos Retalis, Vasiliki Assimakopoulos and Kyriaki-Maria Fameli

Received: 3 March 2024
Revised: 14 April 2024
Accepted: 16 April 2024
Published: 23 April 2024

1. Introduction

Air pollution is a current global concern that affects the health of exposed living things [1–3]. According to the World Health Organization (WHO) and the Pan American Health Organization (PAHO), from 2016 to 2021, more than 12 million deaths were linked to environmental conditions every year [4,5].

The presence of polluting substances causes air pollution. The most common ones being monitored are ozone (O_3), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and particulate matter (PM), which can be emitted into the environment naturally and/or by anthropogenic activities, thus affecting air quality and causing diseases and premature deaths in exposed people [6–13].

PM is one of the most harmful pollutants when inducing physiological damage, oxidating tissues it lands on [14]. For this reason, this work reviews patented drone-assisted air monitoring technology that at least measures PM.

PM consists of solid and/or liquid particles suspended in the air, the sizes of which vary depending on the emission source. PM is usually classified according to particle size: $PM_{2.5}$ is defined as particulate matter with an aerodynamic diameter of equal to or less than 2.5 µm, and PM10 is defined as particulate matter with an aerodynamic diameter of equal to or less than 10 µm [13,15].

Cyclone separators are used to separate large particles from an air sample when aiming to measure particles of a specific size (e.g., $PM_{2.5}$, PM_{10}). These devices are fed by dirty air, creating a vortex that allows small particles to travel up, while large particles remain in the cyclone since they have more inertia than small particles, not allowing the vortex to influence them [16]. A cyclone separator must be placed at the sensor's air inlet to allow a more precise measurement.

Different types of air quality sensors exist for use in ambient air monitors according to the substance(s) to be measured, where electrochemical (for measurement of chemical substances concentration such as CO and O_3) and light-scattering sensors (for measurement of particulate matter concentration using laser or infrared light) act as examples [17,18].

To be able to manage air quality, ambient air is monitored [19]. The concentration of air pollutants such as $PM_{2.5}$ and/or PM_{10} is sensed by sensors that are either static (such as sensors placed on ground-fixed monitoring stations) or mobile (such as those placed on terrestrial or aerial vehicles, among others) [20,21].

Some limitations that static air quality sensors include are the need for additional sensors to monitor air quality in large areas, limited spatial resolution, and a wrong spatial distribution which may affect information accuracy [22,23].

Mobile air quality sensors allow measuring air quality in large areas using a single device [23]. They can be placed, among other carriers, in terrestrial vehicles, wearable devices (e.g., a personal air monitor), and drones [22,24–27]. These last devices allow for measuring air quality at different distances from the ground (around 100 m for rotary-wing drones, and 3 km for fixed-wing drones) [1,28]. Using drones to monitor air quality would aid in preventing implied risks when an operator makes measurements during a natural disaster such as volcanic eruption or fires, as well as during chemical disasters, where air quality monitoring is important. It would also prevent accidents that may occur when maintenance is to be carried out in a sensor located at a very high height. However, using drones as carriers of air quality sensors presents a limitation. The movement of the drone's propellers produces atmospheric turbulence that can affect the sampled concentration parameter, making the measurements inaccurate, since the drone's propellers induce conditions different from those considered "normal conditions" where the concentration of the pollutant is to be measured [29].

1.1. Drones

Drones can fly autonomously or wirelessly controlled by, for example, a remote controller, a smartphone, or a computer from a ground station.

Several types of drones exist, such as fixed-wing and rotary-wing drones. Fixed-wing drones can travel longer distances and fly at higher altitudes than rotary-wing drones, but they need a large, clear space to take off and land. They can only move forward, remain in motion, and need a large space to make turns. Rotary-wing drones allow x-y-z movement, offer better maneuverability, and can take off and land in a small space, but they present many limitations such as a short flying time, short flying distance, and are vulnerable to high winds [30].

Rotary-Wing Drones

A rotary-wing drone has multiple propellers moved by rotors that generate the required airflow for the drone to fly [31–35]. These propellers are placed around the body of the vehicle in a mast. They are in constant motion [34], making air constantly flow in a direction from the top face to the bottom face of the propellers, which defines the turbulent airflow region.

Rotary-wing drones are named according to the number of rotors they use to move. Their payload capacity varies according to the number of rotors they have.

Among rotary-wing drones, quadcopters (four rotors) and hexacopters (six rotors) are the best-known types of drones [34].

To maintain equilibrium and prevent the drone from spinning in the opposite direction from the rotors during flight, a quadcopter places four rotors equally distributed around the body of the drone, where two rotors spin clockwise, and two rotors spin counterclockwise, as shown in Figure 1 [36].

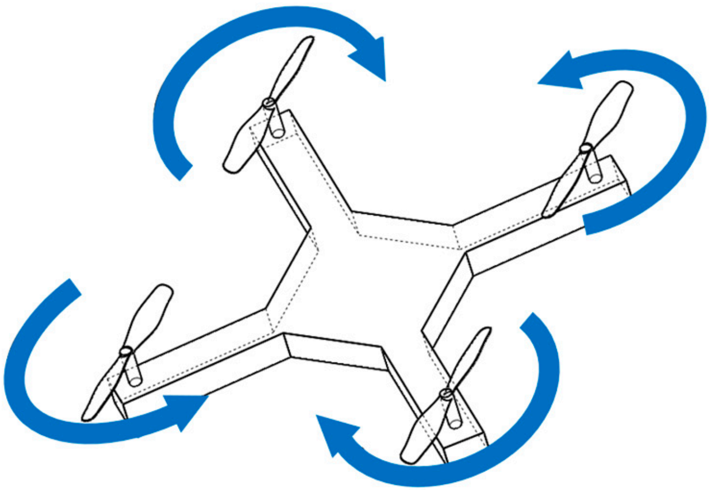

Figure 1. Movement of propellers in a quadcopter.

Drones have been used to monitor particulate matter in ambient air, and drone-based particulate matter monitoring systems are currently commercially available. Table 1 shows examples of current commercially available drone-based particulate matter monitoring systems.

Table 1. Examples of commercially available drone-based particulate matter monitoring systems [37–42].

Model/Name	Manufacturer	Detected Substances/Pollutants
DJI M30 drone gas detection air quality pollution monitoring sensor [37]	Drone-Payload, Shenzhen, China	$PM_{2.5}$, PM_{10}, SO_2, CO, NO_2, O_2, O_3, VOCs, CH_4, CO_2, HF, H_2S, NH_3, HCl, H_2, Cl_2, PH_3, NO, HCN
Drone Air Quality Pollution Monitoring System for DJI Matrice 300 [38]	UAVFORDRONE, Shenzhen, China	$PM_{2.5}$, PM_{10}, SO_2, CO, NO_2, O_2, O_3, VOCs, CH_4, CO_2, H_2S, NH_3, HCl, H_2, Cl_2, PH_3, TSP
Prana Air-Air Quality Monitoring Drone [39]	Prana Air, Delhi, India	PM, SO_2, NO_2, CO_2, NH_3, O_3
DR2000 Drone-Based Environmental Monitoring and Air Quality Analyzer [40]	Scentroid, Whitchurch-Stouffville, Canada	PM_1, $PM_{2.5}$, PM_4, PM_{10}, VOCs, CO_2, CH_4 Total Reduced Sulfurs (TRS)
Sniffer4D—Mobile Air Pollutant Mapping System [41]	TPI, Warszawa, Poland	$PM_{2.5}$, PM_{10}, SO_2, H_2S, TSP, O_3, NO_2, NH3, H_2, CO, HCl, VOCs
AirDron [42]	SoftBlue SA, Warszawa, Poland	PM_1, $PM_{2.5}$, PM_{10}, CH_2O, HCl, HCN, NH_3, H_2S, VOCs

Although analyzing scientific literature regarding drone-assisted air pollution monitoring is not the scope of this work, some examples of scientific journal publications on this field are presented in Table 2.

Table 2. Examples of drone-assisted air pollution monitoring scientific journal publications [43–52].

Title	Detected Substances/Pollutants	Year of Publication
Development of Autonomous Hexacopter UAVs for Smart City Air Quality Management [43]	$PM_{2.5}$	2023
Air quality monitoring and forecasting using smart drones and recurrent neural network for sustainable development in Chennai city [44]	Liquid petroleum gas, propane, CH_4, H_2, $PM_{2.5}$, PM_{10}, VOC, CO, CO_2, NO_2, SO_2	2022
MesSBAR—Multicopter and Instrumentation for Air Quality Research [45]	PM_1, $PM_{2.5}$, PM_4, PM_{10}, CO, NO, NO_2, O_3	2022
Air quality assessment system based on self-driven drone and LoRaWAN network [46]	CO, NO, NO_2, SO_2, PM_1, $PM_{2.5}$, PM_{10}, H_2, CH_4, CO_2	2021
Autonomous monitoring, analysis, and countering of air pollution using environmental drones [1]	CO_2, CO, NH_3, SO_2, PM, O_3, NO_2	2020
Developing a Modular Unmanned Aerial Vehicle (UAV) Platform for Air Pollution Profiling [47]	PM_1, $PM_{2.5}$, PM_{10}, NO_2	2018
Characterization of a Quadrotor Unmanned Aircraft System for Aerosol-Particle-Concentration Measurements [48]	PM, CO_2	2016
A study of vertical distribution patterns of $PM_{2.5}$ concentrations based on ambient monitoring with unmanned aerial vehicles: A case in Hangzhou, China [49]	$PM_{2.5}$	2015
Towards the Development of a Low Cost Airborne Sensing System to Monitor Dust Particles after Blasting at Open-Pit Mine Sites [50]	PM_{10}	2015

Review articles concerning drone-assisted air quality monitoring such as [25,51] have been published. However, available reviews focus on scientific literature and may lack technical solutions found in the patent literature.

Several patents of mobile apparatuses that measure particulate matter concentration outdoors (e.g., drones) have been published. However, these patents might include some imprecisions when not considering air turbulence produced by the movement of the drone's propellers.

This work reviews available patents to present the overall state, strengths, and areas for improvement of patented drone-assisted environmental monitoring systems and devices, focusing on aspects such as the type of drone, measurement technology of the PM sensors, and measured substance, among others.

2. Methodology

The methodology of this work comprised the following five stages (see Figure 2).

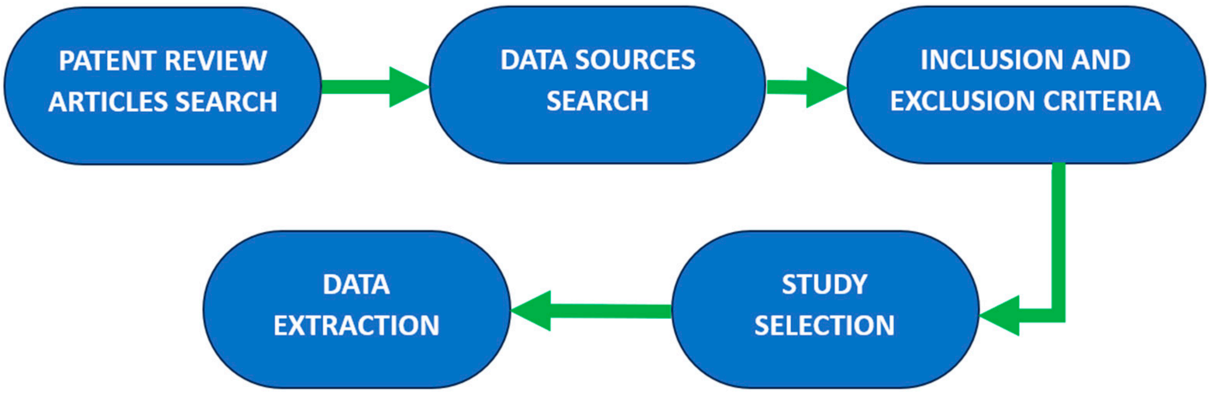

Figure 2. Methodology stages.

2.1. Patent Review Articles Search Methodology

The literature was first explored in SCOPUS and IEEEXPLORE for the existence of recent patent review articles in drone-assisted air quality monitoring.

The query strings used to search in the SCOPUS database were ALL (“Review article” AND “Drone” AND “Environmental Monitor” OR “Patent” AND “Drone” AND “Environmental Monitor” OR “Review article” AND “Drone” AND (“PM2.5” OR “PM10”) OR “Patent” AND (“PM2.5” OR “PM10”)), ALL (“Review article” AND “UAV” AND “Environmental Monitor” OR “Patent” AND “UAV” AND “Environmental Monitor” OR “Review article” AND “UAV” AND (“PM2.5” OR “PM10”) OR “Patent” AND (“PM2.5” OR “PM10”)), and ALL(“Review article” AND “Aircraft” AND “Environmental Monitor” OR “Patent” AND “Aircraft” AND “Environmental Monitor” OR “Review article” AND “Aircraft” AND (“PM2.5” OR “PM10”) OR “Patent” AND (“PM2.5” OR “PM10”)). The searches output zero results.

The search in the IEEEXPLORE database was carried out using the query (“All Metadata”:“Review Article” OR “All Metadata”:”Patent Review” OR “All Metadata”:”Patent”) AND (“All Metadata”:”Environmental Monitor” OR “All Metadata”:”Drone” OR “All Metadata”:”UAV” OR “All Metadata”:”Aircraft”) AND (“All Metadata”:”PM2.5” OR “All Metadata”:”PM10”), outputting zero results.

Since no patent review articles were found regarding the usage of drones to monitor air quality, this paper would supply useful information when aiming to enhance drone-assisted particulate matter monitoring in the air.

2.2. Data Sources and Search Strategy

A search was conducted to find patents on atmospheric pollution monitoring using drones. For this, six different input query strings were defined.

Three different patent search engines were used to search for patents: Google Patents, WIPO’s Patentscope, and the United States Patent and Trademark Office (USPTO). These search engines were selected since both Google Patents and WIPO’s Patentscope include patents from patent offices worldwide, while the USPTO patent search tool presents an advantage because it includes an advanced search interface that allows grouping results by family and shows results in a table with specified information selected by the user that permits transferring data with ease to a spreadsheet.

To conduct the searches, two blocks of mesh terms were defined: (1) synonyms for unmanned aerial vehicle: “drone”, “UAV”, “aircraft”; (2) measured substance: “PM 2.5”, “PM 10”. Subsequently, six input query strings were defined by grouping the mesh terms using the Boolean operator “AND”. The input query strings were (1) “Drone” AND “PM 10”, (2) “Drone” AND “PM 2.5”, (3) “UAV” AND “PM 10”, (4) “UAV” AND “PM 2.5”, (5) “Aircraft” AND “PM 10”, (6) “Aircraft” AND “PM 2.5”.

All search strings were adapted for each search engine.

2.3. Inclusion and Exclusion Criteria

To select the studies, the following inclusion and exclusion criteria were defined, which are shown in Table 3.

Table 3. Inclusion and exclusion criteria.

Inclusion	Exclusion
Must include particulate matter sensors (PM_{10}, $PM_{2.5}$)	Static environmental sensor
Sensor is placed in a drone	Indoor air monitoring
All patents regardless of the language were screened	

2.4. Study Selection

The study selection process was carried out by the first and second authors (E.A.-C. and D.C.-G.) using a similar methodology to the Preferred Reporting for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) [52].

The flowchart of the carried-out stages in this section is shown in Figure 3. During the first stage, the identification of patents was carried out, and the search results from the search engines were consolidated after removing duplicated documents.

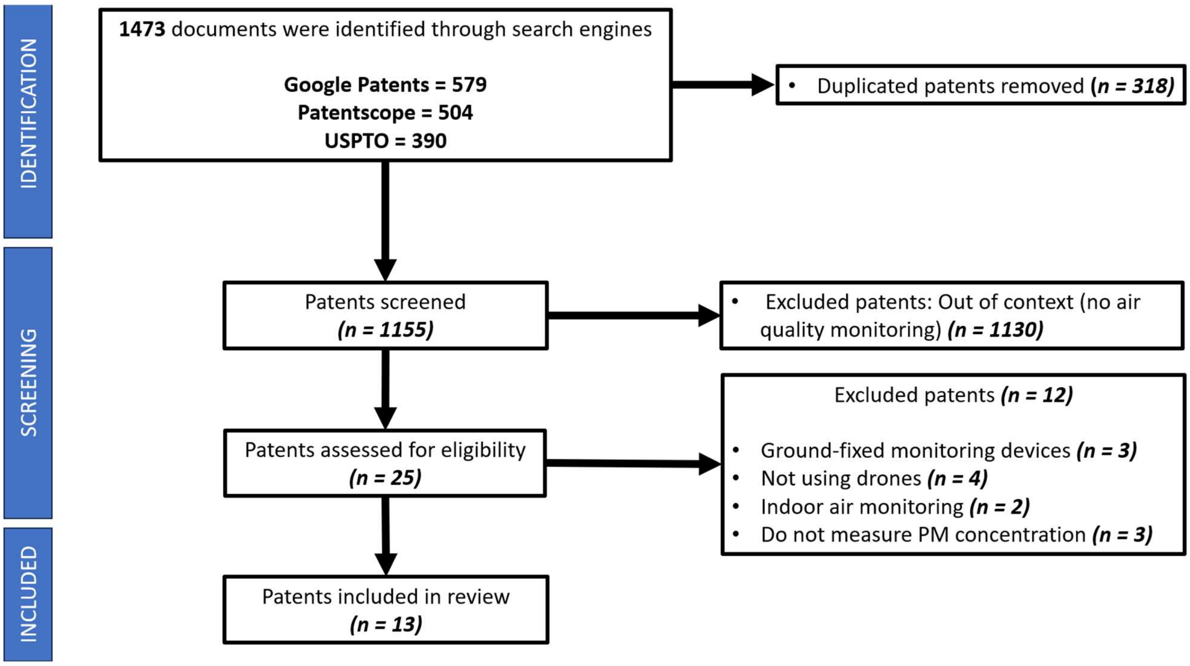

Figure 3. Patents search strategy flowchart.

During the second stage, the screening of the consolidated results from the previous stage was carried out by reading the title and abstract of every patent, where all patents that did not meet the inclusion and exclusion criteria were removed, and the remaining patents were assessed for eligibility. Patents in a different language from English and Spanish were translated using machine translation.

The patents assessed for eligibility were full-text reviewed to remove those not meeting the inclusion and exclusion criteria.

During the third stage, the remaining patents from the previous stage were selected to be included in the review.

2.5. Data Extraction

The specific data extracted from the reviewed patents were the patent number, title of the invention, status (active or pending), grant date, inventor, assignee, type of drone, measurement technology of the PM sensor(s), measured substance(s), whether it includes a mechanism to cope with the turbulence produced by the drone's propellers, and whether it included a cyclone separator. The data to be extracted were selected to identify the current technological state of patents in the realm of drone-assisted air pollution monitoring to provide researchers and developers with a starting point to create and enhance technology in this field.

3. Results

Drone-assisted air quality monitoring is a current growing trend due to recent air pollution concerns. Figure 4 shows the temporal distribution (last 10 years) from the Web of Science database when searching for the terms "drone air quality" in all fields, showing

1 result from 2014, 0 results from 2015, 4 results from 2016, 3 results from 2017, 8 results from 2018 (which shows the highest increase from previous year of 166%), 16 results from 2019, 21 results from 2020, 42 results from 2021, 52 results from 2022, and 51 results from 2023.

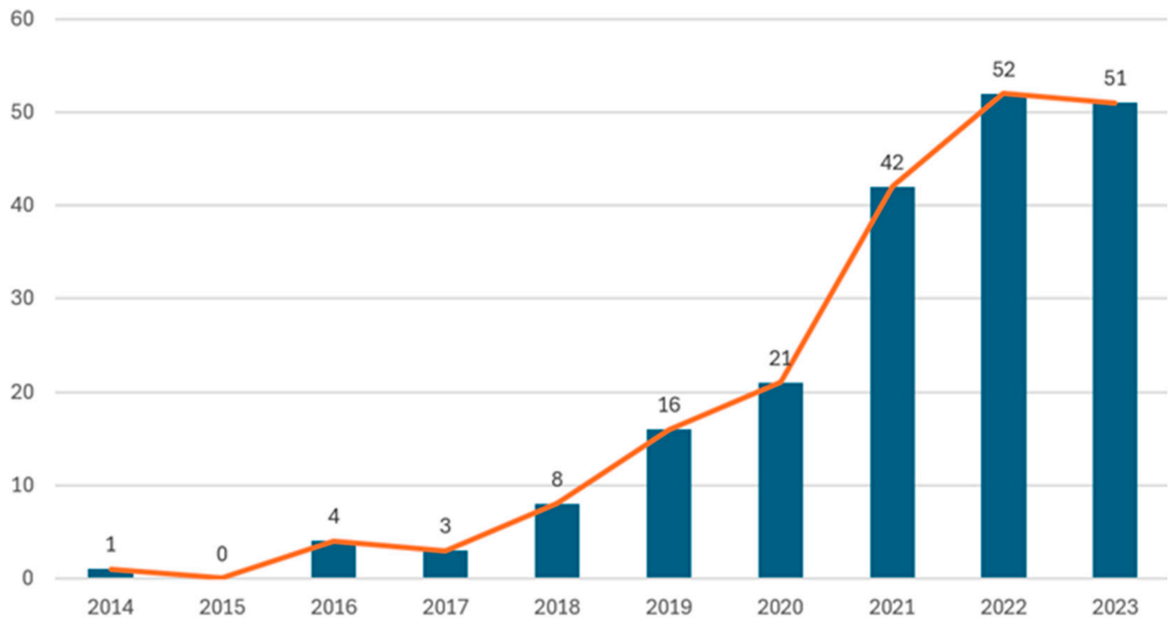

Figure 4. Temporal distribution of scientific publications concerning drone-assisted air quality monitoring from 2014 to 2023 found in the Web of Science database.

Since 2017, the number of articles has increased year by year until 2022. In 2023, the number of published articles did not increase; instead, the number of articles decreased by one with respect to 2022. The highest increase in a single year occurred in 2018 (166%), followed by the increase presented in 2021 (100%).

As shown in Figure 3, the patent search yielded 1473 documents. In Table 4, the number of documents from each search engine is presented. It is identified in Table 4 that Google patents provided 579 documents, followed by WIPO's PatentScope with 504, and finally USPTO with 390, of which 318 were duplicates. In the screening phase, 1155 patent documents were analyzed to determine whether drones for air pollution monitoring had been developed. Only 13 patents met this inclusion criterion presented in Table 3, which was to present the design of a drone for monitoring outdoor air pollution.

Table 4. Patent search strategy results.

Source	**Input Query String**					
	"Drone" AND "PM 10"	**"Drone" AND "PM 2.5"**	**"UAV" AND "PM 10"**	**"UAV" AND "PM 2.5"**	**"Aircraft" AND "PM 10"**	**"Aircraft" AND "PM 2.5"**
Google Patents	70	11	29	5	440	24
Patentscope by WIPO	72	41	11	7	290	83
USPTO	87	22	26	5	110	140

3.1. Patents Analysis

Figure 5 shows the country of origin of the identified patents. Data show that China is in the leading position in the research and development of air pollution monitoring drones with a patent ratio of 53.84%. The remaining patents found in this work correspond one to each of the following countries: Unites States, South Korea, Poland, India, Japan, and Germany.

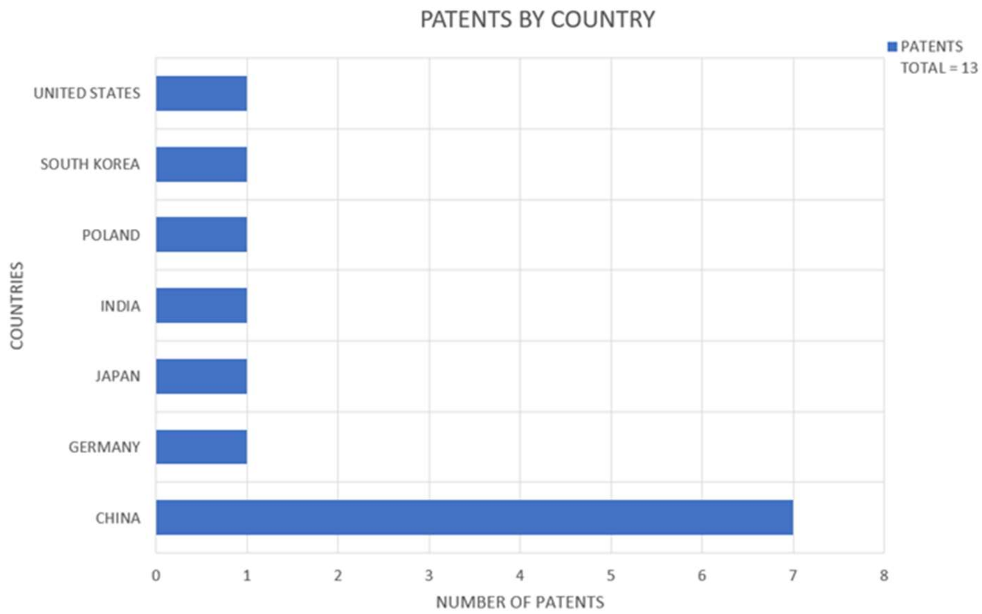

Figure 5. Number of patents per country.

In terms of patents, it was found that 69.23% (9/13) are currently active and the rest are under review. According to the World Intellectual Property Organization (WIPO), each patent reviewed is classified according to its corresponding technical field. Figure 6 shows this classification and shows that two main classes were identified: G (Physics) and B (Performing operations; Transporting). Regarding class G, 53.84% (7/13) of patents belong to the G01 measurement and testing subclass. The subclass G01 typically encompasses patents related to measuring and testing technologies, including devices and methods for quantifying various parameters, such as physical dimensions, electrical characteristics, chemical composition, and environmental factors. These patents often involve innovations in instrumentation, sensor technologies, data analysis techniques, and quality control methodologies. Regarding class B, two belong to subclass B64C39/02. This subclass groups aircraft that are used for several general purposes with general payloads; therefore, several patents that use drones to carry air quality and/or meteorological parameter sensors fall in this subclass.

It was identified in the reviewed patents that $PM_{2.5}$ and PM_{10} are the most commonly measured pollutants since they pose significant health risks to humans when inhaled. These fine particles can penetrate deep into the respiratory system, reaching the lungs and even entering the bloodstream. Long-term exposure to $PM_{2.5}$ and PM_{10} has been linked to various respiratory and cardiovascular diseases, including asthma, bronchitis, heart attacks, and strokes [53]. Additionally, $PM_{2.5}$ and PM_{10} can carry harmful substances such as heavy metals, organic compounds, and other pollutants, exacerbating their health effects [54]. Therefore, monitoring and controlling levels of $PM_{2.5}$ and PM_{10} in the air are crucial for protecting public health and mitigating the impacts of air pollution [55,56]. This confirms the need to specifically address the presence of these pollutants in future technological innovations.

Other atmospheric pollutants different from PM such as O_3, CO, and SO_2 were identified in several patents as well.

None of the reviewed patents include a mechanism or method to cope with air turbulence generated by the drone's propellers, but one patent (CN112305163A) states that wind affects measurement's accuracy and includes the wind parameter with every atmospheric pollutant concentration measurement.

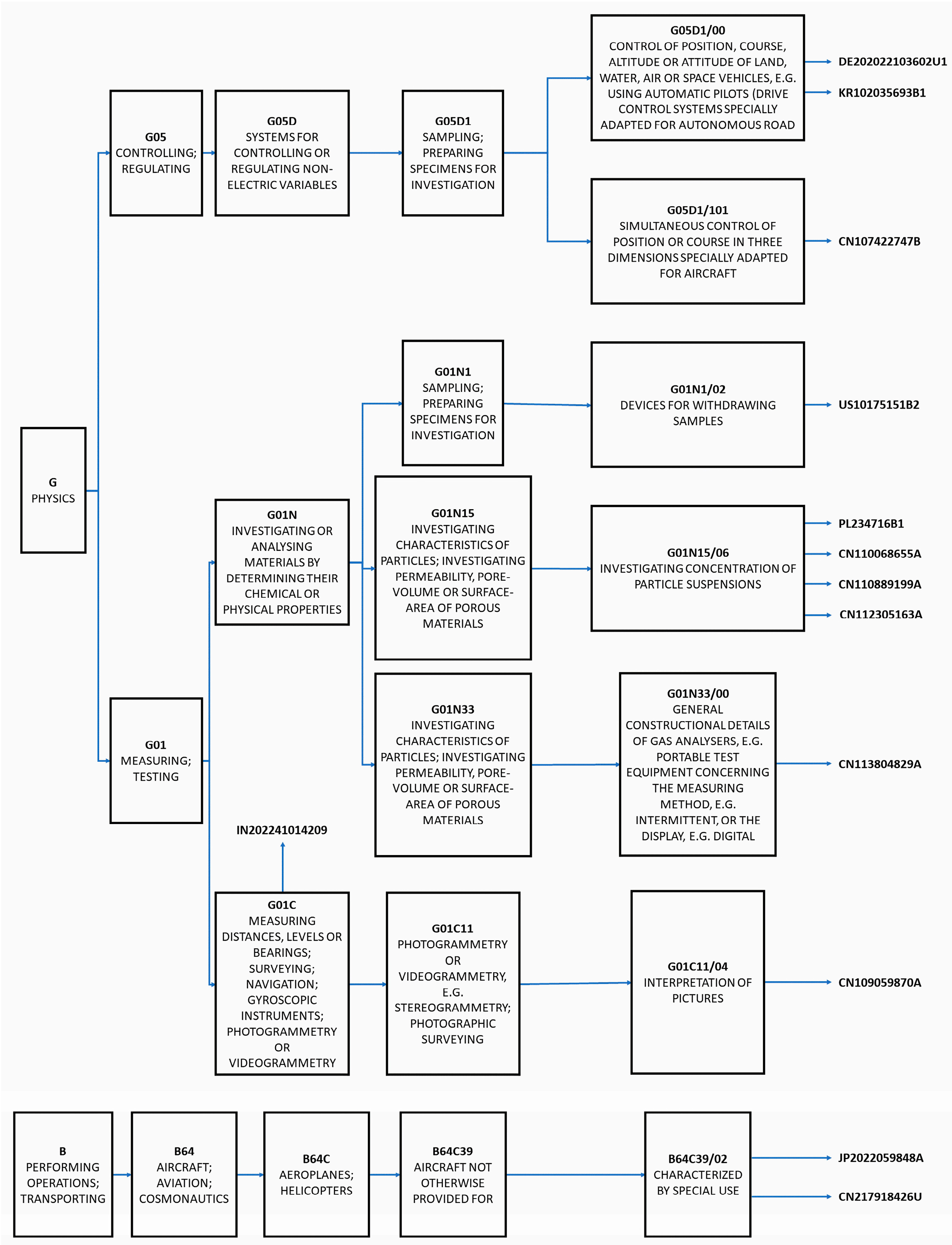

Figure 6. Patents classification diagram showing sections, classes, subclasses, groups, and subgroups.

Only 53.84% (7/13) of patents mention the type of drone used, from which 71.42% (5/7) were found to be rotary-wing drones.

The technology used by the PM sensors is only specified in two patents, where one patent mentions the use of a light-scattering laser sensor, and the other patent mentions the use of a light-scattering infrared sensor.

Finally, none of the reviewed patents mention the inclusion of a cyclone separator to assure pm measurement accuracy.

Additional technological aspects not included in Section 2.5 were identified such as spatial distribution analysis, camera integration, Global Positioning System (GPS) tracking unit inclusion, among others; these are further discussed in Section 4.

3.2. Patents Summary

In this section, a summary of the identified patents and their categorization considering their main objective is presented. The categories identified in this study include air pollution monitoring, assessment, and control. These categories cover different aspects of the air pollution management cycle and are essential to effectively address this environmental problem.

3.2.1. Air Pollution Monitoring

Air pollution measurement involves the systematic assessment of air quality to quantify the presence and concentration of pollutants in the atmosphere. This activity involves the use of various instruments and techniques to monitor pollutants such as particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and volatile organic compounds (VOCs). Sensor-equipped monitoring stations are strategically placed at various locations to collect data on pollution levels. These stations continuously measure air quality parameters and send the data to a central database or monitoring network. The collected data are then analyzed to assess air quality trends, identify sources of pollution, evaluate the effectiveness of pollution control measures, and inform decision-making processes designed to protect public health and the environment from the adverse effects of air pollution. This category includes patents whose main objective is only to monitor air quality, not assess air quality.

Patents in this category are:

- Patent IN202241014209, India, 2022. This invention uses a drone to detect the concentration of CO, CO_2, NO_2, SO_2, PM, and Volatile Organic Compounds (VOC) in the air at a specific altitude and geographical coordinates in a specific period using an infrared light-scattering sensor. Information is stored in a cloud server, which is periodically updated and transmits information to a device with a Graphical User Interface (GUI) to display it to users [57].
- Patent US10175151B2, USA, 2019. This invention consists of a rotary-wing drone, whose number of rotors vary according to the lifting needs, including an air monitoring system, a GPS module, and a wireless transmitter such as IEEE 802.11. An air quality sensor detects the concentration of pollutants. If the concentration of impurities in air is higher than a defined threshold, an air sample is taken using a gas sampling bag or a vacuum canister. Air quality information is wirelessly transmitted to a ground station [58].
- Patent CN217918426U, China, 2022. This invention provides a drone equipped with $PM_{2.5}$ and PM_{10} sensors which are not specified, since it can be any commercial sensor to be selected according to the needs of the user. The aim of this invention is to solve the presented problem when the sight of the camera included in a drone is obstructed by water drops. The drone includes a high-definition camera covered by a glass chamber, to prevent water drops from vapor liquefaction from being produced on the camera lens surface. When a water drop is produced on the glass cover and obstructs the camera lens, a rod is spun by a motor to remove the water drop without damaging the high-definition camera's lens. The improvement of this invention is not focused

on air quality monitoring, although the device's purpose is to monitor outdoor air quality [59].

- Patent CN109059870A, China, 2020. This consists of a system to detect, through an infrared camera and a geographic location module, the source of air pollutant discharge, identifying the illegal operation of coal-burning boilers. If the temperature threshold detected by the infrared camera is reached, the concentration of PM_{10} and $PM_{2.5}$ is measured. Data are stored by transmission to a ground station through a non-specified protocol [60].
- Patent PL234716B1, Poland, 2020. This presents a remotely controlled quadcopter with a differential measurement air monitor device. This invention aims at solving the problem presented when a chimney contains more than one smoke opening. The device comprises two air inlets, each with a sensor for measuring concentration of PM_{10}, $PM_{2.5}$, CO_2, O_3, SO_2, and HCl in the intake air. A differential measurement circuit receives the signal of every sensor. A display that contains the pollutant concentration measured by every sensor and the difference measured by the differential measurement circuit is combined with measurement systems. The air inlets are mounted in the bottom face of the drone and are able to rotate around a vertical axis from 0 to 90 degrees in opposite directions to each other. A camera is located between the inlets, allowing the operator to know the position of the inlets [61].

3.2.2. Air Pollution Control

Air pollution control refers to a set of strategies, policies, and technologies implemented to reduce and reduce the emission of pollutants into the atmosphere, thereby improving air quality and protecting public health and the environment. This multifaceted action includes regulatory measures such as emission standards and regulations aimed at limiting pollutant emissions from industrial enterprises, vehicles, and other sources.

The only patent that corresponds to this category is:

- Patent DE202022103602U1, Germany, 2022. This invention uses a set of quadcopters that are capable of identifying a region with a higher $PM_{2.5}$ concentration with respect to other regions. After every drone detects the $PM_{2.5}$ concentration where they are located, quadcopters group at the region where the drone that detected the highest $PM_{2.5}$ concentration is located to purify air in the polluted identified region [62].

3.2.3. Assessing the Air Quality and Pollutant Ratio

The assessment involves analyzing and interpreting these data to understand the extent and sources of pollution and to assess compliance with air quality standards.

Patents in this category are:

- Patent KR102035693B1, South Korea, 2019. This presents an invention that generates three-dimensional spatial information using a drone integrated with an infrared camera, a laser scanner, a GPS device, and a pollutant concentration sensor group that transmits the measured concentration of PM_{10}, O_3, SO_2, CO, NO_2, and Pb through a communication device into a data-receiving unit using serial transmission. The received data generate numerical values for the air pollution index and its distribution in a three-dimensional map using geographical location information. The data are stored in a database [63].
- Patent JP2022059848A, Japan, 2022. This uses a set of bicopters that consist of slave drones that communicate with a master drone to measure air quality by detecting the concentration of $PM_{2.5}$ with a high time resolution in a three-dimensional region. Information is sent to a base station that can be either fixed to the ground or mounted in a vehicle. The drones also include meteorological parameter sensors such as wind sensors and humidity sensors to be able to predict the source of the detected $PM_{2.5}$ by knowing its trajectory. Slave drones communicate with the master drone by Wi-Fi, and the master drone communicates with the base station by mobile data to allow a larger communication range [64].

- Patent CN110068655A, China, 2022. This invention aims to solve the presented problem when it is required to measure air quality at high altitudes in the atmosphere and acquire ground images to create a map. Taking a picture at a very long distance from the ground affects image resolution while taking a picture close to the ground does not allow for measuring air quality at high altitudes in the atmosphere. This invention creates a high-resolution geospatial map that includes the concentration parameter of PM_{10}, $PM_{2.5}$, CO, NO, SO_2, NO_2, and O_3. A drone that is capable of reaching very high heights is equipped with a GPS module, a data acquisition module, a data memory module, and a data pre-processing unit. The device measures air quality high in the air and moves close to the ground in a desired region to take a high-resolution picture of the ground after. A geospatial map is created using dedicated software after taking several pictures of the ground in a desired region. A stereograph is produced when superposing stereoscopic images are taken by the plane's camera, creating a three-dimensional map [65].
- Patent CN112305163A, China, 2023. This invention combines wind parameter information with an air monitoring system to identify acquired data inaccuracy. The invention uses a fixed-wing drone to measure the concentrations of $PM_{2.5}$, PM_{10}, O_3, NO_x, CO, and SO_2 in the atmospheric environment. At the same time, it stores location data using a GPS module and wind parameter data such as wind speed and wind direction using a wind parameter module. The data of an air sample are collected in the first step within 1 s of time resolution. In the second step, the data packets are sent to the control and operation module through a 4G signal. In the third step, the sent data in the second step are obtained by the control and operation module. In the fourth step, the data packets are processed using MATLAB software (version number not specified) to create matrices containing the concentration of every measured pollutant, wind speed, wind direction and location coordinates. In the fifth step, the data are post-processed to determine regions of high pollutant concentration for each individual pollutant and the coordinates of the centroid of every high pollutant concentration region are afterwards corrected using the height parameter [66].
- Patent CN107422747B, China, 2023. This comprises an environment monitoring and sampling device that consists of an information processing unit, a flight control unit, a positioning unit, a data transmission unit (based on signal modulation principles of GSM and Wi-Fi, and the like), an obstacle detection unit, an image acquisition unit, a sampling unit (a jar with a choke valve and a solenoid valve, wherein the solenoid valve controls the opening and closing of the jar, and the choke valve controls the flow speed of the atmospheric sample into the tank), and an atmospheric environment sensor group ($PM_{2.5}$, PM_{10}, O_3, and black carbon concentration, concentration, humidity, and temperature sensors). The invention aims to improve previous inventions in the field of environmental monitoring using drones by including an obstacle detection unit. The obstacle detection module comprises six ultrasonic ranging sensors and depth image cameras located at the front, back, left, right, upper, and lower parts of the drone, automatically monitoring obstacles near the drone in real time. The air pollutant concentration measurements are used to create a three-dimensional map to trace the source of the detected pollutants [67].
- Patent CN113804829A, China, 2020. This invention consists of a real-time monitoring system of atmospheric pollution at different heights that measures the concentration of PM_{10}, $PM_{2.5}$, PM_1, O_3, NO_2, and SO_2. $PM_{2.5}$ concentration is measured using a laser light-scattering sensor which is specified to be a TSI SidePakAM520 type sensor and is calibrated regularly according to its requirements. The invention comprises five steps. The first of them acquires air quality information, pollution source information, meteorological conditions, and local regional topographic characteristics to provide a complete technical scheme for integrally monitoring atmospheric pollution. In the second step, statistical analysis is performed on historical data to perform a pollutant diffusion simulation based on an air quality diffusion model in combination

with terrain, landform, vegetation, and other information, judging a main pollution transmission channel in the area. In the third step, an observation point distribution scheme in the research area is determined by performing a comparison of the air quality measured parameter and the simulated values. In the fourth step, a real-time monitoring network is constructed where the centroid of each researched pollutant emission area is determined through vehicle-mounted navigation. In the fifth and final step, satellite information, meteorological information, pollution source information and simulation methods, and distribution characteristics in the area are integrated to judge the mutual transmission relationship among cities, determine the PM flux, perform pollution characteristics analysis, and provide early warning [68].

- Patent CN110889199A, China, 2022. This invention aims to improve previous inventions that create a gridded plane with PM concentration data among a researched region. The improvement is made by detecting $PM_{2.5}$ and PM_{10} concentration, as well as TSP (Total Suspended Particles) data in a three-dimensional space, which requires measuring air quality at different heights from the ground. This is conducted using a drone that carries a PM concentration detector, which allows the building of many gridded planes with PM concentration information. Afterwards, the highest values of PM concentration on every grid are joined to build a plane that contains the highest PM concentration on every grid. Additionally, a gridded plane is created using the average PM concentrations in the vertical space for every grid [69].

Table 5 shows the list of all patents in grant date chronological order that met the inclusion criteria and shows the extracted data as indicated in Section 2.5.

Additional identified technological aspects not considered in the methodology's "data extraction" section are presented in Table 6. The aspects mentioned include the inclusion of sampling function, inclusion of GPS tracking unit, whether spatial distribution analysis is carried out, and the integration of a camera.

Table 5. List of patents that met the inclusion criteria. Extracted data from patent records.

ID	Patent #	Title	Status	Grant Date	Inventor	Assignee	Type of Drone	PM Sensor(s) Measurement Technology	Measured Substance(s)	Copes with Turbulence Produced by Propellers	Includes Cyclone Separator
A	US10175151B2 [58]	Environmental monitoring UAV system	Active	8 January 2019	Yaaqov Avakov	Sami Shamoon College Of Engineering (R.A.)	Rotary-wing	Not mentioned	Any/not specified	No	Not included
B	KR102035693B1 [63]	Method of monitoring air pollution and system for the same	Pending	23 October 2019	Kwon Seung Joon	N/A	Not mentioned	Not mentioned	PM_{10}, O_3, SO_2, CO, NO_2, Pb	No	Not mentioned
C	PL234716B1 [61]	Unmanned aircraft with differential air pollution measuring instrument	Pending	31 March 2020	Dariusz Tymiński	Spolka Jawna, Univ Wroclawski	Quadcopter	Not mentioned	PM_{10}, $PM_{2.5}$, CO_2, O_3, SO_2, HCl	No	Not mentioned
D	CN109059870A [60]	Boiler Air Pollutant Emission supervisory systems and method for inspecting based on unmanned plane image	Active	13 October 2020	Anonymous	Henan Blue Sky Yunhai Aviation Technology Co., Ltd.	Not mentioned	Not mentioned	PM 10, $PM_{2.5}$	No	Not mentioned
E	CN113804829A [68]	Atmospheric pollution space-air-ground integrated real-time monitoring system and method	Pending	17 December 2021	Yu Jiayan	Sichuan Ecological Environment Monitoring Station, Chongqing Ecological Environment Monitoring Center, Chongqing Institute of Green and Intelligent Technology of CAS	Fixed-wing	Laser	PM_{10}, $PM_{2.5}$, PM_1, O_3, NO_2, SO_2	No	Not mentioned

Table 5. *Cont.*

ID	Patent #	Title	Status	Grant Date	Inventor	Assignee	Type of Drone	PM Sensor(s) Measurement Technology	Measured Substance(s)	Copes with Turbulence Produced by Propellers	Includes Cyclone Separator
F	IN202241014209 [57]	A system and method for assessing the air quality and pollutant ratio at determined altitude of	Active	8 April 2022	R. Rani Hemamalini	N/A	Not mentioned	Infrared	CO, CO_2, NO_2, SO_2, PM, Volatile Organic Compounds (VOC)	No	Not included
G	JP2022059848A [64]	Atmospheric environment measuring method and wireless sensor system	Pending	14 April 2022	Kiguchi Osamu	Akita Prefectural University	Bicopter	Not mentioned	$PM_{2.5}$	No	Not mentioned
H	CN110068655A [65]	A kind of air-ground integrated atmospheric monitoring system in day	Active	22 April 2022	Wang Haowei	Institute of Urban Environment of CAS	Not mentioned	Not mentioned	PM_{10}, $PM_{2.5}$, CO, NO, SO_2, NO_2, O_3	No	Not included
I	DE202022103602U1 [62]	Airborne computer system for air pollution control	Active	20 July 2022	Anonymous	Graphic Era Deemed to be University	Quadcopter	Not mentioned	$PM_{2.5}$	No	Not included
J	CN110889199A [69]	Layout optimization method of port atmospheric particulate matter concentration online detector	Active	23 September 2022	Feng Xuejung	Hohai University HHU	Not mentioned	Not mentioned	$PM_{2.5}$, PM_{10}, TSP (Total Suspended Particles)	No	Not mentioned
K	CN217918426U [59]	Air quality monitoring unmanned aerial vehicle	Active	29 November 2022	Deng Yong Bing	Guogu Aviation Technology Hangzhou Co., Ltd.	Quadcopter	Not mentioned	$PM_{2.5}$, PM_{10}	No	Not included

Table 5. *Cont.*

ID	Patent #	Title	Status	Grant Date	Inventor	Assignee	Type of Drone	PM Sensor(s) Measurement Technology	Measured Substance(s)	Copes with Turbulence Produced by Propellers	Includes Cyclone Separator
L	CN112305163A [66]	Atmospheric pollution monitoring system based on fixed-wing unmanned aerial vehicle and data processing method	Active	7 April 2023	Liu Wei	Northwestern Polytechnical University	Fixed-wing	Not mentioned	$PM_{2.5}$, PM_{10}, O_3, NO_x, CO, SO_2	Only considers affectation caused by the natural movement of wind	Not included
M	CN107422747B [67]	Unmanned aerial vehicle system for on-line monitoring of atmospheric environment and controlled sampling of atmosphere	Active	20 June 2023	Peng Zhongren	Shanghai Jiaotong University	Not mentioned	Not mentioned	$PM_{2.5}$, PM_{10}, O_3, black carbon	No	Not mentioned

Note: “N/A” means “not applicable”, “No” means “does not cope with air turbulence produced by propellers”.

Table 6. Technological aspects not considered in the "data extraction" section of methodology of patents that met the inclusion criteria [57–69].

ID	Patent #	Includes Sampling Function	Inclusion of GPS Tracking Unit Explicitly Mentioned	Does Spatial Distribution Analysis	A Camera Is Integrated in the Drone
A	US10175151B2 [58]	✓	✓		
B	KR102035693B1 [63]		✓	✓	✓
C	PL234716B1 [61]		✓		✓
D	CN109059870A [60]		✓		✓
E	CN113804829A [68]		✓		
F	IN202241014209 [57]		✓		
G	JP2022059848A [64]		✓	✓	
H	CN110068655A [65]		✓	✓	✓
I	DE202022103602U1 [62]				
J	CN110889199A [69]			✓	
K	CN217918426U [59]				✓
L	CN112305163A [66]		✓		
M	CN107422747B [67]	✓	✓	✓	✓

Note: "✓" means that the specified technological aspect is included in the patent.

4. Discussion

A comprehensive patent review has been achieved after extracting specific data from 13 patents. This work's results supply additional information not included in previous reviews in this field such as [25,51] where the scientific literature is reviewed. This patent review, together with previous scientific literature reviews, supplies a wider overview on drone-assisted particulate matter monitoring by complementing the review of scientific literature with patent literature.

The most relevant data extracted from this review were the measured atmospheric pollutants, the type of drone, and whether the invention copes or not with the turbulence produced by propellers. Other data intended to be extracted during the methodology such as the technology used by the PM sensors, the data collection method, or whether the drone includes a cyclone separator were not mentioned in most patents, since it was not relevant for the aim of the inventors. However, ignoring the sensor's functioning and the methods to collect data does not ensure the quality of the data.

Most patents included in this review are classified under the G01N (Measuring; testing) class, according to the IPC, and include several additional specific classifications according to their included features such as image detection, spatial distribution analysis, and sampling capability, among others.

Drone-assisted PM detection in air quality monitoring is a trend that surged not so long ago. As a matter of fact, the oldest found patent in this field was published in 2019. This patent not only measures atmospheric pollutant concentrations such as PM, but also takes air samples to be analyzed offline. The sampling feature stopped being included in future inventions until patent M, which was the most recent one found in this field.

4.1. PM Spatial Distribution Analysis

Analyzing PM spatial distribution requires an adequate spatial resolution, which is an advantage that drones present over static sensors in air quality monitoring. Previous existing technology consisted of making the spatial distribution analysis using data from ground-fixed sensors, which is limited by the spatial distribution of sensors.

Patent B was the first published patent to analyze PM spatial distribution, together with G, H, J and M; patent G was found to be the most innovative regarding spatial distribution analysis of atmospheric pollutants, since it measures pollutant concentration with several drones at different locations at the same time. This includes more accurate time information than only measuring at different locations with a single drone.

4.2. Integration of Camera

Integrating a camera (e.g., infrared camera or visible-light camera) in a drone is of interest for several reasons, such as for taking pictures of the ground.

Patent B was the first patent to integrate a camera in the drone to recognize ground data to be included in generated three-dimensional maps. Other patents also include a camera to allow the user to control the device more easily. Another purpose of integrating a camera on a drone is to detect high pollution regions through infrared images and measure air quality specifically where pollutant concentration is known to be high, like patent D, which was the first patent published by the China National Intellectual Property Administration (CNIPA), which is a country recognized for its concerns in environmental pollution, where most of the patents (D, E, H, J, K, L, and M) included in this review were published. Additionally, patents C, H, K, and M integrate a camera in the drone as well.

4.3. Air Purification

Purification of air is usually conducted by purifier units that include an air filter that collects particles of certain sizes from air that is vacuumed through an inlet. Air purification was only included on patent I, which combines drone-assisted air quality monitoring with drone-assisted air purification, using a set of drones that monitor concentration of air pollutants on different locations at the same time to detect high polluted regions, making all drones travel to that region and purify air with a built-in air filter unit.

4.4. Inclusion of GPS Tracking Unit

A GPS tracking unit communicates with satellites that detect the location of the unit, which makes drone flight safer and allows autonomous flight. In this aspect, the only reviewed patents that do not explicitly mention the inclusion of a GPS tracking unit are I and J. However, patent I mentions that the comprised drones fly autonomously to a location and mentions the inclusion of a control unit as well.

4.5. Additional Technological Aspects

Most patents explicitly mention that the comprised drones communicate with a ground station included in the system. J and K are the only patents that do not explicitly mention the inclusion of a ground station, since instead of focusing on the whole monitoring system, patent J describes the method to create a gridded plane with PM concentration data, and patent K focuses on preventing drops of water to obstruct the included high-definition camera's lens.

Patent G and I were the only patents that were found to use a set of drones instead of a single drone to monitor air pollution.

On further inventions, patent E proposes one of the most notable inventions in drone-assisted air quality monitoring when providing an early warning for high concentrations of air pollutants. This patent presents a method to judge the relationship between pollutants' concentrations, their source, and meteorological parameters to predict air pollutants' transmission among cities.

Based on the extracted data regarding the detected pollutant(s), the main atmospheric pollutant of interest that inventions measure is particulate matter. However, the operation method of the PM sensors is not specified on most patents, nor is the inclusion of a cyclone separator to ensure accurate PM measurements mentioned. Only patents E and F specify that PM sensors work with laser and infrared light, respectively, but it is not mentioned if low-cost sensors are used. Although only a few available low-cost sensor performances have been thoroughly evaluated, these sensors' measurements have shown a high correlation with measurements performed by research-grade sensors [70]. For this reason, using low-cost sensors would reduce the cost of drone-assisted air quality monitoring without compromising data accuracy [71].

Additionally, none of the reviewed patents specify the drone's payload, which is a critical component in the rotary-wing drone's stability, and a reduced payload would imply a limitation of the number of components that a rotary-wing drone can carry (e.g., camera, pollutants sensors, meteorological parameters sensors) [72]. However, patent E specifies that the comprised fixed-wing drone supports a large payload, which is not specified.

Regarding the type, most drones used in air quality monitoring are rotary-wing drones since they can move along a vertical space with more ease than fixed-wing drones, although a fixed-wing drone can travel longer distances than rotary-wing drones.

It is noteworthy that none of the reviewed patents propose a mechanism, device, or system to cope with air turbulence produced by the drone's propellers, but patent L considers the inclusion of wind parameter (direction and speed) to take into consideration its affectation in the measured pollutant's concentration accuracy but does not prevent the affectation.

Although daily sensors calibration via proper reference instruments is required to ensure data accuracy, only patent E explicitly mentions that the used PM sensor is regularly calibrated according to its requirements.

Most of the reviewed patents' innovations focus on improving different aspects of an existing monitoring system, or specific methods to generate air pollution data like air pollutant spatial distribution maps. However, they do not address improvements that would ensure accuracy in the air quality measurements, such as coping with turbulence produced by the drone's propellers or including a cyclone separator to enhance PM measurements. As a matter of fact, some patents even state that the type of sensors or drone may vary according to the user's needs.

A limitation of this work is that machine translation was used to translate documents whose original language is different from English and Spanish, which may lead to limited interpretation of some very specific terminology in this field; however, to reduce the susceptibility to this problem, several translation tools were used.

Another limitation that this work presents is that only open access patent databases were used to search for patents. For this reason, patents found on paid patent databases may be overlooked.

5. Conclusions

Since atmospheric pollution has increased at a very high rate in recent years, and atmospheric pollution monitoring with stationary stations is limited to the location of these, drone-assisted air quality monitoring is currently a growing trend, and relevant improvements need to be made. The availability of mobile air quality monitoring devices, specifically drones equipped with atmospheric pollutants sensors, is of great importance in managing air pollution and preventing exposure of living things to polluted air, since identifying atmospheric pollution levels and the sites of emissions of atmospheric pollutants would aid the environmental policy-making process.

Most improvements made to drone-assisted air quality monitoring systems have been focused on different aspects from the comprised drone(s), such as detecting pollutants' spatial distribution, three-dimensional mapping, and including sensors for different atmospheric pollutants, among others, instead of ensuring the accuracy of the air quality measurements by the carried sensors. For this reason, drones comprising atmospheric pollutants sensors still present a weakness when not considering the affectation that the turbulence produced by the drone's propellers presents.

This work's findings evidence a field of improvement on atmospheric pollutants monitoring on drones, since future inventions in this field must be oriented to make measurements accurate by coping with turbulence produced by the drone's propellers.

Additionally, since most drones used in the reviewed patents are rotary-wing drones, whose main limitation is the flight time, future work must also consist of improving battery duration. These findings could help researchers and developers to create an equilibrium between physical characteristics such as weight and size, and performance characteristics such as battery duration to ensure a suitable distance range together with wind resistance, among other relevant requirements for drone-assisted air quality measurement.

Author Contributions: Conceptualization, E.A.-C., D.C.-G. and M.A.R.; methodology, E.A.-C. and D.C.-G.; validation, M.A.R., J.P.G.-V. and R.L.A.; formal analysis, D.C.-G., J.P.G.-V. and M.A.R.; investigation, E.A.-C. and D.C.-G.; writing—original draft preparation, E.A.-C. and D.C.-G.; writing—review and editing, D.C.-G., E.A.-C., M.A.R., J.P.G.-V., R.L.A. and A.R.O.-V.; visualization, M.A.R., J.P.G.-V. and A.R.O.-V.; supervision, D.C.-G.; funding acquisition, M.A.R., D.C.-G. and J.P.G.-V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Universidad Autónoma de Baja California (UABC) Project funding nunber: 2453 and Consejo Nacional de Humanidades, Ciencia y Tecnología (CONAHCyT) E.A.-C. Scholar fellowship CVU: 1055121.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in Google Patents at patents.google.com reference numbers 59–69, USTPO Patent Public Search at https://ppubs.uspto.gov/pubwebapp/ (accessed on 13 April 2024) reference number 58, and Patentscope by WIPO at https://patentscope.wipo.int/search/en/search.jsf (accessed on 13 April 2024) reference number 57. These data were derived from the mentioned resourced available in the public domain.

Acknowledgments: We thank Universidad Autónoma de Baja California (UABC) and CONAHCyT for the scholar fellowship of E.A.-C.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Pollutants and Substance's Nomenclature

HCl	Hydrogen chloride
HCN	Hydrogen cyanide
H_2S	Hydrogen sulfide
Pb	Lead
H_2	Molecular hydrogen
Cl_2	Molecular chlorine
PM	Particulate matter
O_2	Molecular oxygen
O_3	Ozone
VOC	Volatile organic compound
CH_4	Methane
CH_2O	Formaldehyde
SO_2	Sulfur dioxide
CO	Carbon monoxide
CO_2	Carbon dioxide
NO_2	Nitrogen dioxide
NO	Nitrogen monoxide
NH_3	Ammonia
PH_3	Phosphine

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