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Review Article

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A systematic global review of fixed air quality monitoring stations: Spatial distribution, typologies, measured pollutants, technologies, regulatory standards, and research gaps

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ABSTRACT

Air pollution is a global threat that significantly affects human and environmental health, and fixed Air Quality Monitoring Stations (AQMS), play a pivotal role in assessing ambient air conditions and informing regulatory policies. This systematic review provides a global overview of fixed air pollution monitoring stations, focusing on the geographical distribution of stations, classification, pollutants measured at each station, measurement techniques for each pollutant, monitoring frameworks, and implementation challenges. A comprehensive search of PubMed, Scopus, Web of Science, and grey literature identified 17 eligible studies covering diverse regions across Europe, Asia, Africa, and the Americas. This assessment uncovers Critical disparities in air quality monitoring architectures, revealing: (i) non-uniform station distribution patterns, (ii) technology adoption gaps, and (iii) pollutant coverage imbalances that collectively hinder comparable air quality assessments across regions and While high-income countries operate and maintain sophisticated networks and advanced, reference-grade analyzers, low- and middle-income countries use low-resolution, short-term, or inexpensive sensors that provide limited and fragmented data. This review, synthesizing global evidence, highlights the urgent need for equitable, reliable, and policy-driven monitoring systems worldwide.

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Review

Air pollution continues to be one of the most serious environmental threats to human health. According to World Health Organization (WHO) estimates, more than 90% of people worldwide breathe air that fails to meet WHO safety standards [1]. Air pollution monitoring is crucial to reduce the effects of pollution and falls under the Sustainable Development Goals (SDGs), namely SDG 3, SDG 11, and SDG 15 [2]. Accurate, frequent, and resolved measurements of air pollutants are necessary to make an estimate of human exposure, analyze the pollution trends, furnish data for mitigation schemes, and measure the effectiveness of environmental policy [3, 4].

Air quality monitoring stations constitute the foundation of ambient air monitoring systems in the majority of countries [5]. These stations are typically classified as urban, suburban, background, industrial, or traffic, depending upon the environment and the influence of the surrounding area [6] and are mounted in strategically selected places, which are used to continuously measure the concentrations of various pollutants in the ambient air [5].These stations are established to monitor continuously the levels of specific "criteria pollutants" regulated because they have significant health and environmental impacts. These stations are typically installed by governmental agencies for monitoring the principal pollutants such as Particulate Matter (PM_{10}, $PM_{2.5}$), Nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), Ozone (O_3) and Carbon monoxide (CO) [7].

Fixed air pollution stations monitor criteria pollutants using various monitoring techniques and methods. For example, the beta-attenuation technique is one of the general real-time techniques for measurements of ambient Particulate Matter (PM) [8, 9]. It entails the measurement of the attenuation of beta radiation while traveling through a particulate sample collected on a filter tape [9].

Fixed air pollution stations play a vital role in providing reliable, high-resolution data that form the core of air quality management systems [7, 10]. Their data enables successful environmental monitoring, policy formulation, and protection of public health, especially when combined with other monitoring and modeling approaches [10]. Their limited spatial resolution cannot replicate the environment in local variability of the levels of pollution, especially in the case of inhomogeneous towns [11]. High initial installation and maintenance expenses, fixed infrastructure needs, and a lack of flexibility for movement lower their utility [5]. Some equipment used in these stations, i.e., passive samplers, also cannot detect short-term spikes in pollution [11]. These constraints underscore the need to fill in fixed stations with low-cost sensors and mobile monitoring techniques to enhance spatial resolution as well as the overall efficiency of air quality monitoring [12].

The objective of this review is to present an equitable international overview of fixed air quality monitoring stations, focusing on spatial coverage, technological approach, guidelines utilized, and knowledge gaps to inform public health interventions as well as environmental policy.

Data sources, search strategies, and eligibility criteria

This systematic review was conducted by standard methodologies and in line with the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). We systematically searched three major databases—PubMed, Scopus, and the Web of Science Core Collection—from their inception through April 6, 2025و using a structured set of keywords (e.g.,“Air Quality Station” OR “Fixed station” OR “Air Quality Measurement Station” AND “Criteria air pollutant” OR “CAP” OR “Particulate matter” AND “Real time” OR “Continuous” OR “Surveillance”) centered on a conceptual framework focused on fixed air quality monitoring stations and criteria pollutants . To enhance the sensitivity of our review and capture potentially relevant studies, we also screened gray literature sources, including Google Scholar, and manually reviewed the reference lists of relevant systematic reviews. The conceptual framework also informed the development of inclusion and exclusion criteria.

Study selection and data extraction

After removing duplicates, titles and abstracts were screened, followed by full-text reviews, all independently conducted by two reviewers (E.N. and S.J.). Duplicates and irrelevant items were managed using EndNote software. Data extraction was also independently performed by two reviewers (M.H. and N.N.) using a pre-designed Excel worksheet. Any discrepancies during the screening or data extraction phases were resolved through consultation with two additional reviewers. The following information was extracted from the eligible studies: publication details (year, country, and region/city); study characteristics (geographical description of monitoring stations, number of stations per study area, classification of monitoring stations); pollutants measured at each station and the corresponding meteorological parameters; measurement techniques used at the stations; guidelines and standards applied in each region; and identified research gaps and challenges.

Fig. 1 shows the systematic review's study selection procedure. A total of 1454 Articles were collected from the systematic literature search, with 175 from PubMed, 535 from Scopus, 544 from Web of Science, and 200 from Google Scholar. After eliminating 761 duplicate entries, 693 Articles were reviewed, and an additional 650 Articles were excluded based on their titles and abstracts. 43 Articles were first reviewed, then 2 Articles after gray literature was added to the library for data extraction. After checking the full text of the Articles, finally, 17 Articles were finally selected for data extraction.

This review presents a comprehensive analysis of the global diversity in the structure, functionality, and regulatory frameworks of air quality monitoring stations. Drawing on data extracted from 17 peer-reviewed studies, the findings reflect a wide range of geographical, environmental, and socio-political contexts spanning both developed and developing nations.

Collectively, these studies offer valuable insights into how different regions approach air quality monitoring in terms of infrastructure, technological application, and policy alignment. Over 100 monitoring stations were documented across the selected sources, highlighting considerable variation in monitoring objectives, spatial distribution, technical configurations, and compliance with national or international standards. a general summary of the extracted data is presented in Table 1. The studies are assessed according to key comparative parameters, including station type and purpose, geographic distribution, target pollutants, measurement technologies, meteorological integration, siting characteristics, and referenced guidelines. The reviewed literature encompasses case studies from a diverse set of countries: Germany, Spain, China, Kenya, Ecuador, England, Pakistan, Canada, India, Malaysia, Italy, Belgium, Norway, Croatia, Lithuania, Bangladesh, Sri Lanka, Nepal, Vietnam, Ghana, and Nigeria—depicting a broad international scope in air quality monitoring research.

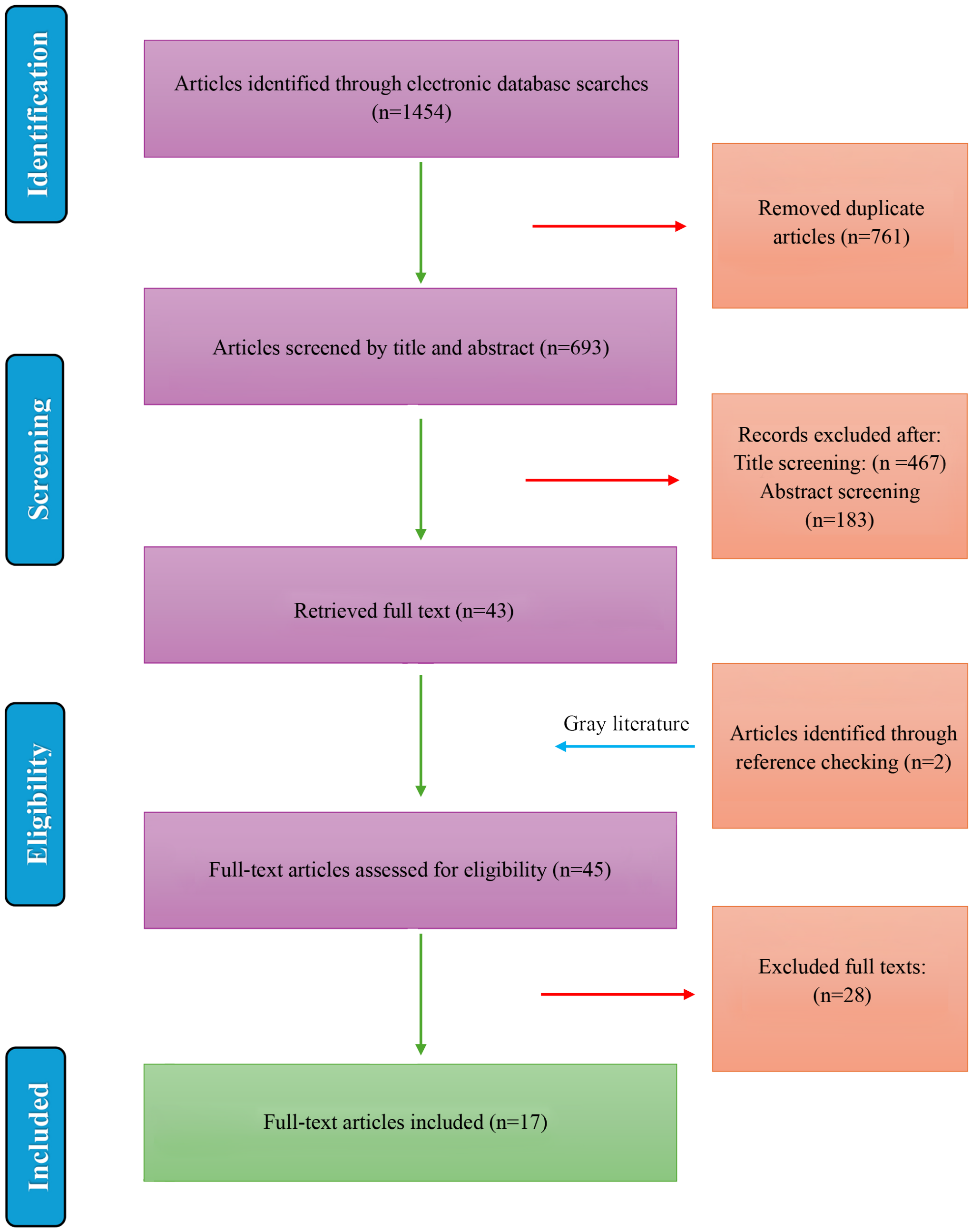

Fig. 1. PRISMA flow diagram of studies

Table1. Comparative summary of study parameters from reviewed literature

Article number	Reference	Country	Name of Province/City	All stations checked (Yes/No)	Type of monitoring station	Measured Pollutants	Elevation from the ground	Distance from road, industry, and...	Meteorological parameters
1	[13]	Germany	Stuttgart	YES	Total=6 1 Background 3 traffic 1Commercial 1 Hot spot	S*1: PM_{10}, $PM_{2.5}$, NO_2, NO and O_3 S2: PM_{10}, $PM_{2.5}$, NO_2, NO S3: PM_{10}, $PM_{2.5}$, NO_2, NO S4: NO_2, NO S5: NO_2, NO S6: PM10, $PM_{2.5}$, NO_2, NO and O_3	–	–	temperature, humidity, pressure, wind speed, solar radiation, and precipitation
2	[14]	Spain	Madrid	YES	Urban traffic Urban industrial Urban background Suburban background Rural background	SO_2, NO_x (NO and NO_2), CO, O_3, PM_{10}, $PM_{2.5}$, and C_6H_6	–	–	temperature, solar radiation, and wind speed
3	[15]	Spain	Madrid	YES	Urban Suburban Rural Traffic Industrial Background	PM_{10} were measured at all fixed stations except one (this paper just studied PMs on all stations)	–	–	–
4	[16]	Spain	The city of Valencia	NO	Only one of the seven stations was examined in this study: Street	NO_2, CO, NO, NO_x, O_3, PM_1, PM_{10}, $PM_{2.5}$	15m	Located in a parking lot adjacent to cropland and other	–

Table 1. Continued

Article number	Reference	Country	Name of Province/City	All stations checked (Yes/No)	Type of monitoring station	Measured Pollutants	Elevation from the ground	Distance from road, industry, and...	Meteorological parameters
5	[17]	China	Hong Kong	YES	Total=16 3 roadside stations and 13 ambient stations	CO, NO_2, NO_x, O_3, SO_2, and respirable and fine suspended particulates (RSP and FSP)	Roadside AQ stations: 3.0-4.5 m ambient AQ stations: 11.0- 28.0 m	–	–
6	[18]	Kenya	Nairobi	YES	Informal settlement, Industrial/ Informal settlement, Traffic (Highway), Suburban, Urban, background	NO, NO_2, SO_2, PM_1, $PM_{2.5}$ and PM_{10}	–	–	temperature and relative humidity
7	[19]	Ecuador	City of Cuenca	NO	Urban Traffic Station	O_3, CO, NO_2, SO_2, $PM_{2.5}$	–	Located near the main square of Cuenca, positioned close to traffic	Temperature, relative humidity, wind speed, barometric pressure, solar radiation, and precipitation

Table 1. Continued

Article number	Reference	Country	Name of Province/City	All stations checked (Yes/No)	Type of monitoring station	Measured Pollutants	Elevation from the ground	Distance from road, industry, and...	Meteorologic al parameters
8	[20]	England	Sheffield	YES	Total=9 3Urban BG 2Urban Industrial 2 Roadside 1 Urban Centre 1 Urban Traffic	S1: Urban BG NO_2, PM_{10} S2: Urban Industrial NO_2, PM_{10}, $PM_{2.5}$ S3: Roadside NO_2, PM_{10}, SO_2 S4: Urban BG NO_2, PM_{10}, O_3 S5: Urban BG NO_2, PM_{10}, O_3 S6: Roadside NO2, PM10 S7: Urban Industrial NO_2 S8: Urban Centre NO_2, O_3, PM_{10}, $PM_{2.5}$ S9: Urban Traffic NO, NO_2, NO_x	_	S1:10 S2:90 S3:10 S4:50 S5:100 S6:3 S7:120 S8:20 S9:3	_
9	[21]	Pakistan	Lahore	YES	One of them is a residential area as well as Small industrial area. Another is a general air quality monitoring station	$PM_{2.5}$, SO_2, CO, O_3, NO_x, NO_2, NO	One of them is (25 ft from ground level)	About 3 km away from One of these sites is an industrial center	Temperature, Windspeed, and Radiation

Table 1. Continued

Article number	Reference	Country	Name of Province/City	All stations checked (Yes/No)	Type of monitoring station	Measured Pollutants	Elevation from the ground	Distance from road, industry, and...	Meteorological parameters
10	[22]	India	Delhi	YES	Total=6 Residential: 3 Industrial: 2 Mixed use: 1	5 stations: SPM, PM_{10}, NO_2, SO_2 1 of stations: SPM, PM_{10}, CO, NO_2, SO_2	2 of them:5 m Others: 10 m	–	–
11	[23]	Malaysia	Klang Valley	NO	4 selected sites: residential and background	PM_{10}, NO_2, SO_2, CO, O_3	–	S1: at a Primary School S2: at a Primary School S3: at the Water Resource Department S4: at the Malaysian Meteorological Department	wind speed, temperature, and UV radiation and humidity

Table 1. Continued

Article number	Reference	Country	Name of Province/City	All stations checked (Yes/No)	Type of monitoring station	Measured Pollutants	Elevation from the ground	Distance from road, industry, and...	Meteorological parameters
12	[24]	Italy	Emilia-Romagna	YES	Total=46 36 traffic stations, 8 backgrounds 2 industrials	CO, NO, NO_2, O_3, PM_{10}, TSP, C_6H_6	–	–	–
13	[25]	China	Taiwan	YES	Total=76 56 generals 6 traffic 5 industrial 2 national-park 4 baseline 3 off-island	CO, NOx, SO_2, PM and O_3 half of the 76 AQS NMHC in half of the stations	–	–	–
14	[26]	China	74 key cities	NO	–	$PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and O_3	–	–	–

Table 1. Continued

Article number	Reference	Country	Name of Province/City	All stations checked (Yes/No)	Type of monitoring station	Measured Pollutants	Elevation from the ground	Distance from road, industry, and...	Meteorological parameters
15	[27]	China	Beijing, Changchun, Changsha, Chengdu, Fuzhou, Guangzhou, Guiyang, Haerbin, Haikou, Hangzhou, Hefei, Huhehaote, Jinan, Kunming, Lasa, Lanzhou, Nanchang, Nanjing, Nanning, Shanghai, Shenyang, Shijiazhuang, Taiyuan, Tianjin Wulumuqi,Wuhan , Xi'an, Xining, Yinchuan, Zhengzhou, Chongqing	NO	–	$PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and O_3	–	–	–
16	[28]	Canada	Hamilton, Ontario	NO	–	$PM_{2.5}$, NO_2, NO, NO_x, CO, SO_2, O_3	–	–	–

Table 1. Continued

Article number	Reference	Country	Name of Province/City	All stations checked (Yes/No)	Type of monitoring station	Measured Pollutants	Elevation from the ground	Distance from road, industry, and...	Meteorological parameters
17	[29]	Lithuania	Preila	NO	Background	SO_2 NO_2 $SO_4$2– +NO_3 NH_4 SUM (NH_4++ NH_3) (HNO_3 + NO_3)	2	2.3 km from the town of Preila, 8 km from Nida, 40 km from the industrial port of Klaipeda, 90 km from Kaliningrad, and 12 km from the mainland of Lithuania	temperature, relative humidity, precipitation, solar radiation, and wind direction

Geographial overview of air quality monitoring networks

The gegraphical distribution of fixed air pollution monitoring stations is characterized by a sparse and uneven spatial arrangement, often limited by high installation and maintenance costs. These stations are typically concentrated in urban areas, especially in city centers and regions with significant industrial or traffic-related pollution sources, to monitor key pollutants such as NO_2, particulate matter (PM_{10}, $PM_{2.5}$), SO_2, CO_2, and O_3 [30, 31]. Globally, the placement of fixed monitoring stations often follows regulatory guidelines to ensure representative coverage, especially in urban areas where pollution sources and population exposure are concentrated. However, many regions still face challenges with sparse rural coverage, which can affect the accuracy of regional and national air quality assessments [32].

A total of 19 articles were reviewed in this study. Among these, 41.2% focused on European countries, including studies from Spain (3), Germany (1), England (1), Lithuania (1), and Italy (1). 35.3% of the studies addressed Asian countries, specifically China (4) and Pakistan (1). The Americas were represented by 11.8% of the studies, with one study each from Canada and Ecuador. Finally, 5.9% of the research was conducted in Africa, represented by a single study from Kenya.

The global distribution of air quality monitoring studies reviewed in this paper is visually represented in Fig. 2. This map displays the number of original research articles associated with each country, based on the 17 studies included in the final analysis. The visualization highlights the geographical concentration of research efforts in regions such as East Asia and Western Europe, while also revealing underrepresented areas, particularly across parts of Africa and South America. The scarcity of studies from Africa and South America limits insights into monitoring challenges in these regions; future reviews should prioritize literature from these continents. This spatial representation provides context for understanding the global research landscape in air quality monitoring.

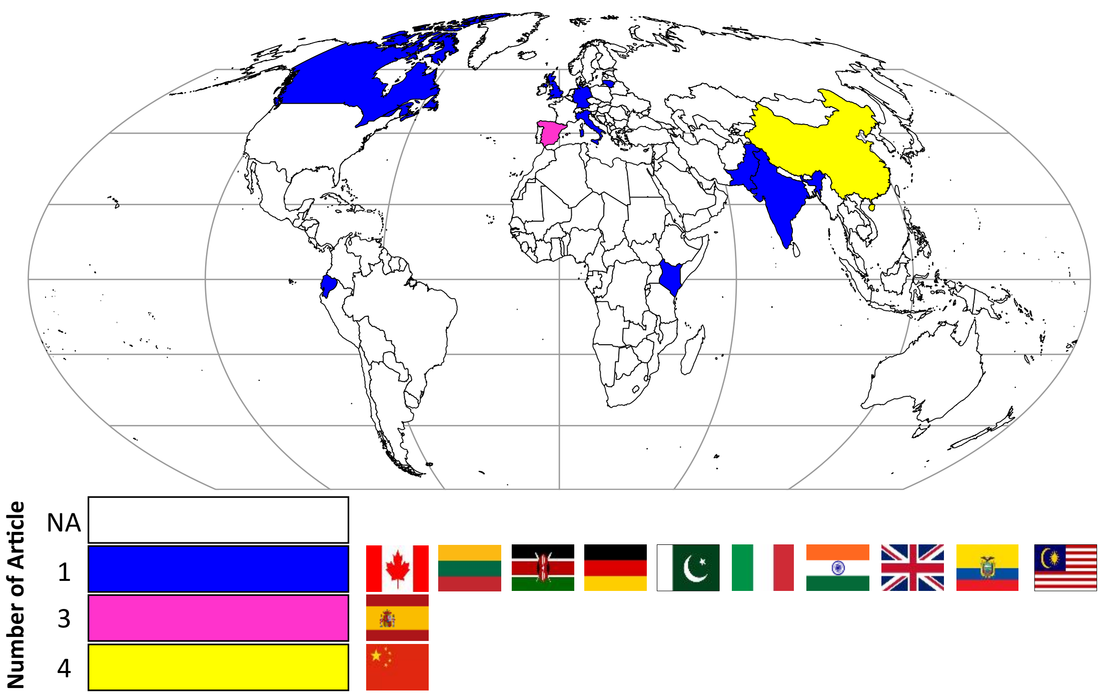

Fig. 2. Global distribution of air quality monitoring studies

The number of fixed air pollution monitoring stations varied significantly across the countries and cities examined in this review, while some nations, such as China and Spain, reported extensive fixed station networks, others, including Ecuador and Kenya, documented only a single monitoring site. This variation reflects differences in national air quality management strategies, availability of financial and technical resources, and the extent of urbanization. Table 2 summarizes the number of fixed air quality monitoring stations reported for each country and, where applicable, for specific cities. These figures provide insight into the scale and coverage of monitoring infrastructures within different geographical and political contexts.

Table 2. Number of fixed air quality monitoring stations

No.	Country	Name of Province/City	Number of fixed stations	Study ID	No.	Country	Name of Province/City	Number of fixed stations	Study ID
1	Germany	Stuttgart	6	Samad et al, 2023 [13]	27	China	Hefei	10	[27]
2	Spain	Madrid	23	Galán-Madruga et al [14]	28	China	Huhehaote	8	[27]
3	Spain	The city of Valencia	7	Lorenzo-Sáez et al, 2021 [16]	29	China	Jinan	8	[27]
4	Spain	Madrid	23	Galán-Madruga, 2021 [15]	30	China	Kunming	7	[27]
5	India	Delhi	6	Sharma et al, 2013 [22]	31	China	Lasa	6	[27]
6	Lithuania	Preila	3	Davuliene et al, 2020 [29]	32	China	Lanzhou	5	[27]
7	India	_	836	Gulia et al, 2019 [33]	33	China	Nanchang	9	[27]
8	Bangladesh	_	11	Gulia et al, 2019 [33]	34	China	Nanjing	9	[27]
9	Srilanka	_	78	Gulia et al, 2019 [33]	35	China	Nanning	8	[27]
10	Nepal	_	12	Gulia et al, 2019 [33]	36	China	Shanghai	11	[27]
11	Bhutan	_	3	Gulia et al, 2019 [33]	37	China	Shenyang	12	[27]
12	Vietnam	_	29	Gulia et al, 2019 [33]	38	China	Shijiazhuang	8	[27]
13	Ghana	_	5	Gulia et al, 2019 [33]	39	China	Tianjin	15	[27]
14	Nigeria	_	5	Gulia et al, 2019 [33]	40	China	Wulumuqi	7	[27]
15	Kenya	Nairobi	6	Gulia et al, 2019 [33]	41	China	Wuhan	10	[27]
16	Pakistan	_	70	Gulia et al, 2019 [33]	42	China	Xi'an	13	[27]
17	Pakistan	Lahore	2	Tabinda et al, 2016 [21]	43	China	Xining	4	[27]
18	Canada	The City of Hamilton	18	Adams and Kanaroglou, 2016 [28]	44	China	Yinchuan	6	[27]
19	England	Sheffield	9	Said Muniret et al 2019 [20]	45	China	Zhenzhou	9	[27]

Table 2. Continued

No.	Country	Name of Province/City	Number of fixed stations	Study ID	No.	Country	Name of Province/City	Number of fixed stations	Study ID
20	Italy	Emilia-Romagna	46	Sajani et al,2004 [24]	46	China	Chongqing	17	[27]
21	China	Hong Kong	16	Huang et al, 2020[17]	47	China	Changsha	10	[27]
22	China	Taiwan	76	Chen et al, 2014 [25]	48	China	Chengdu	9	[27]
23	China	Fuzhou	6	Zhao et al, 2016 [27]	49	China	Beijing	13	[27]
24	China	Guangzhou	12	Zhao et al, 2016 [27]	50	China	Changchun	10	[27]
25	China	Guiyang	10	Zhao et al, 2016 [27]	51	China	Haikou	5	[27]
26	China	Haerbin	12	Zhao et al, 2016 [27]	52	China	Hangzhou	11	[27]

Classification and typology of monitoring stations

Fixed air quality monitoring stations are typically categorized into three main types: roadside (traffic-oriented) stations, which are placed near major roads to measure pollution primarily from vehicles; urban stations, located within city centers or densely populated areas to assess the combined effects of traffic, industry, and residential sources on air quality; and background (rural or suburban) stations, situated away from direct pollution sources to provide baseline data on regional air quality and long-range pollutant transport [34]. In the reviewed articles, the classification of station types includes more detailed items such as Suburban, Urban Traffic, Urban Industrial, Residential, Mixed use, Informal settlement, and so on, which are presented in Table 1. Regulatory agencies use these classifications to design monitoring networks that capture both pollution hotspots and broader regional trends [35].

As it is shown in Table 1, siting strategies varied across countries, with some stations placed in central urban areas (e.g., Cuenca, Ecuador), while others were deployed along major transportation corridors (e.g., Madrid and Hong Kong). The siting decisions were often influenced by national regulations, distribution, and the specific pollutants targeted for monitoring. In many cases, details on site selection criteria were not explicitly stated, indicating a need for greater transparency in reporting.

In several cases, the studies provided specific information about the placement of stations. For instance, in Cuenca, Ecuador, the fixed monitoring station was installed near the city's main square and close to traffic routes, functioning as an urban traffic station. In Madrid, Spain, a total of 23 fixed stations were identified, distributed across traffic, industrial, and background environments. Similarly, Stuttgart, Germany, employed a mixed network of stations, including roadside, background, commercial, and hot spot types.

Some stations were installed adjacent to high-traffic areas or close to industrial zones, while others were located in relatively clean or residential regions to capture background pollutant levels.

Fixed air pollution measurement stations generally measure pollutants at a height of 1.5 to 4 mabove ground, targeting the zone most relevant to human exposure and regulatory standards [36] , Studies often measure pollutants at varying heights to understand how pollution concentrations change vertically. For instance, urban or highway studies might measure from ground level up to 5 m or higher, especially when examining near-surface pollution dispersion and accumulation [37] and according to our review, elevation above ground level also varied, with inlets typically positioned between 3 to 15 m, depending on the station's objective and the surrounding built environment.

Measured pollutants and meteorological parameters

Fixed air quality monitoring stations commonly measure a core set of pollutants that are crucial for assessing air quality and public health risks. The primary pollutants monitored include Particulate Matter ($PM_{2.5}$ and PM_{10}), Nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), Ozone (O_3), and Carbon monoxide (CO) [38]. Roadside or traffic-oriented stations typically emphasize pollutants from vehicle emissions, such as NO_2, CO, and particulate matter. Urban stations monitor a broader mix, including O_3, SO_2, and particulate matter, reflecting the combined impact of traffic, industry, and residential sources. Background or rural stations focus on regional or baseline levels of pollutants like O_3 and particulate matter, capturing long-range transport and natural background concentrations [39]. In addition to these, stations, especially those near industrial complexes-may also monitor hazardous Volatile Organic Compounds (VOCs) such as benzene, xylene, formaldehyde, and others, as well as Polycyclic Aromatic Hydrocarbons (PAHs) [38].

As shown in Fig. 3, the distribution illustrates the proportion of articles measuring each pollutant. Among the reviewed studies, Nitrogen dioxide (NO_2) emerged as the most frequently measured pollutant, appearing in 88.2% of the studies, underscoring its critical role as an indicator of traffic-related emissions and urban air pollution. Particulate matter ($PM_{2.5}$ and PM_{10}) and Ozone (O_3) were also prominently monitored, with 64.7% of studies including $PM_{2.5}$, and 70.6% of studies measuring PM_{10} and O_3, respectively. These pollutants reflect ongoing concerns about airborne particles and photochemical smog. Notably, Carbon monoxide (CO) and Sulfur dioxide (SO_2) were each measured in 70.6% of the articles, indicating a renewed or sustained focus on these gases, possibly due to their persistent health impacts or relevance in specific industrial or urban contexts.

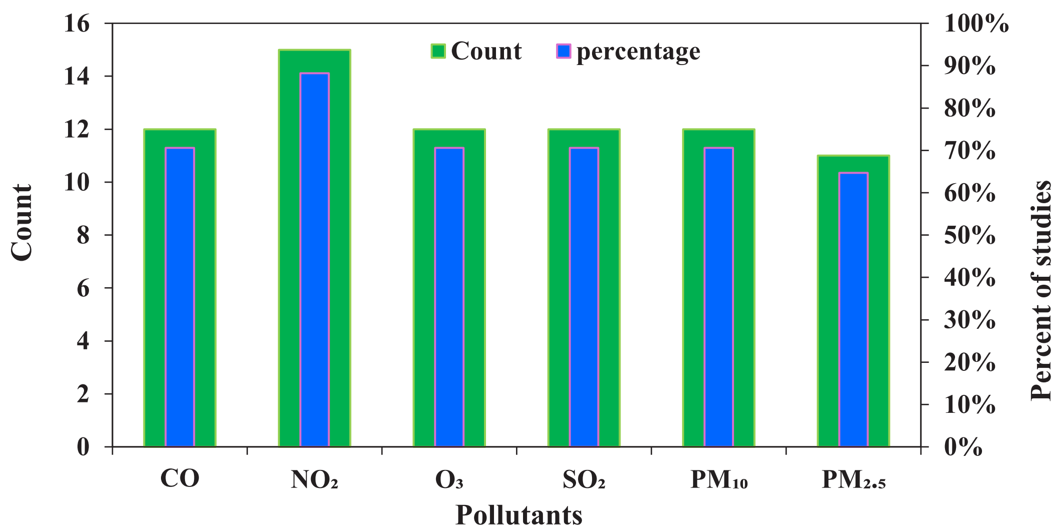

Fig. 3. Contribution of Different Pollutants in the Reviewed Studies

In addition to pollutant concentrations, fixed stations also record key meteorological parameters that influence air quality. These typically include temperature, relative humidity, wind speed and direction, atmospheric pressure, and sometimes solar radiation or precipitation. Monitoring these meteorological factors is essential, as they directly affect the dispersion, transformation, and accumulation of air pollutants, and are crucial inputs for air quality forecasting and modeling [40].

The parameters measured at the stations studied include temperature, humidity, pressure, wind speed, solar radiation, precipitation, relative humidity, barometric pressure, wind direction, and radiation. The integration of meteorological data with pollutant monitoring supports more accurate interpretation of air quality dynamics, improves pollution modeling, and assists in the identification of major emission sources. However, inconsistencies in meteorological reporting across the studies suggest a need for more standardized data collection and presentation in future monitoring efforts.

Measurement technologies by pollutant

Fixed monitoring stations are the backbone of air quality assessment in cities and regions. These stations employ a range of methodologies to quantify various air pollutants, depending on monitoring objectives, pollutant types, and available resources. The main categories of measurement technologies include:

Reference-Grade Instruments: Regulatory agencies like the Environmental Protection Agency (EPA) use high-precision monitors at fixed sites. These instruments are considered the gold standard for measuring air pollutants due to their accuracy and reliability, though they are costly and thus limited in number [41].Sampling and Laboratory Analysis: Traditional approaches involve collecting air samples at fixed intervals and analyzing them in laboratories. This method is highly accurate, but can be resource-intensive and slow [42].

=Continuous Automatic Monitoring: Many fixed stations are equipped with automated analyzers that provide real-time data on pollutant levels. These devices use techniques such as: Optical Sensors: For particulate matter, optical sensors can count and size airborne particles, providing continuous $PM_{2.5}$ and PM_{10} measurements [43]. Budapest and Ostrava studies show low-cost optical PM sensors accurately reflect reference methods, even without calibration [44]. Gas Analyzers: Pollutants like NO_2, SO_2, CO, and O_3 are measured using chemiluminescence, UV fluorescence, or infrared absorption methods, depending on the specific gas [45]. Low-Cost Sensors (LCS): Recently, networks of low-cost sensors have been deployed alongside reference stations to increase spatial coverage. While these sensors offer broader monitoring at a lower cost, they require frequent calibration to ensure accuracy and are more susceptible to environmental interferences [46]. Advanced Techniques: Emerging methods include the use of machine learning for pollutant identification and forecasting, as well as innovative optical technologies like hollow-core photonic crystal fibers for in situ particle analysis [43].

The reviewed studies employed a wide range of measurement technologies for air quality monitoring, with approaches differing based on pollutant type, monitoring objectives, and available resources. This section presents a pollutant-specific breakdown of the technologies used, the frequency of data collection, and the regulatory guidelines referenced across countries. For each key pollutant—including O_3, NO_x, SO_2, CO, and particulate matter ($PM_{2.5}$ / PM_{10})— the details are provided in the ‹Table 3, summarizing the reviewed studies in terms of:

Table 3. Techniques for measuring air pollutants at fixed stations

Pollutant	Measurement Technique	Reference
O_3	UV absorption – T-API 400/400A/T400	Huang et al, 2020 [17]
	UV photometry – Teledyne M400E	Astudillo et al, 2020 [19]
	UV absorption	Said Muniret al 2019 [20]
	UV absorption – HORIBA APOA-370	Tabinda et al, 2016 [21]
	Ultraviolet photometry (Antwerp), UV photometry (Oslo), NDUV (Zagreb)	poppel et al, 2023 [47]
	(from 1994 to 2004)Thermo 49 / (from 2004 to present)Ecotech 9810B	Chen et al, 2014 [25]
NO_x	Chemiluminescence	Lorenzo-Sáez et al, 2021 [16]
	Chemiluminescence – -API 200A/T200	Huang et al, 2020 [17]
	Chemiluminescence	Said Muniret al 2019 [20]
	Chemiluminescence –HORIBA APNA-370	Tabinda et al, 2016 [21]
	Chemiluminescence (Antwerp, Oslo, Zagreb)	poppel et al, 2023 [47]
	Spectrophotometry (NO_2 sampler extracts)	Davuliene et al, 2020 [29]
	Thermo 42 / Ecotech 9841B	Chen et al, 2014 [25]
	Electrochemical sensors – Alphasense	Nthusi , 2017 [18]
SO_2	UV fluorescence	Said Muniret al 2019 [20]
	UV fluorescence – HORIBA APSA-370	Tabinda et al, 2016 [21]
	Manual – IS 5182 Part 2 (RDS APM 460)	Sharma et al, 2013 [22]
	Ion Chromatography (IC)	Davuliene et al, 2020 [29]
	Electrochemical sensor – Alphasense	Nthusi , 2017 [18]
CO_2	IR spectroscopy	Huang et al, 2020 [17]
	NDIR – Teledyne M300E	Astudillo et al, 2020 [19]
	NDIR – HORIBA APMA-370	Tabinda et al, 2016 [21]
	NDIR – Antwerp, Oslo, Zagreb	poppel et al, 2023 [47]
	Thermo 48 / Horiba APMA-360	Chen et al, 2014 [25]

Table 3. Contniued

Pollutant		Measurement Technique	Reference
PM	PM_{10} $PM_{2.5}$	TEOM	Said Muniret al 2019 [20]
	$PM_{2.5}$	β-ray attenuation – HORIBA APDA-371	Tabinda et al, 2016 [21]
	PM_{10}	Manual – IS 5182 Part 23 (RDS APM 460)	Sharma et al, 2013 [22]
	PM_{10} $PM_{2.5}$ PM_1	Optical counter (Antwerp), Oscillating microbalance & Light scattering (Oslo), Gravimetry (Zagreb)	poppel et al, 2023 [47]
	PM_1 $PM_{2.5}$ PM_{10}	Laser OPC – Alphasense OPC-N2	Nthusi , 2017 [18]

The comparative analysis of measurement techniques used in fixed air quality monitoring stations reveals significant variability in both technological sophistication and methodological transparency. While some monitoring networks are equipped with high-precision instruments such as UV photometers, chemiluminescence analyzers, TEOM systems, and NDIR-based devices, others rely on manual methods, low-cost sensors, or national standard procedures whose details are not always consistently reported. This inconsistency in instrumentation, and particularly in how methods are documented, limits the ability to compare data across regions and time. Moreover, the lack of harmonized terminology and incomplete reporting of calibration protocols, detection limits, and operating principles weakens the scientific reliability and regulatory utility of the gathered data. These findings highlight the critical importance of improving both technical standardization and methodological clarity in published research involving fixed monitoring stations.

Guidelines and quality assurance protocols

Ambient air quality standards are regulatory limits set on the concentration of specific pollutants in outdoor air to protect public health and the environment. These standards are critical tools for controlling air pollution and guiding policy and regulatory action [48].

International air quality guidelines and national standards demonstrate significant variability, with the World Health Organization (WHO) Air Quality Guidelines (AQGs) serving as the primary global reference, though many countries implement less stringent limits due to economic or technical constraints [49]. Most nations have established National Ambient Air Quality Standards (NAAQS) that often diverge substantially from WHO recommendations - for instance, $PM_{2.5}$ limits in the Eastern Mediterranean Region may exceed WHO AQGs by up to 10-fold due to local policy considerations [50], while the U.S. Clean Air Act's NAAQS employs a dynamic system of periodic revisions informed by emerging health evidence and technological capabilities [51].

International guidelines

World Health Organization (WHO) Air Quality Guidelines (AQGs):

These guidelines are widely used as a reference for setting national standards, though many countries adopt less stringent limits due to local economic or technical considerations.

National ambient air quality standards (NAAQS)

Most countries have established their own NAAQS, which may differ significantly from WHO recommendations. For example, in the Eastern Mediterranean Region, $PM_{2.5}$ standards can be up to 10 times higher than WHO AQGs, reflecting local policy and capacity [48]. In the United States, the Clean Air Act's NAAQS sets limits for these pollutants, with periodic reviews and updates based on new health data and technological feasibility.

In summary, while international guidelines provide a science-backed benchmark, national policies frequently prioritize feasibility over optimal health outcomes. Bridging this gap requires stronger legal frameworks, better monitoring, and political commitment to treat air pollution as a public health emergency.

Table 4. Air Quality Guidelines or Standards

Study No.	Country	City/Region	Referenced Air Quality Guidelines or Standards
1	Germany	Stuttgart	Not explicitly mentioned
2	Spain	Madrid	Spanish national air quality standards, WHO AQG
3	Spain	Madrid	WHO AQG
4	Spain	Valencia	Not explicitly mentioned
5	China	Hong Kong	China National Ambient Air Quality Standards (CNAAQS)
6	Kenya	Nairobi	WHO AQG referred to
7	Ecuador	Cuenca	Not explicitly stated
8	England	Sheffield	UK Air Quality Standards (based on EU directives)
9	Pakistan	Lahore	Pakistan National Environmental Quality Standards
10	India	Delhi	Indian National Ambient Air Quality Standards (NAAQS)
11	Malaysia	Klang Valley	Malaysian Ambient Air Quality Standard (MAAQS)
12	Italy	Emilia-Romagna	European Union Air Quality Directives
13	China	Taiwan	Taiwan EPA Guidelines
14	China	National (74 cities)	CNAAQS
15	China	Multiple cities	CNAAQS
16	Canada	Hamilton, Ontario	Canadian Ambient Air Quality Standards (CAAQS)
17	Lithuania	Preila	EU Air Quality Directives, WHO AQG

The air quality guidelines or standards referenced in the reviewed studies are summarized in Table 4, which presents for each study the country and city or region where monitoring took place, along with the specific regulatory framework mentioned—whether NAAQS, regional directives (e.g., EU standards), or international benchmarks such as the WHO Air Quality Guidelines. As shown, some countries strictly align with international recommendations, while others follow localized standards that reflect regional capacities, legal frameworks, or technical constraints. Several studies did not explicitly mention the use of any specific guideline.

Challenges and research limitations

Many countries continue to face major obstacles in operationalizing their air quality standards. A significant portion of low- and middle-income countries lack the basic infrastructure, such as air monitoring stations or technical expertise, to systematically measure air pollutants.

In several regions, especially across Asia and parts of Africa, there are large population segments without access to any local monitoring data. In many instances, reference-grade air quality monitoring devices are both costly and technically sophisticated. For example, in most South and Southeast Asian countries, traditional monitoring equipment is still predominantly used, which requires considerable financial investment [52]. This contributes to a widening implementation gap between policy and practice.

Air quality monitoring stations face various technical limitations. Reference-grade instruments are typically large, expensive, and require a stable power supply and regular maintenance. On the other hand, newer low-cost sensors lack reliability without proper calibration. Research shows that laboratory calibration alone is insufficient for low-cost sensors; instead, calibration must be performed alongside reference instruments and under standardized quality control protocols [53]. In addition, weak regulatory standards and the lack of legal obligations to ensure accurate data from monitoring networks have placed the burden on governments to meet air quality targets, further adding to the complexity of implementation.

The lack of reliable data is a major obstacle to decision-making. Many regions lack continuous and dense measurements: in Africa, there is, on average, only one monitoring station for every 4.5 million people, and hundreds of cities in developing countries have no monitoring data at all [53]. In addition, there is a lack of sufficient pollutant emission data and computational models; for example, only a few Asian countries have started to inventory pollutants or model air quality. Even in pollution reduction plans and projects, scientific evidence based on local data is often lacking [52].

Conclusion

This systematic review of 17 global studies reveals substantial heterogeneity in fixed air quality monitoring systems, with pronounced disparities between developed and developing nations. The analysis of over 100 monitoring stations across five continents demonstrates significant variations in: (1) station typologies (urban background, industrial, roadside, hotspot); (2) monitoring technologies ranging from reference-grade TEOM analyzers to emerging low-cost optical sensors; and (3) measured pollutants ($PM_{2.5}$, PM_{10}, NO_x, O_3, SO_2, CO). While high-income countries maintain comprehensive networks with open data policies, resource-limited regions - particularly Sub-Saharan Africa and South Asia - exhibit critical deficiencies in monitoring infrastructure, data quality, and accessibility, often relying on non-standardized short-term campaigns or external sensor deployments. Three fundamental challenges emerge: (i) inadequate spatial coverage due to financial constraints, (ii) technical barriers to maintaining precision instrumentation, and (iii) lack of harmonized protocols for calibration, siting, and data validation. To address these systemic issues, we propose a five-point framework: (a) strategic expansion of monitoring networks in underserved areas through international cooperation; (b) development of standardized global protocols aligned with WHO guidelines; (c) capacity building for local operation and maintenance; (d) quality-assured integration of low-cost sensor networks; and (e) establishment of open-data platforms to enhance transparency and policy relevance. Implementation of this integrated approach would significantly advance global air quality monitoring capabilities, particularly in developing regions, enabling evidence-based policymaking and equitable public health protection worldwide.

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Competing interests

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Ethical considerations

Ethical issues (including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the authors.

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