e-ISSN:2582-7219

INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH IN SCIENCE, ENGINEERING AND TECHNOLOGY

Volume 7, Issue 2, February 2024

INTERNATIONAL STANDARD SERIAL NUMBER INDIA

Impact Factor: 7.521

6381 907 438 6381 907 438 ijmrset@gmail.com www.ijmrset.com

| ISSN: 2582-7219 | www.ijmrset.com | Impact Factor: 7.521| Monthly Peer Reviewed & Referred Journal |

| Volume 7, Issue 2, February 2024 |

| DOI:10.15680/IJMRSET.2024.0702003 |

Air Quality Monitoring and Pollution Control Technologies

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ABSTRACT: Air pollution monitoring is the process of collecting and measuring the components of air pollution, notably gases and particulates. The earliest devices used to measure pollution include rain gauges (in studies of acid rain), Ringelmann charts for measuring smoke, and simple soot and dust collectors known as deposit gauges.[1] Modern air pollution measurement is largely automated and carried out using many different devices and techniques. These range from simple absorbent test tubes known as diffusion tubes through to highly sophisticated chemical and physical sensors that give almost real-time pollution measurements, which are used to generate air quality indexes.

KEYWORDS-air quality, monitoring, pollution, control, indexes

I. INTRODUCTION

Air pollution is caused by many things. In urban environments, it can contain many components, notably solid and liquid particulates (such as soot from engines and fly ash escaping from incinerators), and numerous different gases (most commonly sulphur dioxide, nitrogen oxides, and carbon monoxide, all related to fuel combustion). These different forms of pollution have different effects on people's health, on the natural world (water, soil, crops, trees, and other vegetation), and on the built environment.[2] Measuring air pollution is the first step in identifying its causes and then reducing or regulating them to keep the quality of the air inside legal limits (mandated by regulators such as the Environmental Protection Agency in the United States) or advisory guidelines suggested by bodies such as the World Health Organization (WHO).[3] According to the WHO, over 6000 cities in 117 countries now routinely monitor the quality of their air.[4]

Types of measurement

Air pollution is (broadly) measured in two different ways, passively or actively.[5]

Passive measurement

Passive devices are relatively simple and low-cost.[6] They work by soaking up or otherwise passively collecting a sample of the ambient air, which then has to be analyzed in a laboratory. One of the most common forms of passive measurement is the diffusion tube, which looks similar to a laboratory test tube and is fastened to something like a lamp post to absorb one or more specific pollutant gases of interest. After a period of time, the tube is taken down and sent to a laboratory for analysis. Deposit gauges, one of the oldest forms of pollution measurement, are another type of passive device.[7] They are large funnels that collect soot or other particulates and drain them into sampling bottles, which, again have to be analyzed in a laboratory.[7]

Active measurement

Active measurement devices are automated or semi-automated and tend to be more complex and sophisticated than passive devices, though they are not always more sensitive or reliable.[6] They use fans to suck in the air, filter it, and either analyze it automatically there and then or collect and store it for later analysis in a laboratory. Active sensors use either physical or chemical methods.[8] Physical methods measure an air sample without changing it, for example, by seeing how much of a certain wavelength of light it absorbs. Chemical methods change the sample in some way, through a chemical reaction, and measure that. Most automated air-quality sensors are examples of active measurement.[5]

Air quality sensors

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Air quality sensors range from small handheld devices to large-scale static monitoring stations in urban areas, and remote monitoring devices used on aeroplanes and space satellites.

Personal air quality sensors

At one end of the scale, there are small, inexpensive portable (and sometimes wearable), Internet-connected air pollution sensors, such as the Air Quality Egg and PurpleAir.[9] These constantly sample particulates and gases and produce moderately accurate, almost real-time measurements that can be analyzed by smartphone apps.[10] Their data can also be used in a crowdsourced way, either alone or with other pollution data, to build up maps of pollution over wide areas.[11][12] They can be used for both indoor and outdoor environments and the majority focus on measuring five common forms of air pollution: ozone, particulate matter, carbon monoxide, sulfur dioxide, and nitrogen dioxide.[13] Some measure less common pollutants such as radon gas and formaldehyde.[14]

Sensors like this were once expensive, but the 2010s saw a trend towards cheaper portable devices that can be worn by individuals to monitor their local air quality levels, which are now sometimes informally referred to as low-cost sensors (LCS).[9][15] A recent review by the European Commission's Joint Research Center identified 112 examples, made by 77 different manufacturers.[16]

Personal sensors can empower individuals and communities to better understand their exposure environments and risks from air pollution.[17] For example, a research group led by William Griswold at UCSD handed out portable air pollution sensors to 16 commuters, and found "urban valleys" where buildings trapped pollution. The group also found that passengers in buses have higher exposures than those in cars.[18]

Small-scale static pollution monitoring
An EkoSłupek air pollution sensor in Poland. The green light indicates good nearby air quality.

Unlike low-cost monitors, which are carried from place to place, static monitors continuously sample and measure the air quality in a particular, urban location. Public places such as busy railroad stations sometimes have active air quality monitors permanently fixed alongside platforms to measure levels of nitrogen dioxide and other pollutants.[19] Some static monitors are designed to give immediate feedback on local air quality. In Poland, EkoSłupek air monitors measure a range of pollutant gases and particulates and have small lamps on top that change colour from red to green to signal how healthy the air is nearby.[20]

Large-scale pollution monitoring

At the opposite end of the spectrum from low-cost sensors are the large, very expensive, static street-side monitoring stations that constantly sample the various different pollutants commonly found in urban air for local authorities and that make up metropolitan monitoring systems such as the London Air Quality Network[21] and a wider British network called the Automatic Urban and Rural Network (AURN).[22] In the United States, the EPA maintains a repository of air quality data through the Air Quality System (AQS), where it stores data from over 10,000 monitors.[23] The European Environment Agency collects its air quality data from 3,500 monitoring stations across the continent.[24]

The measurements made by sensors like these, which are much more accurate, are also near real-time and are used to generate air quality indexes (AQIs). Between the two extremes of large-scale static and small-scale wearable sensors are medium-sized, portable monitors (sometimes mounted in large wheelable cases) and even built into "smog-mobile" sampling trucks.[25]

Recently, drive-by air pollution sensing systems have emerged as a promising approach for air quality monitoring, utilizing sensors mounted on taxis, buses, trams, and other vehicles.[26] In particular, buses have garnered considerable attention as a mobile sensing platform due to their widespread availability and extensive geographical coverage.[27]

Remote monitoring

Air quality can also be measured remotely, from the air, by lidar,[28] drones,[29] and satellites, through methods such as gas filter correlation.[30] Among the earliest satellite pollution monitoring efforts were GOME (Global Ozone Monitoring Experiment), which measured global (tropospheric) ozone levels from the ESA European Remote Sensing Satellite (ERS-2) in 1995,[31] and NASA's MAPS (Mapping Pollution with Satellites), which measured the distribution of carbon monoxide in Earth's lower atmosphere, also in the 1990s.[32]

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Methods of monitoring for different pollutants

Each different component of air pollution has to be measured by a different process, piece of equipment, or chemical reaction. Analytical chemistry techniques used for measuring pollution include gas chromatography; various forms of spectrometry, spectroscopy, and spectrophotometry; and flame photometry.[1,2,3]

Particulates

Until the late 20th century, the amount of soot produced by something like a smokestack was often measured visually, and relatively crudely, by holding up cards with lines ruled onto them to indicate different shades of grey. These were known as Ringelmann charts, after their inventor, Max Ringelmann, and measured smoke on a six-point scale.[33]

In modern pollution monitoring stations, coarse (PM_{10}) and fine ($PM_{2.5}$) particulates are measured using a device called a tapered element oscillating microbalance (TEOM), based on a glass tube that vibrates more or less as collected particles accumulate on it. Particulates can also be measured using other kinds of particulate matter sampler, including optical photodetectors, which measure the light reflected from samples of light (bigger particles reflect more light) and gravimetric analysis (collected on filters and weighed).[34] Black carbon is usually measured optically with Aethalometer-type instruments.[35]

Ultrafine particles (smaller than $PM_{0.1}$, so generally less than 100 nanometers in diameter) are hard to detect and measure with some of these techniques. Typically, they are measured (or counted) with condensation particle counters, which effectively enlarge the particles by condensing vapors onto them to make bigger and much more easily detectable droplets.[36][37]

The atomic composition of particulate samples can be measured with techniques such as X-ray spectrometry.[38]

Nitrogen dioxide

Nitrogen dioxide (NO_2) can be measured passively with diffusion tubes, though it takes time to collect samples, analyze them, and produce results.[39][40] It can be measured manually or automatically through the Griess-Saltzman method, as specified in ISO 6768:1998,[41][42] or the Jacobs-Hocheiser method.[43]

It can also be measured automatically much more quickly, by a chemiluminescence analyzer, which determines nitrogen oxide levels from the light they give off. In the UK, for example, there are over 200 sites where NO_2 is continuously monitored by chemiluminescence.[44]

Sulphur dioxide and hydrogen sulphide

Sulphur dioxide (SO_2) is measured by fluorescence spectroscopy. This involves firing ultraviolet light at a sample of the air and measuring the fluorescence produced.[45] Absorption spectrophotometers are also used for measuring SO_2. Flame photometric analyzers are used for measuring other sulphur compounds in the air.[46]

Carbon monoxide and carbon dioxide[4,5,6]

Carbon monoxide (CO) and carbon dioxide (CO_2) are measured by non-dispersive infrared (NDIR) light absorption based on the Beer-Lambert law.[47] CO can also be measured using electrochemical gel sensors and metal-oxide semiconductor (MOS) detectors.[48]

Ozone

Ozone (O_3) is measured by seeing how much light a sample of ambient air absorbs.[49] Higher concentrations of ozone absorb more light according to the Beer-Lambert law.

Volatile organic compounds (VOCs)

These are measured using gas chromatography and flame ionization (GC-FID).[50]

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Hydrocarbons

Hydrocarbons can be measured by gas chromatography and flame ionization detectors.[51][52] They are sometimes expressed as separate measurements of methane (CH_4), NMHC (non-methane hydrocarbons), and THC (total hydrocarbon) emissions (where THC is the sum of CH_4 and NMHC emissions).[51]

Ammonia

Ammonia (NH_3) can be measured by various methods including chemiluminescence.[53]

II. DISCUSSION

Air pollution can also be assessed more qualitatively by observing the effect of polluted air on growing plants such as lichens and mosses (an example of biomonitoring).[54][55][56] Some scientific projects have used specially grown plants such as strawberries.[57]

Measurement units

The amount of pollutant present in air is usually expressed as a concentration, measured in either parts-per notation (usually parts per billion, ppb, or parts per million, ppm, also known as the volume mixing ratio), or micrograms per cubic meter (µg/m³). It's relatively simple to convert one of these units into the other, taking account the different molecular weights of different gases and their temperatures and pressures.[58]

These units express the concentration of air pollution in terms of the mass or volume of the pollutant, and they are commonly used for measurements of both gaseous pollutants, such as nitrogen dioxide, and coarse (PM_{10}) and fine ($PM_{2.5}$) particulates. An alternative measurement for particulates, particle number, expresses the concentration in terms of the number of particles per volume of air instead, which can be a more meaningful way of assessing the health harms of highly toxic ultrafine particles ($PM_{0.1}$, less than 0.1 µm in diameter).[59][60] Particle number can be measured with equipment such as condensation particle counters.[36][37]

Urban air quality index (AQI) values are computed by combining or comparing the concentrations of a "basket" of common air pollutants (typically ozone, carbon monoxide, sulphur dioxide, nitrogen oxides, and both fine and coarse particulates) to produce a single number on an easy-to-understand (and often colour-coded) scale.[61]

Air pollution was first systematically measured, in Britain, in the 19th century. In 1852, Scottish chemist Robert Angus Smith discovered (and named) acid rain after collecting rain samples that turned out to contain significant quantities of sulphur from coal burning. According to a chronology of air pollution by David Fowler and colleagues, Smith was "the first scientist to attempt multisite, multipollutant investigations of the chemical climatology of the polluted atmosphere".[62]

In the early 20th century, Irish physician and environmental engineer John Switzer Owens and the Committee for the Investigation of Atmospheric Pollution, of which he was secretary, greatly advanced the measurement and monitoring of air pollution using a network of deposit gauges. Owens also developed a number of new methods of measuring pollution.[63]

In December 1952, the Great Smog of London led to the deaths of 12,000 people.[64] This event, and similar ones such as the 1948 Donora smog tragedy in the United States,[65] became one of the great turning points in environmental history because they brought about a radical rethink in pollution control. In the UK, the Great Smog of London lead directly to the Clean Air Act, which may have had consequences even more far reaching than it originally intended.[66] Catastrophic events like this led to pollution being measured and controlled much more rigorously.[62]

III. RESULTS

An air quality index (AQI) is an indicator developed by government agencies[1] to communicate to the public how polluted the air currently is or how polluted it is forecast to become.[2][3] As air pollution levels rise, so does the AQI, along with the associated public health risk. Children, the elderly and individuals with respiratory or cardiovascular problems are typically the first groups affected by poor air quality. When the AQI is high, governmental bodies generally encourage people to reduce physical activity outdoors, or even avoid going out altogether. When

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wildfires result in a high AQI, the use of masks such as N95 respirators outdoors and air purifiers incorporating HEPA filters indoors are also encouraged.[2]

Different countries have their own air quality indices, corresponding to different national air quality standards. Some of these are Canada's Air Quality Health Index, Malaysia's Air Pollution Index, and Singapore's Pollutant Standards Index.[7,8,9]

Computation of the AQI requires an air pollutant concentration over a specified averaging period, obtained from an air monitor or model. Taken together, concentration and time represent the dose of the air pollutant. Health effects corresponding to a given dose are established by epidemiological research.[4] Air pollutants vary in potency, and the function used to convert from air pollutant concentration to AQI varies by pollutant. Its air quality index values are typically grouped into ranges. Each range is assigned a descriptor, a color code, and a standardized public health advisory.[10,11,12]

The AQI can increase due to an increase of air emissions. For example, during rush hour traffic or when there is an upwind forest fire or from a lack of dilution of air pollutants. Stagnant air, often caused by an anticyclone, temperature inversion, or low wind speeds lets air pollution remain in a local area, leading to high concentrations of pollutants, chemical reactions between air contaminants and hazy conditions.[5]

On a day when the AQI is predicted to be elevated due to fine particle pollution, an agency or public health organization might:

- advise sensitive groups, such as the elderly, children and those with respiratory or cardiovascular problems, to avoid outdoor exertion.[6]
- declare an "action day" to encourage voluntary measures to reduce air emissions, such as using public transportation.[7]
- recommend the use of masks outdoors and air purifiers indoors to keep fine particles from entering the lungs[8]

During a period of very poor air quality, such as an air pollution episode, when the AQI indicates that acute exposure may cause significant harm to the public health, agencies may invoke emergency plans that allow them to order major emitters (such as coal burning industries) to curtail emissions until the hazardous conditions abate.[9]

Most air contaminants do not have an associated AQI. Many countries monitor ground-level ozone, particulates, sulfur dioxide, carbon monoxide and nitrogen dioxide, and calculate air quality indices for these pollutants.[10]

The definition of the AQI in a particular nation reflects the discourse surrounding the development of national air quality standards in that nation.[11] A website allowing government agencies anywhere in the world to submit their real-time air monitoring data for display using a common definition of the air quality index has recently become available.[12]

Indices by location

Australia

Each of the states and territories of Australia is responsible for monitoring air quality and publishing data in accordance with the National Environment Protection (Ambient Air Quality) Measure (NEPM) standards.[13]

Each state and territory publishes air quality data for individual monitoring locations, and most states and territories publish air quality indexes for each monitoring location.

Across Australia, a consistent approach is taken with air quality indexes, using a simple linear scale where 100 represents the maximum concentration standard for each pollutant, as set by the NEPM. These maximum concentration standards are:[13,14,15]

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Pollutant	Averaging period	Maximum concentration standard
Carbon monoxide	8 hours	9 ppm
Nitrogen dioxide	1 hour	0.12 ppm
	1 year	0.03 ppm
Ozone	1 hour	0.10 ppm
	4 hours	0.08 ppm
Sulphur dioxide	1 hour	0.20 ppm
	1 day	0.08 ppm
	1 year	0.02 ppm
Lead	1 year	0.50 $\mu g/m^3$
PM 10	1 day	50 $\mu g/m^3$
	1 year	25 $\mu g/m^3$
PM 2.5	1 day	25 $\mu g/m^3$
	1 year	8 $\mu g/m^3$

The air quality index (AQI) for an individual location is simply the highest of the air quality index values for each pollutant being monitored at that location.

AQI bands, with health advice for each:[14]

AQI	Description	Health advice
0–33	Very Good	Enjoy activities
34–66	Good	Enjoy activities
67–99	Fair	People unusually sensitive to air pollution: Plan strenuous outdoor activities when air quality is better
100–149	Poor	Sensitive Groups: Cut back or reschedule strenuous outdoor activities
150–200	Very Poor	Sensitive groups: Avoid strenuous outdoor activities. Everyone: Cut back or reschedule strenuous outdoor activities
200+	Hazardous	Sensitive groups: Avoid all outdoor physical activities. Everyone: Significantly cut back on outdoor physical activities

Canada

Air quality in Canada has been reported for many years with provincial air quality indices (AQIs). Significantly, AQI values reflect air quality management objectives, which are based on the lowest achievable emissions rate, rather than exclusive concern for human health. The Air Quality Health Index (AQHI) is a scale designed to help understand the impact of air quality on health. It is a health protection tool used to make decisions to reduce short-term exposure to air pollution by adjusting activity levels during increased levels of air pollution. The Air Quality Health Index also provides advice on how to improve air quality by proposing a behavioral change to reduce the environmental footprint. This index pays particular attention to people who are sensitive to air pollution. It provides them with advice on how to protect their health during air quality levels associated with low, moderate, high and very high health risks.[16,17,18]

The AQHI provides a number from 1 to 10+ to indicate the level of health risk associated with local air quality. On occasion, when the amount of air pollution is abnormally high, the number may exceed 10. The AQHI provides a local air quality current value as well as a local air quality maximums forecast for today, tonight, and tomorrow, and provides associated health advice.[15]

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Health risk	AQHI	Health messages	
		At risk population	General population
Low	1–3	Enjoy your usual outdoor activities.	Ideal air quality for outdoor activities
Moderate	4–6	Consider reducing or rescheduling strenuous activities outdoors if you are experiencing symptoms.	No need to modify your usual outdoor activities unless you experience symptoms such as coughing and throat irritation.
High	7–10	Reduce or reschedule strenuous activities outdoors. Children and the elderly should also take it easy.	Consider reducing or rescheduling strenuous activities outdoors if you experience symptoms such as coughing and throat irritation.
Very high	Above 10	Avoid strenuous activities outdoors. Children and the elderly should also avoid outdoor physical exertion.	Reduce or reschedule strenuous activities outdoors, especially if you experience symptoms such as coughing and throat irritation.

China

Hong Kong

On December 30, 2013, Hong Kong replaced the Air Pollution Index with a new index called the Air Quality Health Index.[16] This index, reported by the Environmental Protection Department, is measured on a scale of 1 to 10+ and considers four air pollutants: ozone; nitrogen dioxide; sulphur dioxide and particulate matter (including PM10 and PM2.5). For any given hour the AQHI is calculated from the sum of the percentage excess risk of daily hospital admissions attributable to the 3-hour moving average concentrations of these four pollutants. The AQHIs are grouped into five AQHI health risk categories with health advice provided:[17]

Health risk category	AQHI
Low	1
	2
	3
Moderate	4
	5
	6
High	7
Very high	8
	9
	10
Serious	10+

Each of the health risk categories has advice associated with it. At the low and moderate levels the public are advised that they can continue normal activities. For the high category, children, the elderly and people with heart or respiratory illnesses are advised to reduce outdoor physical exertion. Above this (very high or serious), the general public are likewise advised to reduce or avoid outdoor physical exertion.

Mainland China

China's Ministry of Environmental Protection (MEP) is responsible for measuring the level of air pollution in China. As of January 1, 2013, MEP monitors daily pollution level in 163 of its major cities. The AQI level is based on the level of six atmospheric pollutants, namely sulfur dioxide (SO_2), nitrogen dioxide (NO_2), suspended particulates smaller than 10 μm in aerodynamic diameter (PM_{10}),[18] suspended particulates smaller than 2.5 μm in aerodynamic diameter ($PM_{2.5}$),[18] carbon monoxide (CO), and ozone (O_3) measured at the monitoring stations throughout each city.[19]

International Journal Of Multidisciplinary Research In Science, Engineering and Technology (IJMRSET)

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AQI mechanics

An individual score (Individual Air Quality Index, IAQI) is calculated using breakpoint concentrations below, and using same piecewise linear function to calculate intermediate values as the US AQI scale. and The final AQI value can be calculated either per hour or per 24 hours and is the max of these six scores.[19]

Chinese AQI category and pollutant breakpoints [19]

Individual index	Units are in μg/m^3 except CO, which is in mg/m^3									
IAQI	Sulfur dioxide (SO_2) 24 hour mean	Sulfur dioxide (SO_2) 1 hour mean (1)	Nitrogen dioxide (NO_2) 24 hour mean	Nitrogen dioxide (NO_2) 1 hour mean (1)	PM_{10} 24 hour mean	Carbon monoxide (CO) 24 hour mean	Carbon monoxide (CO) 1 hour mean (1)	Ozone (O_3) 1 hour mean	Ozone (O_3) 8 hour moving average	$PM_{2.5}$ 24 hour mean
0	0	0	0	0	0	0	0	0	0	0
50	50	150	40	100	50	2	5	160	100	35
100	150	500	80	200	150	4	10	200	160	75
150	475	650	180	700	250	14	35	300	215	115
200	800	800	280	1200	350	24	60	400	265	150
300	1600	(2)	565	2340	420	36	90	800	800	250
400	2100	(2)	750	3090	500	48	120	1000	(3)	350
500	2620	(2)	940	3840	600	60	150	1200	(3)	500
Notes:	(1) SO_2,NO_2, and CO 1 hour average concentrations are only for real time reporting. For daily reports, use the 24 hour average concentrations. (2) If the SO_2 1 hour concentration exceeds 800μg/m^3, use the index from the 24 hour concentration instead. (3) If the O_3 8 hour moving average exceeds 800μg/m^3, use the index from the 1 hour concentration instead.									

The score for each pollutant is non-linear, as is the final AQI score. Thus an AQI of 300 does not mean twice the pollution of AQI at 150, nor does it mean the air is twice as harmful. The concentration of a pollutant when its IAQI is 100 does not equal twice its concentration when its IAQI is 50, nor does it mean the pollutant is twice as harmful. While an AQI of 50 from day 1 to 182 and AQI of 100 from day 183 to 365 does provide an annual average of 75, it does not mean the pollution is acceptable even if the benchmark of 100 is deemed safe. Because the benchmark is a 24-hour target, and the annual average must match the annual target, it is entirely possible to have safe air every day of the year but still fail the annual pollution benchmark.[19]

AQI and health implications (HJ 633–2012)[19]

AQI	Air pollution level	Air pollution category	Health implications	Recommended precautions
0–50	Level 1	Excellent (优)	No health implications.	Everyone can continue their outdoor activities normally.
51–100	Level 2	Good (良)	Some pollutants may slightly affect very few hypersensitive individuals.	Only very few hypersensitive people should reduce outdoor activities.

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101–150	Level 3	Lightly Polluted (轻度污染)	Healthy people may experience slight irritations and sensitive individuals will be slightly affected to a larger extent.	Children, seniors and individuals with respiratory or heart diseases should reduce sustained and high-intensity outdoor exercises.
151–200	Level 4	Moderately Polluted (中度污染)	Sensitive individuals will experience more serious conditions. The hearts and respiratory systems of healthy people may be affected.	Children, seniors and individuals with respiratory or heart diseases should avoid sustained and high-intensity outdoor exercises. General population should moderately reduce outdoor activities.
201–300	Level 5	Heavily Polluted (重度污染)	Healthy people will commonly show symptoms. People with respiratory or heart diseases will be significantly affected and will experience reduced endurance in activities.	Children, seniors and individuals with heart or lung diseases should stay indoors and avoid outdoor activities. General population should reduce outdoor activities.
>300	Level 6	Severely Polluted (严重污染)	Healthy people will experience reduced endurance in activities and may also show noticeably strong symptoms. Other illnesses may be triggered in healthy people. Elders and the sick should remain indoors and avoid exercise. Healthy individuals should avoid outdoor activities.	Children, seniors and the sick should stay indoors and avoid physical exertion. General population should avoid outdoor activities.

Europe

The Common Air Quality Index (CAQI)[20] is an air quality index used in Europe since 2006.[21] In November 2017, the European Environment Agency announced the European Air Quality Index (EAQI) and started encouraging its use on websites and for other ways of informing the public about air quality.[22]

CAQI

As of 2012, the EU-supported project CiteairII argued that the CAQI had been evaluated on a "large set" of data, and described the CAQI's motivation and definition. CiteairII stated that having an air quality index that would be easy to present to the general public was a major motivation, leaving aside the more complex question of a health-based index, which would require, for example, effects of combined levels[19,20] of different pollutants. The main aim of the CAQI was to have an index that would encourage wide comparison across the EU, without replacing local indices. CiteairII stated that the "main goal of the CAQI is not to warn people for possible adverse health effects of poor air quality but to attract their attention to urban air pollution and its main source (traffic) and help them decrease their exposure."[21]

The CAQI is a number on a scale from 1 to 100, where a low value means good air quality and a high value means bad air quality. The index is defined in both hourly and daily versions, and separately near roads (a "roadside" or "traffic"

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| DOI:10.15680/IJMRSET.2024.0702003 |

index) or away from roads (a "background" index). As of 2012, the CAQI had two mandatory components for the roadside index, NO_2 and PM_{10}, and three mandatory components for the background index, NO_2, PM_{10} and O_3. It also included optional pollutants $PM_{2.5}$, CO and SO_2. A "sub-index" is calculated for each of the mandatory (and optional if available) components. The CAQI is defined as the sub-index that represents the worst quality among those components.[21]

Some of the key pollutant concentrations in $\mu g/m^3$ for the hourly background index, the corresponding sub-indices, and five CAQI ranges and verbal descriptions are as follows.[21]

Qualitative name	Index or sub-index	Pollutant (hourly) concentration			
		NO_2 $\mu g/m^3$	PM_{10} $\mu g/m^3$	O_3 $\mu g/m^3$	$PM_{2.5}$ (optional) $\mu g/m^3$
Very low	0–25	0–50	0–25	0–60	0–15
Low	25–50	50–100	25–50	60–120	15–30
Medium	50–75	100–200	50–90	120–180	30–55
High	75–100	200–400	90–180	180–240	55–110
Very high	>100	>400	>180	>240	>110

Frequently updated CAQI values and maps are shown on www.airqualitynow.eu[23] and other websites.[20] A separate Year Average Common Air Quality Index (YACAQI) is also defined, in which different pollutant sub-indices are separately normalised to a value typically near unity. For example, the yearly averages of NO_2, PM_{10} and $PM_{2.5}$ are divided by 40 $\mu g/m^3$, 40 $\mu g/m^3$ and 20 $\mu g/m^3$, respectively. The overall background or traffic YACAQI for a city is the arithmetic mean of a defined subset of these sub-indices.[21]

India

The National Air Quality Index (NAQI) was launched in New Delhi on September 17, 2014, under the Swachh Bharat Abhiyan.[24][25][26][27]

The Central Pollution Control Board along with State Pollution Control Boards has been operating National Air Monitoring Program (NAMP) covering 240 cities of the country having more than 342 monitoring stations.[28] An Expert Group comprising medical professionals, air quality experts, academia, advocacy groups, and SPCBs was constituted and a technical study was awarded to IIT Kanpur. IIT Kanpur and the Expert Group recommended an AQI scheme in 2014.[29] While the earlier measuring index was limited to three indicators, the new index measures eight parameters.[30] The continuous monitoring systems that provide data on near real-time basis are installed in New Delhi, Mumbai, Pune, Kolkata and Ahmedabad.[31]

There are six AQI categories, namely Good, Satisfactory, Moderate, Poor, Severe and Hazardous. The proposed AQI will consider eight pollutants (PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, O_3, NH_3, and Pb) for which short-term (up to 24-hourly averaging period) National Ambient Air Quality Standards are prescribed.[32] Based on the measured ambient concentrations, corresponding standards and likely health impact, a sub-index is calculated for each of these pollutants. The worst sub-index reflects overall AQI. Likely health impacts for different AQI categories and pollutants have also been suggested, with primary inputs from the medical experts in the group. The AQI values and corresponding ambient concentrations (health breakpoints) as well as associated likely health impacts for the identified eight pollutants are as follows:

AQI category, pollutants and health breakpoints								
AQI category (range)	PM_{10} (24hr)	$PM_{2.5}$ (24hr)	NO_2 (24hr)	O_3 (8hr)	CO (8hr)	SO_2 (24hr)	NH_3 (24hr)	Pb (24hr)
Good (0–50)	0–50	0–30	0–40	0–50	0–1.0	0–40	0–200	0–0.5
Satisfactory (51–100)	51–100	31–60	41–80	51–100	1.1–2.0	41–80	201–400	0.5–1.0

| ISSN: 2582-7219 | www.ijmrset.com | Impact Factor: 7.521| Monthly Peer Reviewed & Referred Journal |

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Moderate (101–200)	101–250	61–90	81–180	101–168	2.1–10	81–380	401–800	1.1–2.0
Poor (201–300)	251–350	91–120	181–280	169–208	10–17	381–800	801–1200	2.1–3.0
Very Poor (301–400)	351–430	121–250	281–400	209–748	17–34	801–1600	1200–1800	3.1–3.5
Severe (401–500)	430+	250+	400+	748+	34+	1600+	1800+	3.5+

AQI definitions

AQI	Associated health impacts	Colour
Good (0–50)	Minimal impact	Deep green
Satisfactory (51–100)	May cause minor breathing discomfort to sensitive people.	Light green
Moderate (101–200)	May cause breathing discomfort to people with lung disease such as asthma, and discomfort to people with heart disease, children and older adults.	Yellow
Poor (201–300)	May cause breathing discomfort to people on prolonged exposure, and discomfort to people with heart disease.	Orange
Very Poor (301–400)	May cause respiratory illness to the people on prolonged exposure. Effect may be more pronounced in people with lung and heart diseases.	Red
Severe (401–500)	May cause respiratory impact even on healthy people, and serious health impacts on people with lung/heart disease. The health impacts may be experienced even during light physical activity.	Maroon

Japan

According to Japan Weather Association, Japan uses a different scale to measure the air quality index.[21,22,23]

AQI	AQI type	Health information
0–50	Good (良い)	There is no impact on humans. Outdoor activities are always allowed.
51–100	Moderate (適度)	Outdoor activities are often allowed because air is seldom considered unhealthy.
101–200	Unhealthy (不健康)	Outdoor activities are sometimes allowed because air is sometimes considered unhealthy.
201–350	Very unhealthy (非常不健康)	There are serious health hazards. Outdoor activities are seldom allowed.
351–500	Hazardous (危険な)	Pollutants trigger extremely serious health hazards to humans. Outdoor activities are never allowed.

Mexico

The air quality in Mexico City is reported in IMECAs. The IMECA is calculated using the measurements of average times of the chemicals ozone (O_3), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), particles smaller than 2.5 micrometers ($PM_{2.5}$), and particles smaller than 10 micrometers (PM_{10}).[33]

Singapore

Singapore uses the Pollutant Standards Index to report on its air quality,[34] with details of the calculation similar but not identical to those used in Malaysia and Hong Kong.[35] The PSI chart below is grouped by index values and descriptors, according to the National Environment Agency.[36]

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PSI	Descriptor	General health effects
0–50	Good	None
51–100	Moderate	Few or none for the general population
101–200	Unhealthy	Mild aggravation of symptoms among susceptible persons i.e. those with underlying conditions such as chronic heart or lung ailments; transient symptoms of irritation e.g. eye irritation, sneezing or coughing in some of the healthy population.
201–300	Very Unhealthy	Moderate aggravation of symptoms and decreased tolerance in persons with heart or lung disease; more widespread symptoms of transient irritation in the healthy population.
301–400	Severe	Early onset of certain diseases in addition to significant aggravation of symptoms in susceptible persons; and decreased exercise tolerance in healthy persons.
Above 400	Hazardous	PSI levels above 400 may be life-threatening to ill and elderly persons. Healthy people may experience adverse symptoms that affect normal activity.

South Korea

The Ministry of Environment of South Korea uses the Comprehensive Air-quality Index (CAI) to describe the ambient air quality based on the health risks of air pollution. The index aims to help the public easily understand the air quality and protect people's health. The CAI is on a scale from 0 to 500, which is divided into six categories. The higher the CAI value, the greater the level of air pollution. Of values of the five air pollutants, the highest is the CAI value. The index also has associated health effects and a colour representation of the categories as shown below.[37]

CAI	Description	Health implications
0–50	Good (좋음)	A level that will not impact patients with diseases related to air pollution.
51–100	Moderate (보통)	A level that may have a meager impact on patients in case of chronic exposure.
101–250	Unhealthy (나쁨)	A level that may have harmful impacts on patients and members of sensitive groups (children, aged or weak people), and also cause the general public unpleasant feelings.
251–500	Very unhealthy (매우 나쁨)	A level that may have a serious impact on patients and members of sensitive groups in case of acute exposure.

The N Seoul Tower on Namsan Mountain in central Seoul, South Korea, is illuminated in blue, from sunset to 23:00 and 22:00 in winter, on days where the air quality in Seoul is 45 or less. During the spring of 2012, the Tower was lit up for 52 days, which is four days more than in 2011.[38]

United Kingdom

The most commonly used air quality index in the UK is the Daily Air Quality Index recommended by the Committee on the Medical Effects of Air Pollutants (COMEAP).[39] This index has ten points, which are further grouped into four bands: low, moderate, high and very high. Each of the bands comes with advice for at-risk groups and the general population.[40]

Air pollution banding	Value	Health messages for at-risk individuals	Health messages for general population

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	Low	1–3	Enjoy your usual outdoor activities.	
	Moderate	4–6	Adults and children with lung problems, and adults with heart problems, who experience symptoms, should consider reducing strenuous physical activity, particularly outdoors.	Enjoy your usual outdoor activities.
	High	7–9	Adults and children with lung problems, and adults with heart problems, should reduce strenuous physical exertion, particularly outdoors, and particularly if they experience symptoms. People with asthma may find they need to use their reliever inhaler more often. Older people should also reduce physical exertion.	Anyone experiencing discomfort such as sore eyes, cough or sore throat should consider reducing activity, particularly outdoors.
	Very High	10	Adults and children with lung problems, adults with heart problems, and older people, should avoid strenuous physical activity. People with asthma may find they need to use their reliever inhaler more often.	Reduce physical exertion, particularly outdoors, especially if you experience symptoms such as cough or sore throat.

The index is based on the concentrations of five pollutants. The index is calculated from the concentrations of the following pollutants: ozone, nitrogen dioxide, sulphur ioxide, PM2.5 (particles with an aerodynamic diameter less than 2.5 µm) and PM10. The breakpoints between index values are defined for each pollutant separately and the overall index is defined as the maximum value of the index. Different averaging periods are used for different pollutants.[40]

Index	Ozone, running 8 hourly mean (µg/m^3)	Nitrogen dioxide, hourly mean (µg/m^3)	Sulphur dioxide, 15 minute mean (µg/m^3)	PM$_{2.5}$ particles, 24 hour mean (µg/m^3)	PM$_{10}$ particles, 24 hour mean (µg/m^3)
1	0–33	0–67	0–88	0–11	0–16
2	34–66	68–134	89–177	12–23	17–33
3	67–100	135–200	178–266	24–35	34–50
4	101–120	201–267	267–354	36–41	51–58
5	121–140	268–334	355–443	42–47	59–66
6	141–160	335–400	444–532	48–53	67–75
7	161–187	401–467	533–710	54–58	76–83
8	188–213	468–534	711–887	59–64	84–91
9	214–240	535–600	888–1064	65–70	92–100
10	≥ 241	≥ 601	≥ 1065	≥ 71	≥ 101

United States

United States Air Quality Index		
AQI	Level of health concern	Color
0 to 50	Good	Green
51 to 100	Moderate	Yellow
101 to 150	Unhealthy for sensitive groups	Orange
151–200	Unhealthy	Red
201–300	Very unhealthy	Purple
301–500	Hazardous	Maroon
501-1000	Very Hazardous	Brown

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The United States Environmental Protection Agency (EPA) has developed an Air Quality Index that is used to report air quality. This AQI is divided into six categories indicating increasing levels of health concern. An AQI value over 300 represents hazardous air quality and below 50 the air quality is good.[10]

The AQI is based on the five "criteria" pollutants regulated under the Clean Air Act: ground-level ozone, particulate matter, carbon monoxide, sulfur dioxide, and nitrogen dioxide. The EPA has established National Ambient Air Quality Standards (NAAQS) for each of these pollutants in order to protect public health. An AQI value of 100 generally corresponds to the level of the NAAQS for the pollutant.[10] The Clean Air Act (USA) (1990) requires the EPA to review its National Ambient Air Quality Standards every five years to reflect evolving health effects information. The Air Quality Index is adjusted periodically to reflect these changes.24,25,26

The EPA's table of breakpoints is:[42][43][44]

O_3 (ppb)	O_3 (ppb)	$PM_{2.5}$ (µg/m^3)	PM_{10} (µg/m^3)	CO (ppm)	SO_2 (ppb)	NO_2 (ppb)	AQI	AQI
$C_{low} – C_{high}$ (avg)							$I_{low} – I_{high}$	Category
0–54 (8-hr)	—	0.0–12.0 (24-hr)	0–54 (24-hr)	0.0–4.4 (8-hr)	0–35 (1-hr)	0–53 (1-hr)	0–50	Good
55–70 (8-hr)	—	12.1–35.4 (24-hr)	55–154 (24-hr)	4.5–9.4 (8-hr)	36–75 (1-hr)	54–100 (1-hr)	51–100	Moderate
71–85 (8-hr)	125–164 (1-hr)	35.5–55.4 (24-hr)	155–254 (24-hr)	9.5–12.4 (8-hr)	76–185 (1-hr)	101–360 (1-hr)	101–150	Unhealthy for sensitive groups
86–105 (8-hr)	165–204 (1-hr)	55.5–150.4 (24-hr)	255–354 (24-hr)	12.5–15.4 (8-hr)	186–304 (1-hr)	361–649 (1-hr)	151–200	Unhealthy
106–200 (8-hr)	205–404 (1-hr)	150.5–250.4 (24-hr)	355–424 (24-hr)	15.5–30.4 (8-hr)	305–604 (24-hr)	650–1249 (1-hr)	201–300	Very unhealthy
—	405–504 (1-hr)	250.5–350.4 (24-hr)	425–504 (24-hr)	30.5–40.4 (8-hr)	605–804 (24-hr)	1250–1649 (1-hr)	301–400	Hazardous
—	505–604 (1-hr)	350.5–500.4 (24-hr)	505–604 (24-hr)	40.5–50.4 (8-hr)	805–1004 (24-hr)	1650–2049 (1-hr)	401–500	

Suppose a monitor records a 24-hour average fine particle ($PM_{2.5}$) concentration of 26.4 micrograms per cubic meter. The equation above results in an AQI of:

which rounds to index value of 81, corresponding to air quality in the "Moderate" range.[45] To convert an air pollutant concentration to an AQI, EPA has developed a calculator.[46]

If multiple pollutants are measured at a monitoring site, then the largest or "dominant" AQI value is reported for the location. The ozone AQI between 100 and 300 is computed by selecting the larger of the AQI calculated with a 1-hour ozone value and the AQI computed with the 8-hour ozone value.

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Eight-hour ozone averages do not define AQI values greater than 300; AQI values of 301 or greater are calculated with 1-hour ozone concentrations. 1-hour SO_2 values do not define higher AQI values greater than 200. AQI values of 201 or greater are calculated with 24-hour SO_2 concentrations.[27,28]

Real-time monitoring data from continuous monitors are typically available as 1-hour averages. However, computation of the AQI for some pollutants requires averaging over multiple hours of data. (For example, calculation of the ozone AQI requires computation of an 8-hour average and computation of the $PM_{2.5}$ or PM_{10} AQI requires a 24-hour average.) To accurately reflect the current air quality, the multi-hour average used for the AQI computation should be centered on the current time, but as concentrations of future hours are unknown and are difficult to estimate accurately, EPA uses surrogate concentrations to estimate these multi-hour averages. For reporting the $PM_{2.5}$, PM_{10} and ozone air quality indices, this surrogate concentration is called the NowCast. The Nowcast is a particular type of weighted average that provides more weight to the most recent air quality data when air pollution levels are changing.[47][48] There is a free email subscription service for New York inhabitants – AirNYC.[49] Subscribers get notifications about the changes in the AQI values for the selected location (e.g. home address), based on air quality conditions.

Public availability of the AQI

Real time monitoring data and forecasts of air quality that are color-coded in terms of the air quality index are available from EPA's AirNow web site.[50] Other organizations provide monitoring for members of sensitive groups such as asthmatics, children and adults over the age of 65.[51] Historical air monitoring data including AQI charts and maps are available at EPA's AirData website.[52] Detailed map about current AQI level and its two-day forecast is available from Aerostate web site.[53]

Regulatory Air Monitors and Low Cost Sensors

Historically, EPA has only allowed data from regulatory monitors operated by regulatory or public health professionals to be included in its real time national maps.[54][55] In the past decade, low cost sensors (LCS's) have become increasingly popular with citizen scientists, and large LCS networks haven sprung up in the US and across the globe. Recently, EPA has developed a data correction algorithm[56][57] for a particular brand of $PM_{2.5}$ LCS (the Purple Air monitor) that makes the LCS data comparable to regulatory data for the purpose of computing the AQI. This corrected LCS data currently appears alongside regulatory data on EPA's national fire map.[58]

History of the AQI

The AQI made its debut in 1968, when the National Air Pollution Control Administration undertook an initiative to develop an air quality index and to apply the methodology to Metropolitan Statistical Areas. The impetus was to draw public attention to the issue of air pollution and indirectly push responsible local public officials to take action to control sources of pollution and enhance air quality within their jurisdictions.

Jack Fensterstock, the head of the National Inventory of Air Pollution Emissions and Control Branch, was tasked to lead the development of the methodology and to compile the air quality and emissions data necessary to test and calibrate resultant indices.[59]

The initial iteration of the air quality index used standardized ambient pollutant concentrations to yield individual pollutant indices. These indices were then weighted and summed to form a single total air quality index. The overall methodology could use concentrations that are taken from ambient monitoring data or are predicted by means of a diffusion model. The concentrations were then converted into a standard statistical distribution with a preset mean and standard deviation. The resultant individual pollutant indices are assumed to be equally weighted, although values other than unity can be used. Likewise, the index can incorporate any number of pollutants although it was only used to combine SO_x, CO, and TSP[60] because of a lack of available data for other pollutants.

While the methodology was designed to be robust, the practical application for all metropolitan areas proved to be inconsistent due to the paucity of ambient air quality monitoring data, lack of agreement on weighting factors, and non-uniformity of air quality standards across geographical and political boundaries. Despite these issues, the publication of lists ranking metropolitan areas achieved the public policy objectives and led to the future development of improved indices and their routine application.

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Vietnam

On November 12, 2019, Vietnam Environment Administration issued Decision No. 1459/QD-TCMT on promulgating Technical Guidelines for calculation and publication of Vietnam Air Quality Index (VN_AQI).[61]

AQI range	Air quality	Color
0–50	Good (Tốt)	Green
51–100	Moderate (Trung bình)	Yellow
101–150	Bad (Kém)	Orange
151–200	Unhealthy (Xấu)	Red
201 - 300	Very unhealthy (Rất xấu)	Purple
301 - 500	Hazardous (Nguy hại)	Brown

IV. CONCLUSION

Air pollutants are atmospheric substances—both naturally occurring and anthropogenic—which may potentially have a negative impact on the environment and organism health. With the evolution of new chemicals and industrial processes has come the introduction or elevation of pollutants in the atmosphere, as well as environmental research and regulations, increasing the demand for air quality monitoring.[1]

Air quality monitoring is challenging to enact as it requires the effective integration of multiple environmental data sources, which often originate from different environmental networks and institutions.[2] These challenges require specialized observation equipment and tools to establish air pollutant concentrations, including sensor networks, geographic information system (GIS) models, and the Sensor Observation Service (SOS), a web service for querying real-time sensor data.[2] Air dispersion models that combine topographic, emissions, and meteorological data to predict air pollutant concentrations are often helpful in interpreting air monitoring data. Additionally, consideration of anemometer data in the area between sources and the monitor often provides insights on the source of the air contaminants recorded by an air pollution monitor.

Air quality monitors are operated by citizens,[3][4][5] regulatory agencies,[6][7] non-governmental organisations [8] and researchers[9] to investigate air quality and the effects of air pollution. Interpretation of ambient air monitoring data often involves a consideration of the spatial and temporal representativeness[10] of the data gathered, and the health effects associated with exposure to the monitored levels.[11] If the interpretation reveals concentrations of multiple chemical compounds, a unique "chemical fingerprint" of a particular air pollution source may emerge from analysis of the data.[12]

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Air sampling

Passive or "diffusive" air sampling depends on meteorological conditions such as wind to diffuse air pollutants to a sorbent medium. Passive samplers, such as diffusion tubes, have the advantage of typically being small, quiet, and easy to deploy, and they are particularly useful in air quality studies that determine key areas for future continuous monitoring.[13]

Air pollution can also be assessed by biomonitoring with organisms that bioaccumulate air pollutants, such as lichens, mosses, fungi, and other biomass.[14][15] One of the benefits of this type of sampling is how quantitative information can be obtained via measurements of accumulated compounds, representative of the environment from which they came. However, careful considerations must be made in choosing the particular organism, how it's dispersed, and relevance to the pollutant.[15]

Other sampling methods include the use of a denuder,[16][17] needle trap devices, and microextraction techniques.[18]

Environmental monitoring describes the processes and activities that need to take place to characterize and monitor the quality of the environment. Environmental monitoring is used in the preparation of environmental impact assessments, as well as in many circumstances in which human activities carry a risk of harmful effects on the natural environment. All monitoring strategies and programs have reasons and justifications which are often designed to establish the current status of an environment or to establish trends in environmental parameters. In all cases, the results of monitoring will be reviewed, analyzed statistically, and published. The design of a monitoring program must therefore have regard to the final use of the data before monitoring starts.

Environmental monitoring includes monitoring of air quality, soils and water quality.

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| ISSN: 2582-7219 | www.ijmrset.com | Impact Factor: 7.521| Monthly Peer Reviewed & Referred Journal |

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7.521

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