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EXAMINING THE LOCATIONAL APPROACH TOWARDS OPTIMAL SITING OF AIR QUALITY MONITORING STATIONS IN INDIA

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Abstract

Increasing air pollution levels globally has been one of the major environmental risks on the ecosystem having multiplier effects on the human health. This pressing issue has necessitated the establishment of regulatory bodies tasked with monitorization and assessing pollution levels. This monitoring is particularly crucial in urban areas where human activity and population density are prevalent. Effective air quality monitoring is pivotal in formulating and implementing sustainable environmental policies. In the context of India, various measures have been taken to establish Air Quality Monitoring Stations (AQMS). These stations play a pivotal role in shaping action plans aimed at enhancing overall air quality throughout the country. This research paper presents a systematic literature review of various approaches and methods for the selection of air quality monitoring station sites based on a review of 25 published works. This paper provides an overview of the design techniques employed by studies over the past three decades. Furthermore, this study meticulously scrutinizes the guidelines and initiatives that govern the selection of optimal locations for these crucial monitoring stations. The culmination of this comprehensive analysis lies in the identification of diverse evaluation criteria, which hold the potential to facilitate a comprehensive and holistic approach to air quality management. The research aims to bridge existing gaps in the literature and offer recommendations for an optimal approach to positioning air quality monitoring stations in urban areas across India and globally. This approach seeks to enhance the management of air quality and contribute to the realization of improved environmental conditions.

Key words: Air Quality Monitoring Stations (AQMS), air quality modelling, GIS based approach, monitoring, site selection

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1. Introduction

Industrial development has long been recognized as a major contributor to environmental degradation, leading to severe stress on ecosystems and natural components such as soil, water, and air (Patnaik, 2018). In developed nations, there has been a significant resurgence of interest in environmental issues, while developing countries are increasingly acknowledging the environmental challenges they face. As these developing countries undergo processes of industrialization and urbanization, it is believed that they may have a significant impact on environmental pollution (Baloch et al., 2022; Shukla and Parikh, 1992). The World Health Organization (WHO) defines air pollution as the contamination of the environment both indoors and outdoors by any physical, chemical or biological agent that modified the natural characteristic of the environment (WHO, 2022). Cities worldwide, particularly in developing nations like India, are experiencing rapid expansion (Elbir et al., 2010). With the substantial growth in manufacturing and urbanization over the past few decades, air pollution has become a pressing issue in India, the second most populous country in the world (Garaga et al., 2018). Exposure to air pollution is now considered one of the most significant global environmental health threats (Das et al., 2021).

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According to estimates by the WHO, the combined effects of ambient and household air pollution are responsible for approximately 7 million deaths each year, primarily due to non-communicable diseases (WHO, 2021). A staggering 99% of people worldwide are exposed to air quality that exceeds WHO guidelines, with low- and middle-income countries bearing the brunt of this burden (UN-Habitat, 2022). Human exposure to fine particulate matter, commonly known as $PM_{2.5}$, or inhalable tiny particles, is a leading cause of air pollution related deaths (World Bank Group, 2021).

India's air quality concerns have been a growing focus of global attention. According to the World Air Quality Reports, India ranked among the top three (IQAir, 2020) and top five (IQAir, 2022) countries with the highest concentrations of particulate matter 2.5 (PM2.5). Air quality in many Indian cities has consistently been ranked among the most polluted in the world (Mahato and Ghosh, 2020). Northern India, with its high population density, experiences some of the most severe impacts of air pollution (Guo et al., 2019). Numerous studies have examined $PM_{2.5}$ levels in Indian cities (Sarkar et al., 2018; Guttikunda et al., 2019). Shockingly, India has one of the highest rates of air pollution-related health issues globally, with nearly 100% of its population residing in areas where $PM_{2.5}$ concentrations exceed the World Health Organization's guideline of 10 ug/m3 on an annual average basis (Balakrishnan et al., 2019; Brauer et al., 2019). In 2021, India was home to 12 of the world's top 20 most polluted cities, with Bhiwadi in Rajasthan's Alwar district earning the dubious distinction of being the world's most polluted regional city. These alarming statistics are derived from data collected by PM2.5 air monitoring stations in over 106 countries worldwide and reported in the World Air Quality Reports published by the UN Habitat under the UN Environment Programme (UN-Habitat, 2022).

Effective environmental policies and strategies to address these challenges largely depend on robust air quality monitoring systems (AQMS). The fundamental objective of air quality monitoring is to collect data that empowers environmentalists, scientists, and policymakers to collaborate in improving and establishing global environmental and health standards (Abdul-Wahab et al., 2019). The need for regulatory agencies to monitor pollution levels has increased over time, especially in densely populated urban areas, where human activities are concentrated. Choosing the optimal locations for AQMS is a critical element in establishing, managing, and maintaining air quality in these regions (Alsahli and Al-Harbi, 2018).

Assessment of ambient air quality typically relies on measurements from a limited numbers of monitoring locations (Vitali et al., 2016), and the data gathered from these AQMS forms the basis for virtually all air pollution mitigation strategies (Alsahli and Al-Harbi, 2018). The effectiveness of emission reduction initiatives, compliance with standards, and prioritization of pollution sources all heavily rely on air quality measurements. Large urban centers often have air quality monitoring networks (AQMN) in place, which provide data for various purposes, including evaluating the effectiveness of management strategies and ensuring regulatory compliance. However, the criteria for network structure are now determined by only a few variables, rather than striving to create a network capable of performing multiple tasks (Munir et al., 2019) as shown in Fig. 1. In 2021, many Central and South Asian countries expanded their air quality networks by increasing the number of monitors providing public PM2.5 concentration data (IQAir, 2022).

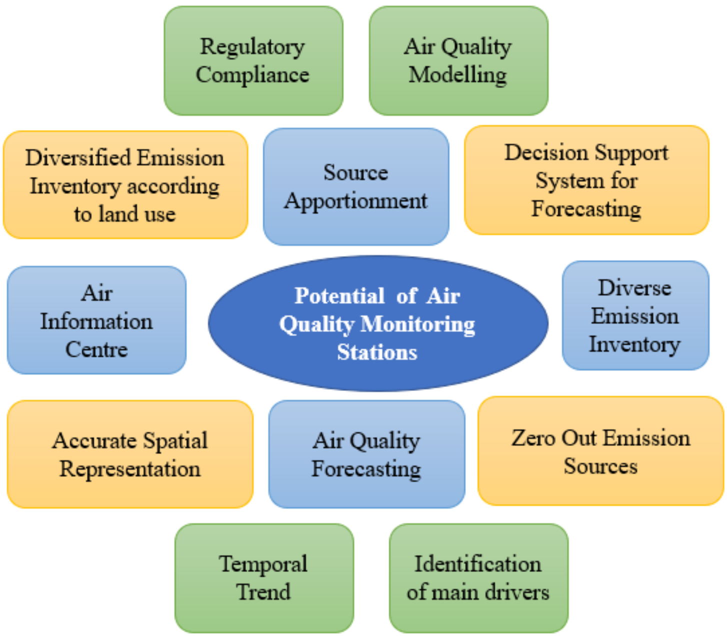

Fig. 1. Potential of air quality monitoring database

India's monitoring network density is significantly different from that of similar countries. For example, India's monitor density, with one monitor for every 6.8 million people, is much lower than that of other densely populated countries like China (1.2 monitors/million), the USA (3.4 monitors/million), Japan (0.5 monitors/million), Brazil (1.8 monitors/million), and most European countries (2-3 monitors/million people) (Brauer et al., 2019). As of now in 2023, there are 938 functioning air quality monitoring stations spread across India, according to the Manual Ambient Air Quality Monitoring (CAAQM) list, highlighting the need for an expanded and more comprehensive air quality monitoring network to address the ongoing challenges of air pollution in the country.

2. Materials and method

2.1. Guideline for location of AQMS in India

Setting up ambient Air Quality Monitoring Stations (AQMS) in India is a critical undertaking, and the process involves several key considerations to ensure the accuracy and relevance of the collected data. One of the primary steps in this process is the acquisition of background information, which serves as the foundation for effective air quality monitoring (CPCB, 2003). This historical data includes valuable insights into emission sources, health conditions, demographics, population growth, land use patterns, and epidemiological research, which all play a pivotal role in understanding the potential outcomes and, notably, the health consequences of public exposure to air pollutants. The Indian Standard 5182 (part 14): 2000 Method for measurement of air pollution outlines the specifications for the site location and distribution of Air Quality Monitoring Stations in India, with a focus on ensuring the accuracy and relevance of the collected data.

2.1.1. Location of monitoring stations

The selection of suitable sites for air quality monitoring stations is a critical decision that involves several key factors to consider. The location of these monitoring stations should primarily take into account the type of instruments used for sampling, available resources, physical accessibility, and security against potential loss or tampering (BIS IS 5182-14, 2000). Monitoring should be concentrated in areas where air pollution is a known issue or is anticipated to become one, such as industrial zones, urban areas, and busy traffic intersections. One of the primary objectives of air quality monitoring is to both understand the existing air quality status and track trends over time. Therefore, it is vital to monitor air quality in major cities and other metropolitan areas to facilitate meaningful comparisons and trend identification. The choice of the monitoring domain is of paramount importance because an ill-considered choice can lead to data that may not align with monitoring goals or provide useful insights. In general, several conditions should be met when selecting a site for an air quality monitoring station. Table 1 outlines various parameters that are taken into consideration during the site selection process, ensuring that the stations are strategically placed to effectively capture air quality data across different regions in India.

Table 1. Selection of air quality monitoring stations in India (BIS IS 5182-14, 2000)

Sr. No.	*Parameters*	*Definitions*	*General conditions*
1.	Representative site	A site is considered typical if the data it produces accurately depicts the amounts and variability of the different contaminants in the surrounding area.	The location should be far from significant sources of pollution. Domestic chimneys should be at least 25 meters distant from the station.
			The location should be at least one meter away from absorbent surfaces such absorbent construction materials.
			The location should be chosen so that no imminent land use changes, rebuilding's, etc. are anticipated and that it is anticipated to remain a representative site for a considerable amount of time.
2.	Comparability	The specifics of each place should be as uniform as feasible to facilitate comparison of air quality data from several sites.	It should be open on all sides; that is, the intake shouldn't be in a small area.
			The sampling input for traffic pollution monitoring should be 3 m above the street level.
			A 200 m buffer must be maintained between sampling locations and unpaved roads and streets when doing so.
3.	Physical requirements	Depending on the kinds of instruments being used, the location of the station should meet one or more of the following criteria.	The site needs to be accessible for a very long time.
			Site sheltering and amenities like adequate electricity, water, a phone line, etc. should be supplied.
			It ought to be weatherproof and impervious to vandals.
4.	Topographical and meteorological factors	When choosing a monitoring site, topographical and meteorological conditions must also be taken into	Winds brought on by daytime heating and nighttime cooling may have an impact on the movement of pollutants, resulting in either a buildup of pollutants or dilution.
			The local winds may be directed in a certain direction by canyons or valleys, increasing the wind speed.

		account. These elements result in a meteorological phenomenon that may impact the dispersion of air pollution.	Large bodies of water may result in a land-sea breeze wind pattern, which may affect the movement of pollutants.
			The precipitation that results from the mountainous or hilly terrain may change the pollutant concentration.
5.	General requirements	After deciding on a location for a monitoring station, the site can be chosen by utilizing air quality modelling to determine the maximum concentration.	The inlet's height must be between 3 and 10 meters above ground level.
			More than 20 meters must separate the sampler from trees.
			Any air flow obstruction, such as a building, must be located farther away from the sampler than twice its height.
			In three of the four quadrants, airflow ought should be unhindered.
			There shouldn't be any fumes from an incinerator or furnace nearby.

2.1.2. Numbering and distribution of monitoring locations

To establish a robust and effective air quality monitoring network, it is crucial to start by comprehending the existing levels and trends of local air pollution. This knowledge forms the cornerstone for determining both the number of monitoring stations needed and their strategic distribution. This decision-making process can be informed by prior air quality data or by analyzing the isopleth distribution of ambient pollutant concentrations. Several key factors influence the number of sampling locations required for an effective monitoring network. These factors include the geographical area to be covered, the variability in pollutant concentration across this area, specific data requirements, the pollutants to be monitored, and the utilization of demographic information as an indicator of potential health consequences and declining air quality. The choice of pollutants to be monitored is of particular significance, as different pollutants may have distinct dispersion patterns and sources. Therefore, the selection of pollutants plays a pivotal role in determining the number and strategic placement of monitoring stations. For densely populated metropolitan areas,

Table 2 offers valuable guidance by outlining the minimum number of stations and their dispersion to effectively track prevailing pollutants. By taking into account the population size, Table 2 provides tailored recommendations for station numbers and distribution, recognizing that densely populated regions may necessitate a denser network of monitoring stations to accurately capture air quality trends and potential health impacts.

2.2. Criteria for siting AQMS in the EU and USA

In order to establish air quality monitoring networks that provide accurate and meaningful data, careful consideration is given to a range of factors in both the European Union (EU) and the United States of America (USA).

2.2.1. European Union

Within the EU, the location of air quality monitoring stations is guided by criteria that are aligned with Directive 2008/50/EC of the European Parliament. These criteria are divided into two distinct scales: macroscale and microscale. At the macroscale level, the focus is on determining the general locations of monitoring stations within designated zones. A qualitative analysis is employed to assess whether a chosen monitoring station can effectively represent significant urban or suburban residential areas. It is widely acknowledged that monitoring sites known as "urban background" are the most suitable for capturing the exposure experienced by the general population.

Table 2. Population-based minimum station requirement (BIS IS 5182-14, 2000)

Sr. No.	***Pollutant***	***Population of evaluation area***	***Minimum no. of AAQ monitoring station***
1.	Suspended Particulate Matter (SPM)	< 100K	4
		100K-1 million	4 + 0.6 per 0.1 million Population
		1- 5 million	7.5 + 0.25 per 0.1 million Population
		> 5 million	12 + 0.16 per 0.1 million Population
2.	SO_2	< 100K	3
		100K-1 million	2.5 + 0.5 per 0.1 million Population
		1- 10 million	6 + 0.15 per 0.1 million Population
		> 10 million	20
3.	NO_2	< 100K	4
		100K-1 million	4 + 0.6 per 0.1 million Population
		> 1 million	10
4.	CO	< 100K	1
		100K-5 million	1 + 0.15 per 0.1 million Population
		> 5 million	6 + 0.05 per 0.1 million Population

On the microscale, specific criteria are applied to ensure that a monitoring station accurately represents the specific area covered by the macroscale criteria. These microscale criteria, implemented "to the extent practicable," include ensuring unhindered airflow around the sampling probe, positioning the inlet probe away from pollution sources, and carefully setting the inlet sampling height. For instance, traffic-oriented sample probes must be placed at a minimum distance from curbsides and major intersections to accurately assess all pollutants.

2.2.2. United States of America

In the USA, the location of air quality monitoring stations is influenced by the primary objectives of the monitoring program, often centered on safeguarding human health. Monitoring stations are typically situated in populated areas, which may include regions of high concern, urban centers, or near major roadways, such as schools, hospitals, or specific emission sources. Several factors are considered during site selection, including economic considerations to evaluate the costs associated with site selection, security to ensure the safety of the monitoring equipment, and logistics to efficiently manage the equipment and personnel. Atmospheric factors, such as the geographical and temporal variation of pollutants, the influence of buildings, and meteorological conditions, play a pivotal role in determining monitoring station locations. The topography of the area is also taken into account, as it can impact the transport and diffusion of air contaminants. Factors like deep river basins or mountain ranges can significantly affect air quality in localized ways. Additionally, monitoring station sites may be influenced by specific pollutants' characteristics, including the design of emission sources, local meteorology, and the fluctuations in pollutant composition between emission and detection.

Both the EU and the USA have established criteria and guidelines for the placement of air quality monitoring stations to ensure that monitoring networks are strategically positioned. These guidelines address a wide range of considerations, including economic factors, logistics, atmospheric conditions, topographical features, and pollutant-specific requirements. The effective implementation of these criteria is vital for meaningful air quality data collection, which, in turn, contributes to evidence-based air quality management and policy formulation in both regions.

2.3. Research methodology

The research methodology for this paper is grounded in a systematic approach to reviewing and synthesizing existing knowledge in the siting of air quality monitoring station. The process commences with a comprehensive literature search, encompassing relevant databases and academic sources, using specific keywords related to air quality monitoring, siting, air pollution, and pertinent concepts. Inclusion and exclusion criteria are meticulously defined to determine the eligibility of selected articles, considering factors like publication date, focus on siting methodologies, geographical relevance, and research quality. Data extraction ensues, where key information from each chosen study is gathered, including research objectives, methodologies employed, findings, and any site selection criteria or guidelines. The extracted data is systematically categorized based on various criteria such as geographical location, methodology, or pollutants monitored. This organized information is then subjected to in-depth analysis to discern common trends, patterns, and any gaps in the existing literature. Additionally, a comparative assessment of different approaches and criteria used globally, including regions like India, the European Union, and the United States, is undertaken as per the reviewed literature. The aim of this research is to draw informed conclusions about the current state of air quality monitoring station siting, and to provide valuable recommendations for enhancing this vital aspect of air quality management.

2.4. Different approaches and techniques used for site selection of air quality monitoring station (AQMS)

Continuous measurements of target air pollutant concentrations at monitoring sites serve as the foundation for air quality management. This vital process, underpinned by rigorous methodologies, has evolved over the past few decades. It involves careful consideration of instruments, techniques, and data-driven strategies for the selection and placement of air quality monitoring stations. Drawing insights from extensive research in the field, this endeavor seeks to enhance the quantity and strategic distribution of these monitoring stations, ensuring comprehensive coverage and reliable data collection.

The selection of air quality monitoring sites is a multifaceted process that relies on various strategies, each tailored to meet specific criteria and objectives as shown in Table 3. These strategies are designed to ensure that monitoring stations are optimally located to capture spatial variations in pollutant concentrations across the study region. One common approach to site selection is to leverage existing air monitoring stations to gain insights into the spatial distribution of pollutants (Ainslie et al., 2009; Pahlavani, Sheikhian and Bigdeli, 2017). These stations provide valuable data that serves as a foundation for understanding pollutant concentration patterns. Multi-pollutant design principles and advanced techniques such as simulation and optimization are employed to determine the ideal locations for air quality monitoring stations. These methodologies take into account factors like cost, coverage efficacy, and spatial correlations (Chang and Tseng, 1999).

Table 3. Different approaches and techniques for site selection of AQMS

Sr. No.	*Single (S) or multi pollutant (M)*	*Optimisation technique*	*Criteria considered*	*Research location*	*References*
1.	M	Simulation and optimisation model	Cost criteria, equity criteria, efficiency criteria	Taiwan	Chang and Tseng (1999)
2.	M	GIS based Decision support system	Industry, traffic, meteorology, topography, emission factors	Turkey	Elbir (2004); Elbir et al. (2010)
3.	M	Multi-Criteria Decision Making	Security, availability of electricity, pollution levels collaborations, easy access, distance, staff support	Turkey, Poland	Hacıoğlu et al. (2016); Orłowski et al. (2017)
4.	M	GIS Suitability Analysis	Population, major roads, industrial areas, high traffic area, wind direction	Kuwait	Alsahli and Al-Harbi (2018)
5.	S	GIS based tool for Urban Planning	Plan area density, gross floor area ratio, height variability, street canyon density, tall vegetation area density	Belgium and Poland	Badach et al. (2020)
6.	S	Kriging method	Topography map, population density, traffic emissions, meteorological and urbanization conditions	Turkey	Bayraktar and Turalioglu (2005)
7.	M	ANP-OWA Method	Source variables, population variables, spatial variables, pollutant variables	Iran	Kazemi-Beydokhti et al. (2019)
8.	S	Sensitivity analysis	"Violation" criterion, proportional-to-variability" criterion	Spain	Miñarro et al. (2020)
9.	M	GIS-based models	Emission inventory sources, traffic count density, road density, population densities, euclidean distance between sites	United Sates	Pope and Wu (2014)
10.	M	Multiple objective planning system for sustainable air quality monitoring networks	Environmental, social, and economic criteria and sub-criteria	Taiwan	Chen et al. (2006)
11.	M	Multiple-criteria Fuzzy Analytic Hierarchy	Environmental, social and cost criteria	Saudi Arabia	Mofarrah and Husain (2010)
12.	S	Location-Allocation models (LAM)	Land use, population and bio-physical information	Canada	Kanaroglou et al. (2005)
13.	M	Multiple cell approach (MCA)	Spatial distributions for the concentrations of the pollutants emitted from different emission sources	Iran	Elkamel et al. (2008)
14.	M	Synthetic assessment concentration	Cost and budget, terrain conditions, administrative district, population density and spatial coverage	China	Zheng et al. (2011)
15.	M	Principal component analysis (PCA) and Fuzzy C- means (FCM)	Height above sea level, roadways, residential areas, industries (m)	Turkey	Dogruparmak et al. (2014)
16.	S	GIS based approach using MINNI gridded emission database	Spatial representativeness for locating sites with high spatial variability	Italy	Righini et al. (2014)
17.	M	Site redundancy of urban monitoring network	Location, distance, direction and traffic	Taiwan	Chan and Hwang, (1996); Pires et al., (2008); Ibarra-Berastegi et al., (2009)
18.	M	Fuzzy similarity measure and fuzzy c-means clustering	Concentration-response relative risk and population attributable-risk proportion	India	Maji et al. (2017), Doval-Miñarro et al., (2020)
19.	M	Ant Colony Optimization algorithm (ACO) and Genetic Algorithm (GA)	Maximize coverage area, maximize violation detection, sensitivity of stations to emissions sources	Iran	Benis et al. (2016)
20.	S	IDW interpolation and spatial grid statistical method using GIS	Spatial representation of monitoring stations	China	Li et al., (2018)

21.	M	atmospheric dispersion model and genetic algorithm	Population size, initial network size, crossover rate, mutation rate	China	Hao and Xie (2018)
22.	M	Particle swarm optimization algorithm	Wind speed, wind direction, traffic volume, emission rate, vehicle category	India	Sangeetha and Amudha (2021)
23.	M	Robust optimization model	Cost of AQMN, wind direction, wind speed, and efficiencies of different port operations	China	Liu et al. (2023), Wang et al. (2023)
24.	M	Multi criteria decision making	Measurements of five air pollutants (PM10, SO_2, CO, NO_2, and O_3)	Turkey	Zeydan and Pekkaya (2021)
25.	S	Multi-source Variational Mode Transfer Learning (MSVMTL)	Hybrid methods combining data decomposition with deep learning for PM2.5 concentration forecasting	China	Yao et al. (2024)

The integration of air dispersion models and Geographic Information System (GIS) software, like CALMET/CALPUFF, allows for a comprehensive estimation of emissions and pollutant spatial distribution (Elbir, 2004; Elbir et al., 2010).

2.4.1. Multi-Criteria Decision Making (MCDM)

Multi-Criteria Decision Making (MCDM) methods, including Analytical Hierarchy Process (AHP) and ELECTRE III, are used to make informed decisions about station placement. These methods consider a range of factors, such as pollution levels, security, electricity availability, collaborations, staff support, accessibility, and distance (Hacıoğlu et al., 2016). Suitability analysis approaches factor in population density, wind direction, proximity to roads, industries, and high-traffic areas to identify optimal monitoring station locations (Alsahli and Al-Harbi, 2018). For regions with available data, geostatistical techniques like kriging are applied to improve geographic resolution by interpolating pollutant concentrations (Bayraktar and Turalioglu, 2005; Kazemi-Beydokhti et al., 2019). Some studies employ optimization algorithms, while others focus on direct site selection to meet macroscale siting requirements, such as those outlined in the European Directive 2008/50/EC (Ferradás et al., 2010; Lozano et al., 2010).

2.4.2. Multivariate statistical techniques

Several multivariate statistical techniques, including Cluster Analysis (CA) and Principal Component Analysis (PCA), have been employed in various studies to assess redundancy, recommend the addition of new monitoring stations, or assign areas to clusters. (Dogruparmak et al., 2014) and (Doval-Miñarro et al., 2020) used PCA and the fuzzy c-mean (FCM) clustering method. (Chan and Hwang, 1996) employed similarity and spatial variation analysis to compare daily pollution standards index and average pollution concentrations for a complete monitoring network and then with a station removed to identify redundant sites. (Maji et al., 2017) classified air quality monitoring stations in Delhi, India, into clusters based on fuzzy similarity measures (SIM) and FCM.

Various methodologies combine multiple criteria and geographic correlation techniques, utilizing data on population exposure and pollutant concentration to determine the optimal number and placement of ambient air quality stations (Mofarrah and Husain, 2010). In cases where a balance between detecting multiple pollutants is essential, sensitivity analysis is employed to suggest a solution for placing a single monitoring station in smaller cities (Miñarro et al., 2020).

2.4.3. Multi-pollutant approaches

The literature features various techniques, both single and multi-pollutant approaches, used to determine the final location of sampling sites. Many studies involve two or more stations, allowing the flexibility to monitor both traffic-oriented and background areas (EPA, 2008). Single-pollutant approaches are limited in addressing the site selection issue for air quality monitoring stations in Indian cities, as all pollutants must be considered. Therefore, multi-pollutant techniques that assess multiple factors, such as Geographic Information System (GIS)-based models incorporating multi-criteria decision-making and suitability analysis, are instrumental in determining the most suitable sites for AQMS in urban areas of India. These decision support systems help estimate emissions and the geographic distribution of air pollutants in Indian urban regions.

2.4.4. Spatial and temporal considerations

Beyond the selection of monitoring station locations, it is essential to assess the validity of the gathered data. Understanding the temporal and spatial distribution of air quality at the landscape scale is crucial for ecological restoration and regional management decisions. Urban air pollution concentrations exhibit significant variations over short distances due to irregular emission sources, dilution, and physicochemical changes, making current fixed-site monitoring methods inadequate for identifying localized pollution hotspots (Apte et al., 2017). To address this, air quality monitoring stations need to be positioned with higher accuracy, supported by a decision support system that considers temporal and spatial representation. The paper discusses various methods that have undergone extensive research as optimization techniques for air quality monitoring station site selection. These methods aim to improve the accuracy and effectiveness of air quality management in India and beyond.

3. Discussions

In this research, we conduct a systematic review of pertinent studies in the field to investigate advancements in optimizing the design of an Air Quality Monitoring Stations (AQMS). Air pollution poses a persistent threat to both the ecosystem and human health. Recognizing the severity of this issue, the World Health Organization (WHO) has prioritized addressing air pollution through a comprehensive air quality monitoring network. Effective air quality management hinges on the identification and quantification of major pollution sources. The assessment of emission reduction measures and adherence to national and international norms are dependent on the data collected from air quality monitoring stations. Historically, the objective of ambient air quality measurement has been to install fixed-location monitors strategically to provide regional or metropolitan data and evaluate specific sources (Brauer et al., 2019).

However, in India, there is a notable discrepancy in the density and siting of monitoring stations compared to similar nations. The issue is not only about the number of monitoring stations but also the specific locations where they are established. India has guidelines, including those of the Central Pollution Control Board and Indian Standard 5182 (part-14): 2000, that emphasize the importance of selecting the right locations for air quality monitoring stations. While these guidelines consider a range of parameters, there is an emphasis on physical requirements. However, these guidelines tend to lack explicit analytical processes for assessing conditions like emission sources, health status, demographics, and land use patterns (WHO, 2014). This raises concerns about the foundational robustness of India's air quality management system.

In contrast, developed regions like the European Union base their siting criteria on both macro and micro scale considerations, aiming to capture exposure in urban and suburban residential areas (UN ECE, 2012). The USA determines monitoring station locations based on multiple factors, including economic, security, logistics, and atmospheric conditions. This discrepancy in site selection criteria highlights a research gap in accurately locating air quality monitoring stations, despite the global reliance on data from these sources.

In determining the optimal siting of Air Quality Monitoring Stations (AQMS), a variety of parameters should be considered, depending on the availability of data. These parameters encompass environmental, pollutant, spatial, population, and economic variables, each playing a crucial role in the decision-making process as shown in Fig. 2. Environmental variables such as wind direction and topography provide insights into the dispersion patterns of pollutants, influencing the selection of monitoring locations. Pollutant variables, including meteorological data, pollutant maps, and emission inventories, offer valuable information on the sources and distribution of pollutants within the study area. Spatial variables such as proximity to high traffic areas, industries, and distance from roads also factor into the decision-making process, reflecting localized sources of pollution. Population variables, which may be derived from surveys, Urban Local Body (ULB) data, and census data, provide insights into the potential human exposure to pollutants, guiding the placement of monitoring stations. Additionally, economic variables such as cost and security considerations play a role in determining the feasibility of establishing monitoring stations in specific locations.

While each criterion holds importance, the authors emphasize the need for a comprehensive approach that considers the interplay of these variables to ensure effective air quality management. Regarding the prioritization of measurements, the authors suggest that both densely populated areas and pollution hotspots should be considered, as each presents unique challenges and insights into air quality dynamics. By strategically placing monitoring stations in both types of locations, a more holistic understanding of air pollution can be obtained, facilitating targeted interventions and policy decisions aimed at improving air quality for all.

3.1. Methodology for air quality monitoring station selection

When selecting air quality monitoring stations, decision-makers must take into account a range of parameters specific to the study area, leading to complex problem-solving conditions. In such situations, Multi-Criteria Decision Making (MCDM) techniques, Geographic Information Systems (GIS), and hybrid approaches prove invaluable. The selection of these methods hinges on the criteria and available input data, as both MCDM techniques and GIS have limitations with certain types of input data. Hybrid techniques, on the other hand, integrate two MCDM methods and are adaptable to various input data types, making them a favorable choice for decision-makers.

To address the critical need for an effective and comprehensive methodology in air quality monitoring station selection, our approach follows a systematic framework, as illustrated in Fig. 3. This methodology is designed to bridge existing gaps in the literature and provide a clear path for researchers and policymakers. The process initiates with a robust emission inventory, meticulously estimating pollution sources and related pollutants within a specified area. This foundational step establishes the groundwork for subsequent analyses. In line with contemporary studies (Elbir et al., 2010; Kazemi-Beydokhti et al., 2019), our selection criteria encompass a range of factors, including economic considerations, pollutant characteristics, spatial correlations, population density, and environmental variables.

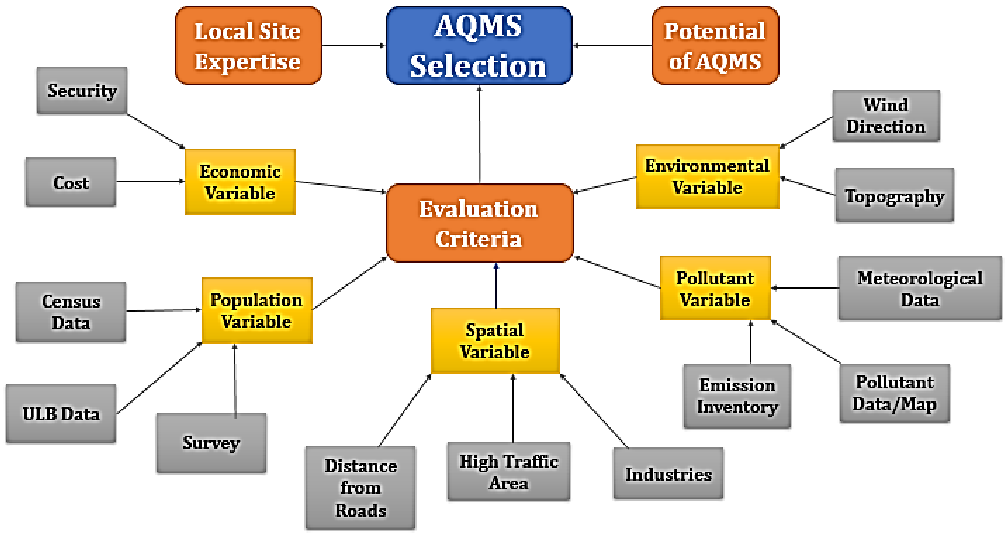

Fig. 2. Criteria for site selection of AQMS in India

These criteria are computed and stored in a Geographic Information System (GIS) database, forming a comprehensive dataset that serves as the basis for decision-making. A pivotal aspect of our methodology is the careful consideration of target pollutants. By focusing on specific local parameters, our approach ensures a tailored and nuanced understanding of air quality dynamics in the study region. This deliberate choice guides subsequent steps in the selection process. Utilizing a multidisciplinary approach, our methodology employs optimization techniques and analyses drawing from statistical, mathematical programming, and GIS models. Fig. 3 provides an overview of the diverse approaches and techniques integrated into our methodology, ensuring a well-rounded and informed decision-making process. These techniques include simulation and optimization models, GIS-based decision support systems, multi-criteria decision-making, and advanced optimization algorithms.

The results of the assessment are critically compared with existing monitoring station locations. If disparities emerge, the process is iteratively refined until an acceptable solution is reached. This iterative refinement ensures that the final selection aligns with the specific objectives of the study and optimally captures spatial variations in pollutant concentrations across the designated region. In summary, our methodology addresses the complexities of air quality monitoring station selection through a systematic, data-driven, and iterative process. By incorporating a range of criteria, optimization techniques, and advanced analyses, we aim to contribute a robust and adaptable framework for researchers and policymakers engaged in air quality management initiatives.

4. Conclusions

In conclusion, this study provides a comprehensive overview of the diverse methodologies employed for the optimal siting of Air Quality Monitoring Stations (AQMS) to enhance air quality management. Air pollution has remained an enduring threat to the environment and human health globally, with urbanization, industrialization, and vehicle emissions contributing significantly to its adverse effects. Regulatory bodies such as the World Health Organization and national initiatives like India's National Clean Air Program have devised strategies to assess air quality through diverse air quality monitoring stations (AQMS) worldwide. The quality of pollutant data gathered from various emission sources directly or indirectly impacts crucial air quality management plans and related actions, particularly in non-attainment cities like those in India. The literature review reveals a plethora of strategies ranging from single to multi-pollutant approaches, each tailored to meet specific criteria and objectives.

The use of Multi-Criteria Decision Making (MCDM) methods, such as Analytical Hierarchy Process (AHP) and ELECTRE III, emerged as a prominent technique, considering factors like pollution levels, security, collaborations, staff support, accessibility, and distance. The exploration of Multi-Pollutant Approaches emphasizes the importance of considering a holistic view when selecting monitoring sites. GIS-based models incorporating multi-criteria decision-making and suitability analysis have proven crucial in urban areas, offering a comprehensive estimation of emissions and pollutant spatial distribution.

Spatial and Temporal Considerations are crucial in ensuring the accuracy of gathered data. Recognizing the significant spatial variations in air pollution concentrations, methods like dispersion models and Geographic Information System (GIS) approaches play a vital role in identifying localized pollution hotspots.

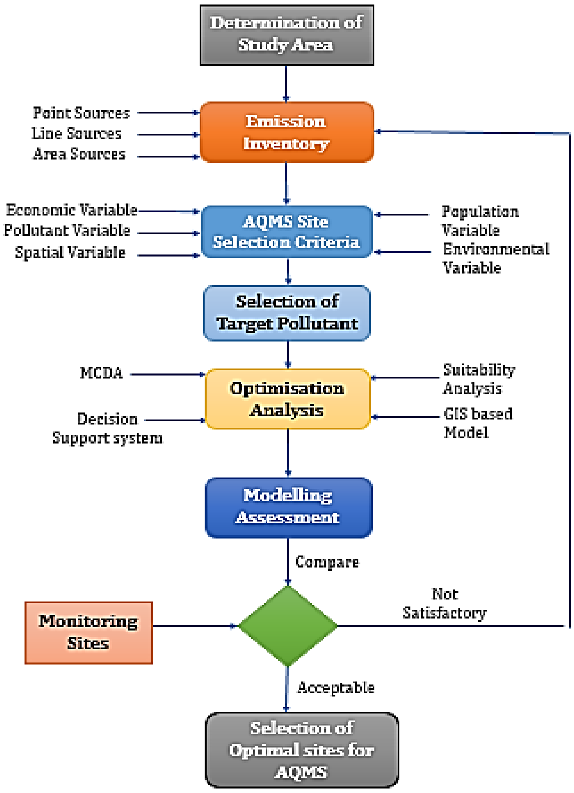

Fig. 3. Systematic structure for optimal siting of air quality monitoring station

Despite the wealth of methodologies discussed in the literature, a noticeable gap remains in seamlessly integrating these techniques into air quality management practices. The study suggests a combined approach that incorporates traditional models and spatial methodologies, providing the potential for more reliable action plans, including source apportionment and hotspot prediction.

In proposing a way forward, it is evident that the criteria for selecting AQMS locations should consider economic, environmental, pollutant, population, and other variables. The emphasis should be on providing high spatial resolution to accurately identify pollution zones. While the physical requirements for AQMS, such as ease of maintenance, are crucial, generating a comprehensive database should be the overarching goal, empowering policymakers to leverage AQMS potential in various air quality management practices.

However, challenges related to data accessibility and the use of substitute data remain recurring concerns. As future research endeavours unfold, addressing these limitations will be pivotal to advancing the field and ensuring more effective air quality management strategies globally.

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