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Review

Cyclone Separator for Air Particulate Matter Personal Monitoring: A Patent Review

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Abstract: Currently, air pollution is a critical public health problem, which means that the daily measurement of urban air quality can be enriched if measured in a personalized way. Personal environmental monitoring devices can guide the population to take action. They can track their daily activities, avoiding situations that could affect their health, allowing them to precisely know the air quality they breathe in real-time in various microenvironments. In this work, we present a review of cyclonic separation technology patents, such as pre-separators in monitoring devices. We focused on the state-of-the-art commercially available personal monitoring devices, the classification of kinds of patents, and a review of cyclone patents and gas–particle separation behaviors. The World Intellectual Property Organization IP's portal and Google Patents search engine were used, using international patent classification plus mesh terms involving a cyclone in an air particulate monitor after predefining inclusion and exclusion criteria such as gas–air cyclones, high efficiency, and fine particle separation. Twenty-nine patents were analyzed according to the main characteristics (e.g., cut point, flow rate, and cyclone improvement) available in the patent document. The wide range of cyclones indicates a maximum flow rate of between 0.5 and 4.5 Lpm and a lower cyclone cut point of 0.8 µm. This review includes a discussion of the most relevant features of the patent documents (flow rate, particle cut point, some cyclone improvements, and technology detection). This paper aims to give an overview of the use of cyclones as pre-separators for personal air monitoring devices and to acknowledge the patented improvements of new inventors or developers.

Keywords: personal monitoring; cyclone separator; pollution monitoring; low-cost monitor; PM sampler; particle matter monitor

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1. Introduction

Despite the recent improvements in air quality in large parts of the world, poor air quality remains a challenge in many urban areas worldwide. In 2013, the World Health Organization (WHO) and the International Agency for Research on Cancer (IARC) concluded that outdoor air pollution and its particulate matter (PM) are carcinogenic to humans, especially in the lung [1]. There is a close relationship between exposure to PM_{10} and $PM_{2.5}$ (particulate matter with aerodynamic diameters ≤10 and ≤2.5 µm, respectively) suspended in the air and health effects. Air pollution has health impacts even at very low concentrations in the short- and long-term [2–5]. However, no threshold has been identified under which no health effect is observed [6]. Therefore, the 2020 WHO Air Quality Guidelines aim to facilitate the setting of standards for permissible concentrations in the air [7].

The USA Environmental Protection Agency (EPA) is a leader in developing and improving instruments, methods, techniques, and other tools to measure and monitor air quality and evaluate air emissions to protect public health and the environment from air pollution [8]. To effectively control air pollutants, it is necessary to implement National Ambient Air Quality Standards (NAAQS) that account for ambient air quality and state-of-the-art methods in using technologies that provide accurate and reliable data. The Federal Reference Method (FRM) and the Federal Equivalency Method (FEM) are the most commonly used. These methods are the gold standard for states and other organizations to assess the implementation of the actions needed to attain NAAQS [9].

A modern cyclone separator is an essential piece of stationary equipment in the air quality field and has been widely used in multifunctional gas–particle separation [10]. Due to its high efficiency, simple structure, easy operation and maintenance, and good environmental adaptability (i.e., temperature, pressure, humidity, and strong corrosion conditions), it has had a strong impact in the fields of chemical and processing engineering, energy technology, environmental science, and material synthesis [11].

Cyclonic separation has displayed an irreplaceably unique role in specific situations and keeps improving separation processes in environmental sciences [12].

A standard cyclone separator generally has: (1) an air inlet, which allows the intake of air with PM; (2) a cylindrical body, which in combination with the inlet, allows the vortex flow to begin (for this reason, it is called a vortex finder); (3) a cone with a determined angle to the vertical axis and whose conical length determines the efficiency of the cyclone; (4) a dust outlet switch, which is a container to collect PM that is separated by the vortex; and (5) an exhaust pipe or PM outlet that is determined by the size of the cyclone cut point, as shown in Figure 1a. After a fluid containing PM enters the cylinder and hits its inner wall, its linear motion becomes a rotating descending spiral. Therefore, the particles are affected by centrifugal forces and impact against the wall. Then, the particles lose inertial force after colliding with the surface and fall along the wall surface of the cone. Figure 1b shows a solid view perspective. Finally, the coarser particles fall into a collector. The airflow reaches the bottom and turns upwards, carrying finer particles toward the exhaust through the exhaust outlet pipe, as shown in Figure 1c.

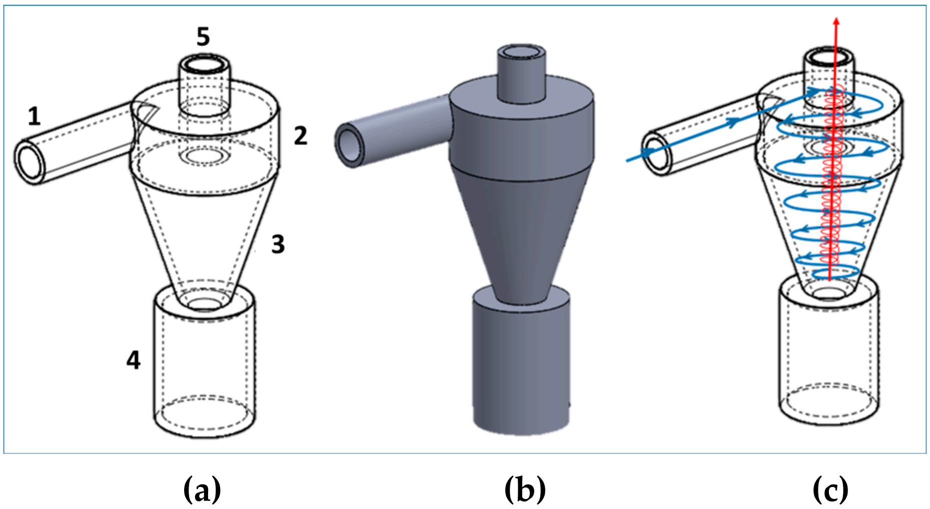

Figure 1. Components of the cyclone: (**a**) numbering cyclone separator elements; (**b**) solid external of a cyclone; (**c**) cyclone internal flow pattern.

The main features of the cyclone separator are its simple structure and geometry; it does not have an internal structure, and it has high efficiency, requires minimal maintenance, and is low in manufacturing cost [13]. Nevertheless, the typical cyclone shows a low efficiency for fine particles [14]. Therefore, many attempts have been conducted to improve the separation performance of cyclone separators, for instance: optimizing the structure and geometrical dimension of the vortex length [15,16]; altering the shape and diameter of the vortex finder (i.e., an internal tube that allows the turbulent flow to start) [17–20];

the use of a single or double inlet [21] or a tangential or spiral inlet [22], modifying the general geometric dimensions of the intake or inlet [23]; a distinct inlet section regarding the cyclone body [24]; a symmetrical inlet and a volute outlet [25]; the cone-tip dimension [26]; the cyclone body height [27]; and the conical length [28].

Different types of cyclone separators have been developed to improve separation efficiency, such as the Lee type [29], the semi-spherical cyclone [30], the Very Sharp Cut Cyclone (VSCC) type [31], the dynamic cyclone [32], the square cyclone [33], and the circumfluent cyclone [34]. A major constraint on the ability to assess personal PM exposures is the cost and physical burden of the monitors themselves, personal air monitors typically consist of a flow pump, a pre-separator as a size selective inlet (e.g., cyclone, impactor, or both) to measure inhalable PM within the wearer's breathing zone, and detection technology (e.g., light scattering). For this reason, the personal monitoring device must be wearable, considering the limitation of the monitor size and weight. Therefore, designing a high-efficiency cyclone for fine particle separation remains a significant challenge for developing improvements within personal monitoring without sacrificing separation efficiency.

The population can have air pollution control with the help of the air quality monitoring system, which allows the user to know the air quality continuously [35]. The EPA standardizes all methods of measuring air pollution; for example, fixed-site monitoring stations for PM are located 7 to 10 m from the ground. Nevertheless, this method gives a neighborhood-wide and urban-wide air quality estimation that is costly to operate [36]. The advantage of introducing a personal environmental monitoring method would be its capacity to provide information on PM concentrations at the individual level (daily activities and work locations), allowing them to know precisely what they are breathing in real-time in different microenvironments. In addition, such monitoring could provide a basis for evaluating PM exposure. This information may allow individuals, especially those most susceptible to the adverse effects of air pollution, to make decisions to reduce their exposure to PM. Eventually, the information may contribute to new regulations for those specific sources of PM most strongly associated with adverse health effects [37].

This paper aims to review the state-of-the-art cyclone separation technology patents and their potential use in personal monitors. We focused on pre-separators in air monitoring devices, existing cyclone patents, and cyclone separation behaviors. We include a discussion of the most relevant features available in the patent document (flow rate, cut point particle size, some cyclone improvements, and technology detection). The scope of our patent review is defined by inclusion criteria for fine particles (PM less than 10 μm), giving an overview of the use of cyclones in monitoring devices to consider the patented improvements for new inventors or air monitoring developers.

State-of-the-Art Personal Devices for Air PM

Personal monitoring devices use commercially available, low-cost sensors capable of estimating air pollutant concentrations continuously. Potential users include sensor developers, scientists, citizens, teachers, students, community organizations such as neighborhood alliances, environmental justice groups, and federal air quality agencies. In addition, the new generation of low-cost and highly portable air quality sensors allows people to use this technology for various applications beyond traditional or equivalent regulatory monitoring. Some of the potential uses of personal monitors are research (i.e., scientific studies aimed at discovering new information about pollution) and personal exposure monitoring (i.e., air quality to which a single person is exposed while doing their usual activities) [38]. Table 1 shows the performance characteristics of commercially available personal environmental monitor devices for PM measuring.

Table 1. Commercial personal environmental monitors.

ID	Monitor	Operating Principle	Maker	Precision	Detection Limit	Cyclone
A	831 Aerocet handle particle counter [39]	Light scattering for mass concentration	MetOne Instruments	N/A	0.5 µm	N/A
B	Personal DataRAM, model pDR1500 [40]	Light scattering for mass concentration	Thermo Scientific	±0.2% of reading or ±0.5 µg/m^3	0.1 µm	Cyclone SCC y GK
C	DC1100 air quality monitor [41]	Light scattering with a laser particle counter	Dylos Corp.	N/A	0.5 µm	N/A
D	microAeth®® model AE51 [42]	Light absorption, 880 nm	Aeth Labs; Black Carbon	±0.1 µg/m^3	<0.16 µg/m^3, 2.5 mL/s, 60-s avg	N/A
E	Sidepack personal aerosol monitor AM520 [43]	Light scattering for mass concentration	TSI Incorporated	±0.1 µg/m^3	0.1 µm	Cyclone type DORRR-Oliver

The current criteria for monitoring stations for environmental pollution consist of devices that meet the FRM or FEM requirements. As shown in Table 1, only models B and E use a cyclone inlet. Model B can use a GK cyclone 2.05 (GK) or a Sharp Cut Cyclone 1.062 (SCC). The GK cyclone separates PM_4 through PM_{10}, and the SCC cyclone separates PM_1 through PM_4 through a series of tangential and round-entry cyclone geometries. The SCC cyclone in particular has a shrouded inlet intended to reduce directionality effects due to breezes in the workplace. The GK 2.05 cyclone was developed for the Finnish Institute of Public Health and designed to be used in a backpack, with the intake tube protruding through a grommet. This design resulted in an excessively long inlet tube for lapel use. Therefore, the unit was redesigned with a more suitable half-length inlet, which required confirmatory testing [44]. Model E uses the Dorr-Oliver cyclone specified by the National Institute for Occupational Safety and Health (NIOSH) monitoring methods, commonly made of plastic and nylon [45,46].

Patent review articles are a tool that helps to understand state-of-the-art inventions, allowing a detailed analysis of the improvements and benefits that different inventors have embodied in their creations. The following patent review focuses on cyclone separators with application in PM monitors.

2. Materials and Methods

2.1. Patents Article Review Search Methodology

Mesh terms that were used to search for patent review articles on cyclone separators with a focus on environmental monitors were "Review article" AND "Patent" OR "Patents," AND "Cyclone" OR "Cyclone Separator" AND "Environmental monitor" OR "Dust monitor" OR "Environmental Pollution" AND "Particle Matter" OR "PM_1" OR "$PM_{2.5}$" OR "PM_{10}"; zero results were obtained by the SCOPUS database. Using the IEEEXplore database with the exact keywords ALL METADATA "Review article" AND "Patent" OR "Patents," ALL METADATA "Cyclone" AND "Cyclone Separator" AND "Environmental monitor" OR "Dust monitor" OR "Environmental Pollution" yielded zero results. No review documents were found on patents for cyclone separators oriented to environmental monitoring, so this work will be helpful for all those interested in developing cyclone separators for monitoring applications beyond personal ones.

2.2. Data Sources and Patents Search Strategy

The patent search strategy was based on a scooping study to find how many patents had been registered for personal monitoring using a cyclone as a particulate matter separator. This process involved trialing and defining mesh terms in the literature database and inclusion/exclusion criteria, as shown in Table 2, using Google Patents and WIPO. For Google Patents, the mesh terms used were: "Cyclone," "Cyclone Separator," "Matter monitor," "Particulate matter," and "$PM_{2.5}$". For Patentscope by WIPO, the International Patent Classifications (IPC) were used to search monitors with cyclone separators, which are classified as follows: G01N 15/06—investigating concentration of particle suspensions, (G01N 15/04 and G01N 15/10 take precedence; by weighing, G01N 5/00) or G01N15/10—

investigating individual particles (this IPC is for all environmental monitors). The screening was based on the search strategy shown in Figure 2.

Table 2. Inclusion and exclusion criteria.

Inclusion	Exclusion
Must be an application for fine particle separation less than PM_{10}	Non-personal monitoring applications
Air–gas cyclones	Industrial applications
High separation efficiency	

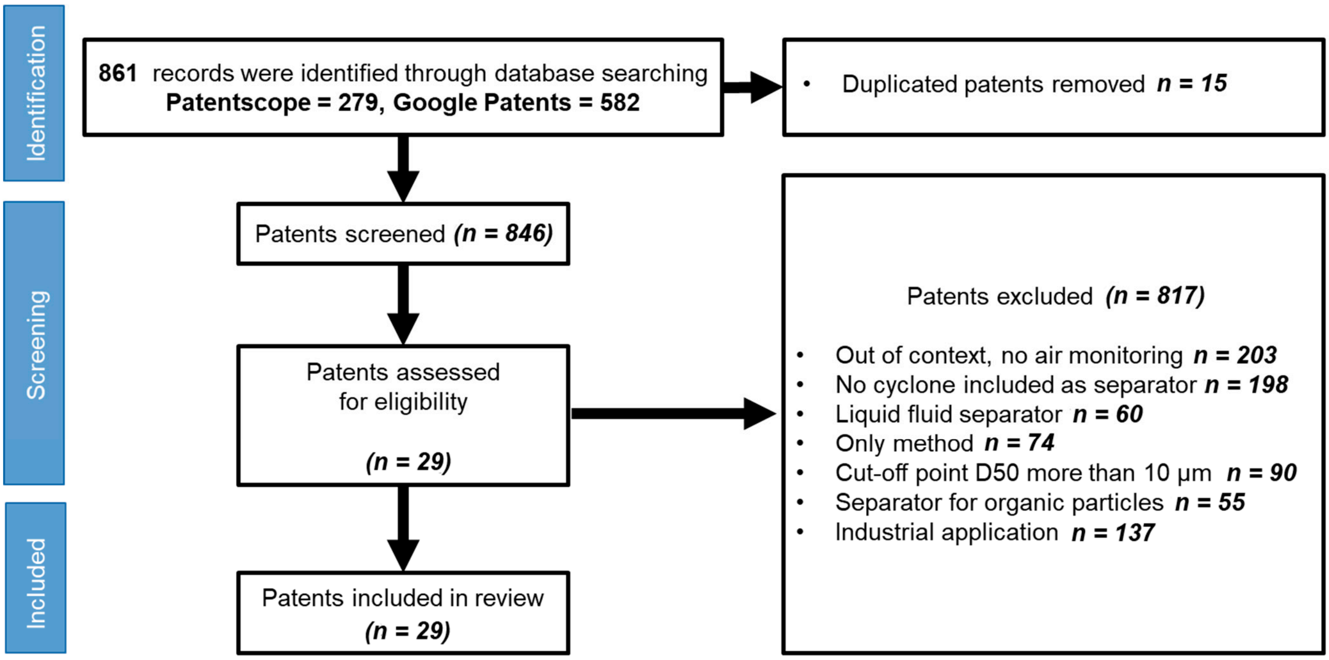

Figure 2. Flow chart of the search methodology in databases.

3. Results

According to the patent search strategy, the results are shown in Table 3.

Table 3. Results from the search strategy.

Mesh Terms	Hits	Meet Inclusion and Exclusion Criteria	Source
"Cyclone," "Cyclone Separator," "Matter monitor," "Centrifugal Separator," "Particulate matter," "$PM_{2.5}$"	582	19	Free search in Google Patents
IC: G01N 15/06 and Cyclone and Separator and Air	75	4	Patentscope by WIPO (IPC)
IC: G01N 15/04 and IC: G01N 15/10 and Cyclone and Separator and Air	80	2	Patentscope by WIPO (IPC)
IC: G01N 5/00 and Cyclone and Separator and Air	124	3	Patentscope by WIPO (IPC)

A total of 29 patents met the inclusion criteria, as shown in Table 4. Figure 3 shows the distribution of found patents by country. Furthermore, B04C, B01J, B01D, and E21 were found under the search strategy using Google Patents.

Table 4. List of patents that met the inclusion criteria. Data extracted from patents' records [47–75].

ID	Country	Patent #	Patent Name	Date	Inventor	Company	ICP	Detection Technology	Flow Rate Lpm	Cut-Point µm	Cyclone Improvement
A	CN	215931601U	Cyclone separator for gas particles and gas particles detection	01/03/2022	Wu Huawei	Thermo Fisher Scientific	B04C/514	Not Mentioned	Not Mentioned	2.5 and 10	Dual cyclone controlled by a passing valve in the same body
B	US	20210405007A1	Low-flow size-selective inlet for air quality sensors	30/12/2021	Paul Alan Solomon	USA Government	G01N 1/28	Light Scattering, quartz balance	0.05 to 1	1 to 10	Ultra-low flow real cyclone and a virtual cyclone operating together in a parallel array
C	US	10775354B2	Autonomous ambient air sampling system for monitoring	15/09/2020	Jaron Hensen	Brigham University	G01N/30	Mass Spectrometer	4 to 8	2.5	Cyclone adapted to a heater chamber
D	CN	210690331U	Gas PM detection system (utility model)	05/06/2020	Wang Yanhui	Shenzhen Eyesky Technology	G01N 15/06	Light Scattering	Not Mentioned	2.5 and 10	Cyclones include a dehydrator unit to remove humidity from the inlet gas
E	CN	209697194 U2	A kind of cyclone separator	29/11/2019	Li Yongzhao Li Binjie	Qindao Chuangke Equipment	B04C 5/00	N/A	Not Mentioned	5 to10	The cyclone inlet air flow tangential angle (45° to 75°)
F	US	20190339185	PM measuring apparatus	07/11/2019	Francois Velge	Kolisch Hartwell, P.C	G01N 15/06	Light Scattering	0.5 to 3	0.8 to 2.2	Cyclone has adaptation to work or just filter air at the outlet
G	CN	208953340U	Automatically switch sampling apparatus for atmospheric particulate matter	07/06/2019	Chen Qi	Peking University	G01N/24	ASCM	4.5	0 to 3 or 0–2.5	Cyclone has different inlet nozzle
H	EP	2569069B1	PM monitor	10/04/2019	Kevin J. Goohs	Thermo Fisher Scientific	G01N 1/22	Light scattering	Not mentioned	2.5 and 10	Cyclone generates gas with a determinate PM concentration
I	US	9945768B	Method and apparatus for a portable $PM_{2.5}$ monitoring device	14/04/2018	Zhongchao Tan	N/A	G01N/22	Light scattering	Not mentioned	2.5	The inlet ports were manufactured to include an angle of less than about 15° to minimize particle loss during the sampling process
J	US	20170370809	Portable air sampling device	28/12/2017	Daniel D. Miller-Lionberg	Colorado State University Research Foundation	G01N 1/22	Light scattering	N/A	1 to 10	The cyclone body belongs to the impactor cap
K	US	20170191974	Measurement device and measurement method	06/07/2017	Akitake Tamura	TOKYO ELECTRON LIMITED	G01N 21/64	Light scattering, plasma emission spectroscopy	Not mentioned	Max 10	Cyclone separates particles to combine with a liquid fluorescent target
L	CN	106872316A	Measure the particle diameter distribution of super low-concentration dust	20/06/2017	Liu Xiaowei	Huazhong University	G01N 15/06	Light scattering	Not mentioned	2.5	No mentioned more features, such as ultralow flow
M	GB	2544285	Ash detector	17/05/2017	Neetin Lad	GreenBank Terotech LTD	G01N 15/14	Microscopy detector	Not mentioned	0 to 2.5	Dual cyclone operation
N	CN	103566840B	System and method for producing high-time diluted $PM_{2.5}$ aerosol	29/04/2015	Luo Zhongyang	Zhejiang University	B01J 13/00	Light scattering	85 to 90	2.5	Cyclone separator to get mass concentration
O	CN	104142289A	Online monitoring system for atmospheric aerosol	12/11/2014	Zeng Limin	Peking University	G01N 15/06	Microscopy detector	Not Mentioned	0.3 to 5	Cyclone separator to get mass concentration

Table 4. *Cont.*

ID	Country	Patent #	Patent Name	Date	Inventor	Company	ICP	Detection Technology	Flow Rate Lpm	Cut-Point µm	Cyclone Improvement
P	CN	104128047A	Fine PM removal device and method with combined action	05/11/2014	Zhang Jian	Central South University	B01D 45/16	Quantitative mass spectrometer	N/A, 800 to 3000Hz acoustic pump	2.5	Present an acoustic agglomerator and a cyclonic separation synergy fine particle method
Q	US	20140060213	Portable nanoparticle sampler	06/03/2014	Shi-nian Uang	Muncy, Geissler, Olds & Lowe, P.C	G01N 1/22	N/A	2	0.1 to 4	Complete sampler with a cyclone combined with a micro-orifice impactor
R	CN	202916165U	Instrument for continually and automatically monitoring fine atmospheric particles	01/05/2013	Dai Bohua	Wuhan Yite Environmental Protection Tech	G01N 15/06	Beta ray method	Not mentioned	2.5	Cyclone separator as a secondary separator with impactors
S	US	20120160010/ 20070068223	Air-sampling device and method of use	28/06/2012	The Hsun B. Chen	USA Health and Human Services	G01N1/22	Light scattering	2	1.94	No mentioned
T	US	20110159596	Substance detector with cyclone	30/06/2011	Alex Keinan	N/A	G01N33/22	Light scattering	Not mentioned	0.1 to 8	The inventor has discovered that adjusting a nozzle angle relative to the cyclone axis can increase the efficiency with which substances are caught
U	CN	1330958C	Device for collecting and monitoring particles of solid source discharged gas	08/08/2007	Zeng Limin	Peking University	G01N 1/20	Light scattering	Not mentioned	2.5 and 10	Cyclones are used in series, obtaining two cut-off points
V	JP	1841044	PM concentration measuring apparatus	04/10/2006	Masara Shinohara	Horiba LTD	G01N 15/06	Light scattering	Not mentioned	2.5	Cyclone is used as particle distributor $PM_{2.5}$ inside of apparatus for particulate density tester
W	US	20060000297A1	The ambient particulate sampler inlet assembly	05/01/2006	Robert Gussman	BGI Instruments	G01N/24	Light scattering	5	1 to 10	Cyclone with a different kind of inlet nozzle jet to increase collection efficiency
X	AU	2003239506	Automatic point source biological agent detection system	11/09/2003	Difurio Gabriel A.	Notthrop Grumman Corporation	C12M/134	Light scattering	800	1 to 15	Added a dry cyclone collector as a pre-separator base
Y	US	6221134	Apparatus and method for separating particles from a cyclonic fluid flow	24/04/2001	Ernest Conrad	G.B.D Corp	B01 45/16	Light scattering	Not mentioned	Max 10	Series cyclones array for increased efficiency
Z	GB	1446760	Aerial prospecting	18/08/1976		Columbia Scient Ind Inc	G01N/22	Not mentioned	Not mentioned	2.5 to 10	Cyclones using inlet ducts of flying aircraft
AA	GB	1417481	Method and apparatus for transferring particles from one fluid stream	10/12/1975	N/A	Barringer Research LTD	B04c/514	Light scattering	Not mentioned	Max 10	Cyclone separator for transferring solids to liquid before analysis in air pollution
AB	GB	1391373	Rock sampling tool	23/04/1975	N/A	Cominco LTD	E21C 35/22	N/A	566	No Mentioned	First portable cyclone
AC	GB	1268709	Monitoring dust concentration	29/03/1972	Badzioch Stalinslaw	Coal Industry Patents LTD	G01N/22	N/A	113 to 183	N/A	Cyclone used as control of PM in plant

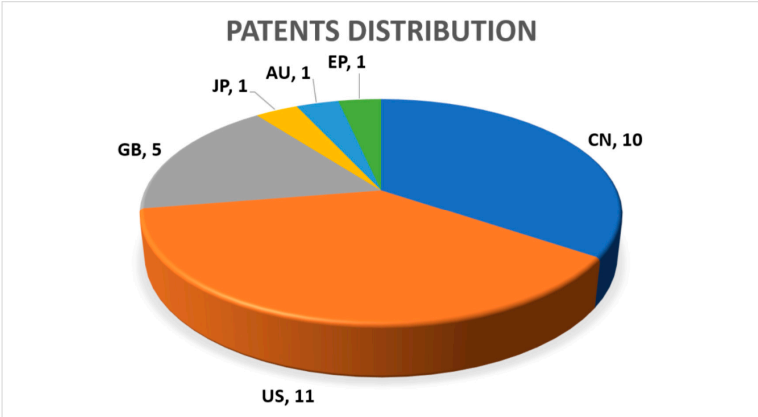

Figure 3. Patent distribution by country: GB (Great Britain), CN (China), US (United States), JP (Japan), EP (European), and AU (Australia).

4. Discussion

The most relevant features extracted from the research of patents were the cyclone cut points and the work air flow rate. However, not all patent details were found in the databases' patent document register. The reason is that the inventor is not obligated to share these technical details if it is not necessary to explain the invention's functioning as a security measure against patent plagiarism. Table 4 shows patented cyclones which share cutoff-point and flow-rate details. They all achieve fine particle separation, including less than 10-micrometer particle size.

Patent AC was registered in 1972 as the first portable monitor that included a cyclone separator of fine particles used for environmental monitoring within a factory; however, it was not until 1975 by patent AB that the first portable environmental device was invented that included a cyclone as a separator and consisted of a monitor that the user could carry with them during sampling.

The standard way to describe this separation performance is the D50 cut point, meaning that the particle size has a 50:50 probability of separation when the cyclone is in equilibrium at a given flow rate. Note that the D50 cut point is the characteristic that describes cyclones in particle size separation. This feature performance in cyclones depends on their operating parameters as the flow rate, without neglecting structural design and material properties. Therefore, the monitor's developer must take into account these characteristics in their monitor since it influences their final detection or quantification system.

Patent B has a low workflow rate with a maximum of 1 Lpm. Patent Q, with the smaller-sized cut-point diameter of 0.8 micrometer, had a maximum flow rate of 2 Lpm. The broad range of cyclones indicates a maximum flow rate between 0.5 to 4.5 Lpm, except for patents N, X, AB, and AC, which work with 90, 800, 566, and 186 Lpm, respectively.

Based on the analysis of the patents, cyclone flow control technology has been changing over time. Most patents used vacuum pumps so the cyclone flow control could determine the correct separation by its cut point. However, patent P uses an acoustic flow generator, and no flow rate data were available in the patent document. Although, the inventor only provides operating frequencies of 800 to 3000 Hz. This acoustic technology represents a significant step forward in using micro-flows to miniature cyclone devices, allowing for a more efficient personal monitor with low power consumption throughout the PM personal monitor. This flow source was found to have a maximum of 10.8 mLpm and low consumption, simple structure, and continuous flow and was without pump body oscillation [76]. The main advantage of these pumps is their low power consumption compared to conventional vacuum pumps; however, the acoustic source needs a separate frequency driver to operate the pump. Nowadays, developers are looking for personal monitors with the lowest possible cost and more ergonomic miniature sizes for the user.

It is a challenge to identify which class of cyclone separator is designed in the patent documents; however, patents A, B, L, and M describe their cyclones as tangential and with a round inlet with the same characteristics as the VSCC class. This type of cyclone could be dimensionally scaled using an empirical family model specific to a given cyclone geometry, and the family model relates the cyclone cut point to the cyclone body diameter and flow rate. Once the family model is known, it can be used to calculate the dimensions of other family members that will result in a specified cut point at a defined working flow rate. Unfortunately, the other patents do not have sufficient information to determine the cyclone class.

Some patents found have a new geometry modification at the inlet; patent E's inventor modified the rectangular inlet installed obliquely according to the inlet air flow tangential angle (45° to 75°). This modification increases the cyclone separator's performance. In the case of the patent I, the inlet ports were manufactured to include an angle of less than 15° to the cyclone axis to minimize particle loss during sampling.

Some patents use more than one cyclone to get a better result in the monitoring process; this method was explained by patent Y in 2001, setting a series of cyclones to increase the separation efficiency. This method was applied by patent M, using a dual pre-separator cyclone developed to monitor the ash concentration of the airplane's indoor air when flying over volcanic areas. In addition, the monitoring applications of patents S and U are used in air sampling devices and can use one or more cyclone separators to collect PM in the same cut-point size. Another example is patent B, where the inventor implemented an arrangement of two cyclones: a first one with a primary cutoff point and a secondary one with an output associated with particles smaller than those targeted by the primary cutoff point. In short, these patents have two cutoffs and outputs for monitoring a range of sized particles. Using multiple cyclones, either in parallel or in series, to treat a more significant workflow rate results in higher efficiencies but at the cost of a significant increase in pressure drop. Higher pressure drops translate to higher energy usage and operating costs. [77].

A filter collects the PM after the separation process according to the monitoring application. Still, in the case of patent N, these particulates are deposited to a liquid substrate to create a liquid with a defined PM concentration. In patent T, the cyclones extract substrates from the atmosphere; this cyclone has a fluid injector at the inlet to make a chemical reaction with the reagent, then it separates this fluid to measure the concentration. Moreover, patent K presents a cyclone that separates particles of less than 10 μm to combine them with a fluorescent liquid target to monitor biological agents (viruses and bacteria) in PM. This patent was considered because it was applied to measure the PM in air. This method was described in 1975 by patent AA, which consisted of a cyclone separator that transfers solids to liquid before the air pollution analysis device. This type of method allows taking advantage of the flow generated by the cyclone to mix the particles with a liquid fluid. If the detection technology used requires it as an input with a specific mass concentration, this would be possible thanks to the fact that the inventors integrated a modification to accomplish it.

The data logging of a personal monitor is one of the functionalities required by the EPA, as well as real-time or online monitoring capabilities. These requirements imply that a cyclone separator should not become saturated prematurely. Most patents use light scattering devices as the PM detection technology, being the most commercially available; however, in our research, we found other detection technologies, such as those in patents G and R, which were designed for online monitoring through an aerosol matter spectrometer and a beta-ray method, respectively. In addition, patent O uses a cyclone to obtain the gas concentration for online monitoring by a microscope analysis technique using a digital camera CCD (charge-coupled device). The disadvantage of these two methods is that the sizes are significantly larger than those of other detection devices, such as light scattering devices.

Some patents are set with an impactor device; patents Q and R combine the cyclone with an impactor, taking advantage of its tangential flow and the capture capacity of an impactor to capture the nanoparticles range. Patent J has a different arrangement where the cyclone body belongs to the impactor cap to integrate a small device. As we have seen, two types of PM pre-separators for monitors exist. The first type is a cyclone separator, and the second one is an impactor or a combination of both. They work similarly since they use physical forces to separate particles. In the case of cyclones, the large-sized particles possess more significant momentum and undergo the primary rotating airflow. Due to the centrifugal inertia that hits the smooth inner surface of the cyclone body, the particles slide into the cup attached at the bottom and separate. The internal rotating airflow carrying smaller particles exits the cyclone and then passes through a filter or interior to the monitor.

On the other hand, impactors separate particles from the main air stream using the principle of inertial mass impaction. As a result, ambient air is allowed to enter the monitor assembly, and the flow path suddenly changes by providing a pressure gradient in a different direction. Large particles with higher momentum move in a straight line due to mass inertia and thus leave the airflow path to enter an empty chamber or pit. The empty chamber is called a "borehole impactor," which contains oil or grease to prevent particle rebound. The primary airflow encounters the obstruction and thus changes its route and passes through a filter that samples the remaining particles [78]. Table 5 lists the advantages and disadvantages of impactors and cyclones.

Table 5. Advantages and disadvantages of impactors and cyclones [79,80].

Cyclones	Impactors
Indoor and outdoor use	Indoor use
Approved for monitoring by EPA	Wind speed sensitive
Low cost	Low cost
Gases and liquids (hydrocyclones)	Gas only

In addition, cyclones have been modified to the point of being combined in a series of arrangements or by an impactor. This combination allows developers to reinforce monitors that require impactors as pre-separators. For example, cyclones are not sensitive to wind speed, which means that cyclones can be used both indoors and outdoors.

Cyclones have been adapting to new sampling technologies such as microscopes and others. For example, patents O and R use beta-ray methods and spectrometers (like the one used in patent G), which is indicative of a continued effort to improve adaptation to different types of technology. Moreover, they can be used indirectly by forming air masses with a determined concentration of particles and later mixing with some liquid to quantify the material involved, as in patent T.

Cyclones tend to develop to the most efficient point using the least amount of flow possible, achieving $PM_{2.5}$ separations. It can be achieved using different technologies in flow control and cyclone geometry. Fluid mechanics indicate that the smaller the dimensions of a cyclone, the smaller the amount of flow will be needed to reach its cutoff point. For example, patent J is a clear example of an improving trend for cyclones and personal monitors; if you are interested in developing a personal monitor, it is highly recommended that you look for a patent for a low-cost miniature PM sensor.

According to the definition by the EPA, low-cost PM sensors are classified by costs below 1000 USD and are built with miniaturized electronic devices [81]. In this research, the most updated patents are A and B. Patent A considers a cyclone as an accessory that is interchangeable; with more efficient control, the device could control the cyclone operation through a passing valve. Model B from Table 1 is based on Patent A using cyclone models SCC and GK. Patent B has an array of real and virtual cyclones operating in parallel, conserving an ultralow workflow. This represents a challenge for new researchers and developers to improve from a 1 to 10 µm cut point and a working flow rate of 0.05 to 1 Lpm.

5. Conclusions

Quantitative measurement of PM requires complex separation and measurement methods and techniques. The use of cyclones in the pre-separation stage improves the measurement procedure. Air pollution is a critical public health problem, meaning that urban air quality must be measured in a personalized and daily way.

No review documents were found on patents for cyclone separators oriented to environmental monitoring, so this work will be helpful for all those interested in developing cyclone separators.

A total of 29 patents were analyzed in this study after a rigorous search described in the patent search strategy. When reviewing the patent registration files, it was challenging to find the details on the size of the cyclone. For this reason, it was impossible to make a geometric comparison between the patents. However, some patents provided details of the airflow and the cutoff point they used to work, including the pumping method or air control. Patent Q, with the smaller-sized cut-point diameter of 0.8 micrometer, had a maximum flow rate of 2 Lpm. The broad range of cyclones indicates a maximum flow rate of between 0.5 and 4.5 Lpm.

The cyclones in the patents are a crucial part of the measurement process, either separating the material and injecting it directly onto the measurement equipment or combining it with a substrate to generate samples of exact concentrations. When cyclones and impactors work together, they can obtain more efficient results than when working separately. In addition, new technologies are being patented that involve the cyclone as a particle pre-separator and are always looking for the lowest energy consumption, as in the case of acoustic pumps used for flow control with lower consumption than a conventional air pump.

Monitoring PM developers must be oriented to improve the miniaturization of electronic devices, including cyclones to low-cost PM sensors.

China and the United States of America have the most patents recorded, two countries recognized for their environmental pollution concerns.

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Abbreviations

ACSM	Aerosol Chemical Speciation Monitor
EPA	Environmental Protection Agency
FEM	Federal Equivalency Methods
FRM	Federal Reference Methods
IARC	International Agency for Research on Cancer
IPC	International Patent Classifications
NAAQS	Ambient Air Quality Standards
NIOSH	Occupational Safety and Health
PM	Particulate matter
SCC	Sharp Cut Cyclone
VSCC	Very Sharp Cut Cyclone
WHO	World Health Organization
WIPO	World Intellectual Property Organization

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