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Application of GIS and Remote Sensing in Ambient Air Quality Assessment in Developing Countries: Methods, Challenges and Future Directions

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ABSTRACT

Ambient air pollution remains one of the major environmental challenges affecting human health and ecosystem sustainability, particularly in developing countries where rapid urbanization, industrial activities, transportation growth, and limited air quality monitoring infrastructure contribute to increasing pollution levels. Conventional ground-based monitoring networks provide valuable air quality information but are often constrained by high operational costs, limited spatial coverage, and inadequate monitoring stations in many developing regions. This review examines the application of Geographic Information Systems (GIS) and remote sensing technologies in ambient air quality assessment in developing countries, with emphasis on major data sources and methodologies, pollutant monitoring and spatial analysis, existing challenges, and emerging trends and future directions. A structured literature review was conducted using Scopus, Web of Science, ScienceDirect, Google Scholar, and PubMed, focusing on peer-reviewed journal articles, review papers, and relevant scientific reports published in English between 2006 and 2026. Studies addressing the application of GIS, remote sensing, satellite observations, and geospatial modelling to ambient air quality assessment in developing countries or regions with limited monitoring infrastructure were prioritized, while selected global studies with significant methodological relevance were also considered. The review synthesizes applications involving satellite observations, Aerosol Optical Depth (AOD), spatial interpolation, geostatistical techniques, ground-based monitoring, meteorological data, and integrated statistical and machine-learning approaches for assessing particulate matter ($PM_{2.5}$ and PM_{10}) and gaseous pollutants, including nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3). The findings demonstrate that integrating GIS and remote sensing can improve pollution mapping, hotspot identification, spatial and temporal assessment, exposure evaluation, and evidence-based environmental management, particularly where conventional monitoring networks are inadequate. However, major challenges include limited ground-validation data, spatial and temporal resolution constraints, atmospheric and environmental uncertainties, technical capacity limitations, data accessibility, financial constraints, and uncertainty associated with modelling and data integration. Emerging directions include artificial intelligence and machine learning, cloud-based geospatial platforms, low-cost air-quality sensors, unmanned aerial vehicles, integration of environmental, climate and health data, and development of localized monitoring frameworks. The novelty of this review lies in its focused synthesis of how GIS and remote sensing can be integrated with complementary monitoring and modelling approaches to address air-quality information gaps in developing countries. Such integration has practical implications for improving environmental monitoring, exposure assessment, pollution-control planning, public-health protection, and sustainable environmental management. Overall, GIS and remote sensing should complement rather than replace conventional monitoring systems, with future progress depending on improved ground validation, local capacity, data integration, and institutional collaboration.

Keywords: Geographic Information System; Remote Sensing; Air Quality Assessment; $PM_{2.5}$; PM_{10}; Satellite Monitoring; Developing Countries; Environmental Management

INTRODUCTION

Air pollution remains one of the most critical environmental challenges affecting human health, climate systems, and ecosystem stability worldwide. Increasing urbanization, industrialization, energy demand, transportation activities, and land-use changes have contributed to rising emissions of major atmospheric pollutants, including particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3). These pollutants are associated with adverse health effects and environmental impacts, making effective air quality monitoring essential for environmental management and public health protection (Kampa & Castanas, 2008; World Health Organization [WHO], 2021).

Particulate matter, particularly fine particles ($PM_{2.5}$), has received significant attention due to its ability to penetrate deep into the respiratory system and its association with increased risks of cardiovascular and respiratory diseases. Long-term exposure to ambient air pollution has been linked to substantial global disease burdens, highlighting the importance of reliable air quality assessment and monitoring systems (Lelieveld et al., 2015; Cohen et al., 2017).

Developing countries face greater challenges in managing air pollution due to rapid population growth, industrial expansion, increased fossil fuel use, transportation emissions, biomass burning, and inadequate environmental monitoring infrastructure. Many regions in Africa, Asia, and Latin America lack sufficient ground-based monitoring stations, resulting in limited information on pollutant distribution, exposure levels, and pollution trends (Amegah & Agyei-Mensah, 2017). Conventional monitoring stations provide accurate measurements but are often constrained by high operational costs, limited spatial coverage, maintenance requirements, and inadequate distribution, particularly in low- and middle-income countries (Martin et al., 2019; Pinder et al., 2019).

The limitations of traditional monitoring systems have encouraged the application of Geographic Information Systems (GIS) and remote sensing technologies as complementary approaches for air quality assessment. GIS provides tools for managing, analysing, and visualizing spatial environmental data, enabling pollutant mapping, spatial interpolation, hotspot identification, and exposure assessment. Remote sensing technologies, particularly satellite-based observations, provide large-scale information on atmospheric pollutants across areas where ground monitoring networks are limited.

Satellite platforms such as the Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging Spectroradiometer (MISR), and Sentinel-5 Precursor equipped with the TROPOspheric Monitoring Instrument (TROPOMI) have improved the monitoring of aerosols and gaseous pollutants, including $PM_{2.5}$, NO_2, SO_2, CO, and ozone (van Donkelaar et al., 2016; Veefkind et al., 2012). Satellite-derived Aerosol Optical Depth (AOD), when combined with chemical transport models, meteorological information, and ground measurements, has been widely applied to estimate surface-level $PM_{2.5}$ concentrations and improve air quality assessment in regions with limited monitoring capacity (van Donkelaar et al., 2016; Hammer et al., 2020).

The integration of GIS and remote sensing has expanded opportunities for identifying pollution hotspots, assessing spatial and temporal variations, estimating population exposure, and supporting evidence-based environmental decision-making. These approaches have been increasingly applied in developing countries to investigate urban pollution, industrial emissions, biomass burning, and other sources of atmospheric pollution. Recent advances in artificial intelligence, machine learning, low-cost sensors, unmanned aerial vehicles (UAVs), and cloud-based geospatial platforms have further improved the potential for developing more accurate and accessible air quality monitoring systems.

Despite these advancements, challenges remain, including limited availability of ground validation data, differences between satellite-derived and surface measurements, technical capacity limitations, restricted access to high-resolution datasets, and financial constraints. Addressing these challenges is necessary to maximize the benefits of GIS and remote sensing technologies for air quality management in developing regions.

Although previous studies have reviewed remote sensing and GIS applications in environmental monitoring, there is still a need for a focused assessment of their application in ambient air quality assessment within developing countries, where monitoring limitations are more pronounced. Therefore, this review examines the application of GIS and remote sensing technologies in ambient air quality assessment in developing countries. Specifically, it discusses major data sources and methodologies, evaluates applications in pollutant monitoring and spatial analysis, highlights existing challenges, and explores emerging trends and future directions for improving air quality assessment and management.

REVIEW METHODOLOGY

This review adopted a structured literature review approach to examine the applications of Geographic Information Systems (GIS) and remote sensing technologies in ambient air quality assessment in developing countries. The review focused on published scientific literature addressing the use of geospatial techniques for monitoring, mapping, modelling, and assessing atmospheric pollutants. Particular attention was given to studies examining particulate matter ($PM_{2.5}$ and PM_{10}) and gaseous pollutants, including nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3), as well as the integration of satellite observations, ground-based measurements, meteorological data, GIS, and spatial modelling techniques.

Literature Search Strategy

A comprehensive literature search was conducted using major academic databases, including Scopus, Web of Science, ScienceDirect, Google Scholar, and PubMed. The search focused on peer-reviewed journal articles, review papers, and relevant scientific reports published in English between 2006 and 2026. This period was selected to capture the substantial development and application of GIS, remote sensing, satellite-based observations, and geospatial modelling techniques in ambient air quality assessment.

The literature search used combinations of keywords related to GIS, remote sensing, air pollution, and developing countries. The principal search terms included:

- GIS and air quality assessment
- Remote sensing and air pollution monitoring
- Satellite-based $PM_{2.5}$ estimation
- GIS mapping of air pollutants
- Remote sensing applications in developing countries
- Satellite air quality monitoring in Africa
- Geospatial techniques for air quality assessment

The search results were screened based on their relevance to the objectives and scope of the review. Particular emphasis was placed on studies that demonstrated the application of GIS, remote sensing, satellite observations, or geospatial modelling to ambient air quality assessment in developing countries or regions where conventional monitoring infrastructure is limited.

Inclusion and Exclusion Criteria

Studies were included when they met the following criteria: **(i)** peer-reviewed journal articles, review papers, or relevant scientific reports; **(ii)** publications written in English; **(iii)** studies focusing on the application of GIS, remote sensing, satellite observations, or geospatial modelling for ambient air quality assessment; and **(iv)** studies conducted in developing countries or regions with limited air quality monitoring infrastructure. Selected global studies were also included where they provided important methodological, technological, or conceptual insights relevant to air quality assessment in developing countries.

Studies unrelated to ambient air pollution assessment, publications without sufficient methodological information, duplicate records, and sources that did not provide relevant scientific or technical information were excluded.

Data Extraction and Synthesis

Relevant information was extracted from the selected literature, including study location, pollutants assessed, data sources, GIS and remote sensing techniques, modelling approaches, applications, challenges, and major findings. The extracted information was organized and synthesized thematically according to the major areas of application identified in the literature.

The synthesis focused on **(i)** major GIS and remote sensing data sources and methodologies; **(ii)** applications in particulate matter and gaseous pollutant assessment; **(iii)** spatial mapping, hotspot identification, exposure assessment, and environmental management; **(iv)** applications across selected developing regions; **(v)** technical, methodological, institutional, and data-related challenges; and **(vi)** emerging technologies and future research directions. This approach enabled the review to identify common applications, limitations, opportunities, and research gaps associated with the use of GIS and remote sensing for ambient air quality assessment in developing countries.

Overview of GIS and Remote Sensing Technologies

Geographic Information Systems (GIS) in Air Quality Assessment

Geographic Information Systems (GIS) are computer-based systems designed for the collection, storage, management, analysis, and visualization of geographically referenced data. GIS integrates spatial and attribute information, allowing researchers to examine relationships between environmental variables, identify spatial patterns, and support decision-making processes. In air quality assessment, GIS has become an important tool for analysing the distribution of atmospheric pollutants and understanding the relationship between pollution levels, emission sources, environmental conditions, and human exposure.

The application of GIS in air quality studies involves the integration of multiple datasets, including pollutant measurements from monitoring stations, satellite observations, meteorological variables, land-use characteristics, traffic information, industrial activities, and population distribution. By combining these datasets, GIS provides a comprehensive framework for evaluating pollution patterns and identifying areas with elevated environmental risks.

One of the major applications of GIS in air quality assessment is spatial mapping of pollutant concentrations. Through geostatistical techniques such as Inverse Distance Weighting (IDW), Kriging, and spline interpolation, GIS can estimate pollutant concentrations between monitoring locations and generate continuous pollution distribution maps. These spatial models are particularly useful in areas where monitoring stations are limited because they provide information about pollution levels across larger geographical areas.

GIS is also widely applied in pollution hotspot identification. Spatial analysis techniques allow researchers to locate areas with high pollutant concentrations and examine possible relationships with emission sources such as industrial facilities, road networks, mining activities, and urban development. Identifying pollution hotspots is essential for environmental planning, regulatory interventions, and targeted pollution reduction strategies.

Another important application is air pollution exposure assessment. GIS enables the integration of air quality data with demographic information, including population density, land use, and locations of sensitive groups such as schools, hospitals, and residential areas. This approach supports the evaluation of population exposure and helps identify communities that may face greater health risks due to air pollution.

GIS has also contributed to the development of air quality models by providing spatial inputs required for statistical and computational analyses. For example, GIS-based models can incorporate information on elevation, vegetation cover, meteorological conditions, and emission sources to improve predictions of pollutant distribution. These applications have become increasingly important in developing countries where limited monitoring infrastructure requires innovative approaches for environmental assessment.

Overall, GIS provides a flexible framework for integrating air quality measurements with spatial, environmental, meteorological, demographic, and land-use information. Its ability to support spatial interpolation, hotspot identification, exposure assessment, and visualization makes it particularly useful in developing countries where monitoring stations are often unevenly distributed. However, the reliability of GIS-based assessments depends strongly on the quality, spatial representativeness, and availability of the underlying datasets.

Remote Sensing Technologies and Satellite-Based Air Quality Monitoring

Remote sensing refers to the acquisition of information about the Earth's surface and atmosphere without direct physical contact, usually through sensors mounted on satellites, aircraft, or unmanned aerial systems. In air quality assessment, remote sensing provides observations of atmospheric composition and environmental conditions over large spatial scales, making it particularly valuable in regions with limited ground-based monitoring networks.

Satellite remote sensing has significantly improved the ability to monitor atmospheric pollutants by providing repeated measurements over time. Different satellite sensors are designed to detect specific atmospheric characteristics, including aerosol properties, trace gases, and atmospheric composition. These observations provide valuable information for studying pollution distribution, emission sources, and temporal changes in air quality.

One of the most widely applied remote sensing approaches in air quality research involves the estimation of particulate matter concentrations. Satellite-derived Aerosol Optical Depth (AOD), which measures the extent to which aerosols prevent the transmission of light through the atmosphere, has been extensively used as an indicator for estimating ground-level $PM_{2.5}$ concentrations. By combining AOD data with meteorological information, chemical transport models, and ground measurements, researchers have developed improved estimates of particulate pollution over areas with limited monitoring stations.

The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra and Aqua satellites has been widely used for aerosol monitoring and PM estimation. Similarly, the Sentinel-5 Precursor (Sentinel-5P) satellite, launched by the European Space Agency, provides high-resolution observations of atmospheric gases, including nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), methane (CH_4), and ozone (O_3). These datasets have expanded the capacity for monitoring pollution sources associated with transportation, industries, energy production, and biomass burning.

Remote sensing is particularly beneficial in developing countries because it provides regional-scale information that may not be available through conventional monitoring networks. For example, satellite observations have been used to assess seasonal variations in air pollution caused by biomass burning, dust events, urban emissions, and industrial activities. This information supports environmental assessment, climate studies, and public health research.

However, satellite-based air quality assessment also has limitations. Satellite measurements represent atmospheric conditions at specific observation times and may not directly correspond to ground-level pollutant concentrations. Factors such as cloud cover, atmospheric conditions, surface reflectance, and spatial resolution

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can influence satellite observations. Therefore, integration with ground-based measurements and atmospheric modelling approaches is often necessary to improve accuracy and reliability.

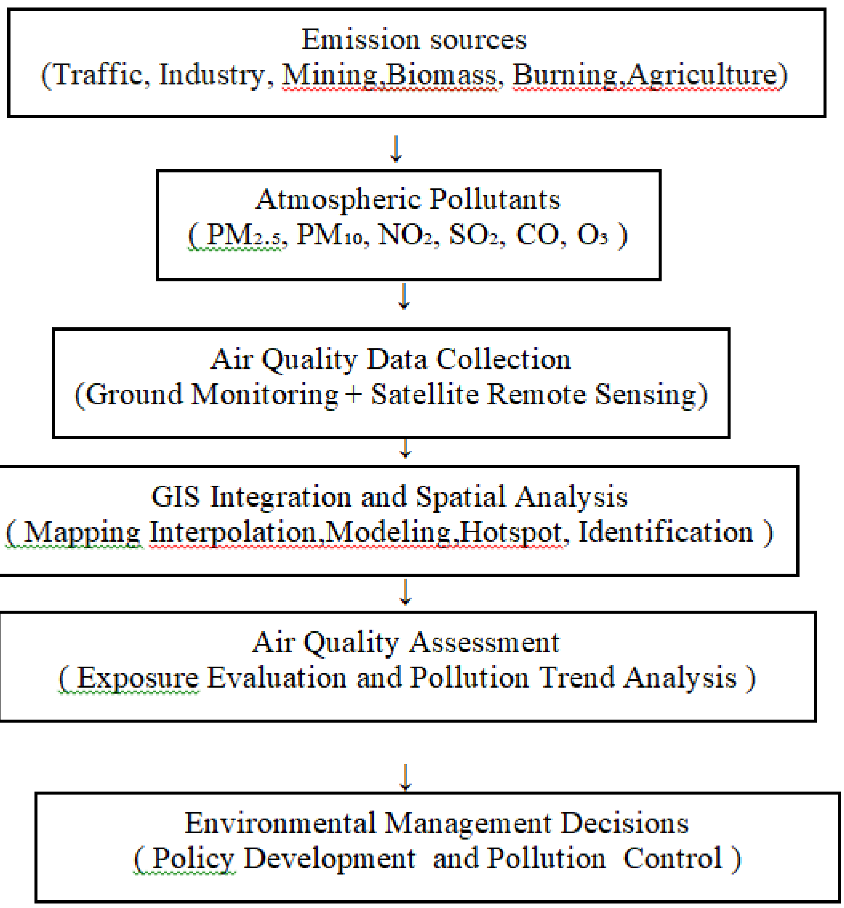
The combination of GIS and remote sensing provides a powerful framework for air quality assessment by linking satellite-derived atmospheric information with spatial analysis techniques. While remote sensing provides broad-scale observations, GIS enables the processing, visualization, and interpretation of these data for environmental management applications. Together, these technologies have become essential tools for improving air quality monitoring, particularly in developing countries where conventional monitoring systems remain limited.

Sources and Types of Air Quality Data in Developing Countries

Reliable air quality assessment depends on the availability of accurate, consistent, and spatially representative datasets. In developing countries, obtaining comprehensive air quality information remains challenging due to limited monitoring infrastructure, financial constraints, and inadequate technical capacity. Consequently, researchers increasingly rely on a combination of ground measurements, satellite observations, meteorological datasets, and modelling approaches to improve understanding of atmospheric pollution patterns (Martin et al., 2019; Pinder et al., 2019).

Figure 1. Conceptual Framework for GIS and Remote Sensing-Based Ambient Air Quality Assessment in Developing Countries

Figure 1 illustrates the integration of emission sources, atmospheric pollutants, ground-based monitoring, satellite remote sensing, GIS, and spatial modelling in ambient air quality assessment. The framework demonstrates how multiple data sources are combined to support pollution mapping, exposure assessment, and evidence-based air quality management in developing countries.



Source: Developed by the authors based on the reviewed literature (2026).

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Ground-Based Air Quality Monitoring Data

Ground-based monitoring remains the traditional approach for measuring ambient air pollutant concentrations. These systems use instruments installed at fixed locations to measure pollutants such as $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3. Data obtained from monitoring stations provide direct measurements of pollutant concentrations and are essential for regulatory compliance, exposure assessment, and validation of satellite-derived estimates (Snyder et al., 2013).

However, many developing countries have inadequate ground monitoring networks compared with high-income countries. Monitoring stations are often concentrated in major cities, while rural areas, industrial zones, and rapidly developing regions may have little or no monitoring coverage. This uneven distribution limits the ability to accurately characterize spatial variations in air pollution and assess population exposure (Amegah & Agyei-Mensah, 2017).

The cost of purchasing, operating, and maintaining advanced monitoring equipment is a major limitation. In addition, challenges such as equipment calibration, power supply, data management, and availability of trained personnel can affect the sustainability of monitoring programmes in developing regions (Pinder et al., 2019). Despite these limitations, ground-based measurements remain critical because they provide the reference data required to validate satellite observations and improve air quality models.

Satellite-Derived Air Quality Data

Satellite remote sensing has become an important alternative and complementary source of air quality information, particularly in areas where ground monitoring networks are insufficient. Satellite instruments provide large-scale observations of atmospheric pollutants and allow researchers to evaluate spatial and temporal variations in air quality over extensive geographical regions (van Donkelaar et al., 2016).

Satellite-derived aerosol products, particularly Aerosol Optical Depth (AOD), have been widely used to estimate surface-level $PM_{2.5}$ concentrations. AOD measurements describe the amount of solar radiation scattered and absorbed by atmospheric particles and can be converted into ground-level particulate matter estimates through statistical models, chemical transport models, and machine learning techniques (van Donkelaar et al., 2016; Hammer et al., 2020).

The availability of satellite missions such as MODIS, MISR, OMI, and Sentinel-5P/TROPOMI has improved the monitoring of both particulate and gaseous pollutants. MODIS has contributed significantly to aerosol monitoring, while Sentinel-5P provides high-resolution observations of trace gases, including NO_2, SO_2, CO, and O_3 (Veefkind et al., 2012).

For developing countries, satellite datasets provide opportunities to overcome limitations associated with sparse monitoring networks. They have been applied to investigate urban pollution, industrial emissions, biomass burning, dust events, and regional transport of pollutants across national boundaries (Pinder et al., 2019).

Meteorological and Environmental Data

Meteorological conditions strongly influence the concentration and distribution of atmospheric pollutants. Variables such as temperature, wind speed, wind direction, rainfall, humidity, and atmospheric pressure affect pollutant dispersion, chemical transformation, and removal processes (Seinfeld & Pandis, 2016).

Integration of meteorological data with GIS and remote sensing observations improves the accuracy of air quality assessment. For example, wind patterns can help identify pollution transport pathways, while temperature and humidity information can improve satellite-based estimates of particulate matter concentrations (Gupta et al., 2006).

Environmental variables such as land use, vegetation cover, elevation, road networks, and industrial locations are also commonly incorporated into GIS-based air quality studies. These datasets help researchers understand relationships between human activities, environmental conditions, and pollutant distribution (Beelen et al., 2013).

Integrated Modelling Approaches

Recent air quality studies increasingly combine multiple data sources through integrated modelling approaches. These approaches involve the combination of ground observations, satellite measurements, meteorological information, emission inventories, and statistical or machine learning models to generate improved pollution estimates (Di et al., 2019).

Machine learning techniques, including random forests, artificial neural networks, and deep learning models, have improved the prediction of pollutant concentrations by identifying complex relationships between environmental variables and air pollution patterns (Li et al., 2020). These approaches are particularly valuable in developing countries where monitoring data are limited but satellite and environmental datasets are increasingly available.

The integration of GIS, remote sensing, and modelling techniques provides a more comprehensive understanding of air pollution patterns and supports evidence-based decision-making. Such approaches are increasingly important for developing countries seeking cost-effective solutions for air quality monitoring and environmental management.

Applications of GIS and Remote Sensing in Ambient Air Quality Assessment

The integration of Geographic Information Systems (GIS) and remote sensing has significantly improved the capacity to monitor, analyse, and manage ambient air pollution, particularly in regions where conventional monitoring networks are inadequate. These technologies provide spatially continuous information, allowing researchers to identify pollution patterns, estimate pollutant concentrations, assess exposure risks, and support environmental decision-making (Snyder et al., 2013; van Donkelaar et al., 2016). In developing countries, where air quality monitoring stations are often limited, GIS and satellite-based approaches have become valuable tools for expanding pollution assessment capabilities.

Mapping and Monitoring of Particulate Matter ($PM_{2.5}$ and PM_{10})

Particulate matter remains one of the most widely studied air pollutants because of its significant impacts on human health and environmental quality. Fine particulate matter ($PM_{2.5}$) is especially important due to its ability to penetrate deep into the respiratory system and its strong association with adverse health outcomes (Pope & Dockery, 2006; Cohen et al., 2017).

Remote sensing has improved the assessment of particulate pollution by providing large-scale observations through satellite-derived aerosol products. Aerosol Optical Depth (AOD) obtained from satellite sensors such as MODIS has been extensively applied to estimate ground-level $PM_{2.5}$ concentrations. By combining AOD measurements with meteorological variables, chemical transport models, and ground monitoring data, researchers have developed high-resolution estimates of particulate pollution over areas with limited monitoring infrastructure (van Donkelaar et al., 2016; Hammer et al., 2020).

GIS techniques are commonly applied to visualize and analyse spatial variations in PM concentrations. Spatial interpolation methods, including Inverse Distance Weighting (IDW) and Kriging, have been used to generate pollution distribution maps from monitoring data. These approaches help identify areas with elevated particulate matter concentrations and support the assessment of spatial exposure patterns (Jerrett et al., 2005).

In developing countries, satellite-based PM assessment has been particularly useful for studying urban pollution, biomass burning, desert dust events, and industrial emissions. For example, studies in African and

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Asian cities have used satellite observations to examine spatial and seasonal variations in $PM_{2.5}$ concentrations where ground-based measurements were insufficient (Amegah & Agyei-Mensah, 2017; Pinder et al.,2019)

Assessment of Gaseous Pollutants Using Remote Sensing

Beyond particulate matter, GIS and remote sensing have contributed significantly to monitoring atmospheric gases, including nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3). These pollutants are associated with transportation activities, industrial processes, energy production, and biomass combustion.

Nitrogen dioxide is one of the most commonly monitored gaseous pollutants using satellite remote sensing. The launch of the Sentinel-5 Precursor satellite equipped with the TROPOspheric Monitoring Instrument (TROPOMI) has provided improved spatial resolution measurements of NO_2 and other atmospheric gases (Veefkind et al., 2012). Satellite-derived NO_2 data have been widely used to investigate traffic emissions, industrial pollution, and urban air quality trends.

Sulphur dioxide monitoring through satellite observations has also provided important information about emissions from power plants, industrial facilities, and volcanic activities. Sensors such as the Ozone Monitoring Instrument (OMI) have been applied to detect SO_2 emissions and assess their spatial distribution over large regions (Levelt et al., 2018).

Carbon monoxide and ozone have also been assessed using satellite platforms. CO observations provide information about incomplete combustion processes, including biomass burning and fossil fuel combustion, while ozone measurements contribute to understanding atmospheric chemistry and secondary pollutant formation (Seinfeld & Pandis, 2016).

GIS enhances the interpretation of satellite-derived gaseous pollutant data by enabling spatial analysis, integration with emission sources, and identification of pollution hotspots. Combining satellite observations with land-use information, transportation networks, and industrial locations allows researchers to better understand pollutant sources and distribution patterns.

Identification of Air Pollution Hotspots

One of the major advantages of GIS-based air quality assessment is the ability to identify pollution hotspots. Hotspot analysis involves locating areas with unusually high pollutant concentrations and evaluating possible relationships with emission sources and environmental characteristics.

GIS techniques such as spatial clustering, interpolation, and overlay analysis are widely used to identify pollution hotspots. These approaches allow researchers to combine air quality measurements with information on roads, industries, population density, and land-use patterns to determine areas requiring priority intervention (Jerrett et al., 2005).

In developing countries, hotspot mapping has been applied in urban environments where traffic congestion, industrial activities, and rapid population growth contribute significantly to air pollution. Satellite observations have also been used to detect regional pollution patterns associated with seasonal biomass burning, agricultural activities, and transboundary transport of pollutants (Kumar et al., 2020).

The identification of pollution hotspots supports environmental planning by helping policymakers develop targeted control strategies. For example, authorities can prioritize emission reduction measures, improve monitoring coverage, and protect vulnerable populations in high-risk areas.

Population Exposure Assessment and Health Risk Evaluation

GIS and remote sensing have become important tools for evaluating human exposure to air pollution. Exposure assessment requires understanding not only pollutant concentrations but also the location and characteristics of exposed populations.

By integrating pollution maps with demographic data, land-use information, and health-related datasets, GIS enables researchers to estimate population exposure and identify communities at increased risk. This approach is particularly valuable in developing countries where health impacts may be underestimated due to limited environmental monitoring and health surveillance systems (Beelen et al., 2013).

Remote sensing-based exposure studies have been used to estimate long-term exposure to $PM_{2.5}$ and evaluate associations with disease outcomes. Satellite-derived pollution estimates provide opportunities for investigating health impacts over large populations and regions where monitoring data are unavailable (Di et al., 2019).

Exposure assessment using GIS also supports environmental justice studies by identifying whether vulnerable communities experience higher pollution burdens due to proximity to industries, major roads, or other emission sources.

Urban and Industrial Air Quality Studies

Urban areas in developing countries are experiencing increasing air quality challenges due to population growth, transportation expansion, energy consumption, and industrial development. GIS and remote sensing provide valuable approaches for monitoring urban pollution patterns and evaluating environmental changes.

Satellite observations have been used to assess urban NO_2 concentrations, particulate matter distribution, and emission trends associated with economic activities and urban expansion. GIS-based analyses help researchers examine relationships between pollution levels and urban characteristics such as road density, land cover, building patterns, and industrial zones (Beelen et al., 2013).

Industrial regions also benefit from geospatial approaches because GIS and remote sensing allow assessment of pollution impacts around mining areas, manufacturing zones, power plants, and other emission sources. These technologies provide cost-effective methods for monitoring large areas and supporting environmental management, particularly where continuous ground monitoring is unavailable.

Applications of GIS and Remote Sensing in Developing Countries: Case Studies

Table 1. Summary of Previous GIS and Remote Sensing-Based Air Quality Studies in Developing Countries

Several studies have demonstrated the effectiveness of integrating GIS and remote sensing techniques for ambient air quality assessment in developing regions. These approaches have been applied to estimate pollutant concentrations, identify spatial patterns, and overcome limitations associated with inadequate ground monitoring networks. Table 1 summarizes selected studies that highlight the applications, data sources, and major findings of GIS and remote sensing-based air quality assessments.

Author(s)	Country/ Region	Pollutant(s) Studied	Data Source	Methods / Technology used	Major Findings
Gupta et al. (2006)	India	PM_{10}, Aerosols	Satellite AOD and ground observations	Remote sensing and statistical analysis	Demonstrated the usefulness of satellite AOD for particulate pollution assessment.
van Donkelaar et al. (2010)	Global including developing regions	$PM_{2.5}$	Satellite AOD, chemical transport models	GIS integration and modelling	Developed global $PM_{2.5}$ estimates using satellite and atmospheric models.
Kumar et	India	$PM_{2.5}$, PM_{10}	Ground monitoring and	GIS-based spatial	Identified spatial variations and urban pollution

al. (2011)			satellite data	analysis	hotspots.
Hammer et al. (2020)	Global (including developing regions)	$PM_{2.5}$	Satellite observations, chemical transport models, and ground monitoring	Integrated satellite-based $PM_{2.5}$ estimation and modelling	Produced high-resolution global $PM_{2.5}$ estimates by integrating satellite observations with chemical transport models and ground measurements
Martin (2008)	Global	Aerosols and trace gases	Satellite remote sensing data	Atmospheric monitoring	Demonstrated satellite capability for regional air pollution monitoring.
Zeng et al. (2018)	China	$PM_{2.5}$	Satellite AOD and land-use data	GIS and machine learning models	Improved $PM_{2.5}$ estimation using spatial datasets and modelling.
Kota et al. (2020)	India	$PM_{2.5}$, PM_{10}	Satellite data and ground monitoring stations	GIS mapping and statistical analysis	Identified seasonal and spatial patterns of particulate pollution.
Adeyemi et al. (2022)	Nigeria	$PM_{2.5}$, PM_{10}	Ground measurements and GIS data	Spatial interpolation and mapping	Highlighted GIS for pollution mapping in data-limited areas.

Table 1 demonstrates that GIS and remote sensing techniques have been widely applied in developing countries to address limitations associated with inadequate ground-based air quality monitoring networks. Studies across Asia, Africa, and other developing regions have integrated satellite observations, ground measurements, and spatial modelling approaches to characterize pollution patterns, estimate exposure levels, and support air quality management decisions. These applications highlight the potential of geospatial technologies to improve air quality assessment, particularly in regions where conventional monitoring infrastructure remains limited

Developing countries face significant air quality challenges due to rapid urbanization, industrialization, increasing energy demand, transportation growth, and changing land-use patterns. However, limited ground-based monitoring networks have created difficulties in obtaining comprehensive air pollution information. The application of GIS and remote sensing has provided opportunities for improving air quality assessment by expanding spatial coverage, identifying pollution sources, and supporting environmental management. This section highlights applications from selected developing regions, including Africa, Asia, and Latin America.

Applications in Africa

Africa remains one of the regions with limited air quality monitoring capacity despite increasing concerns about ambient air pollution. Many African cities experience elevated pollution levels associated with vehicle emissions, household energy use, open burning, industrial activities, and dust events. The scarcity of long-term monitoring stations has encouraged the use of satellite observations and GIS-based approaches for assessing pollution patterns (Amegah & Agyei-Mensah, 2017).

In Nigeria, GIS and remote sensing techniques have been applied to investigate air pollution patterns associated with urbanization, industrial activities, transportation, and energy production. Satellite-derived observations have provided valuable information on the distribution of pollutants such as NO_2, CO, and particulate matter in major urban areas where routine monitoring data are limited. These approaches have supported the identification of pollution hotspots and improved understanding of the spatial distribution of atmospheric pollutants (Obioh et al., 2013).

Remote sensing has also been used to examine the influence of biomass burning and seasonal atmospheric conditions on air quality across different parts of Africa. Satellite observations from MODIS and other platforms have helped identify fire events and estimate aerosol concentrations associated with vegetation burning, particularly during dry seasons (Ichoku et al., 2016). These studies are important because biomass burning contributes significantly to particulate pollution in many African regions.

In South Africa, where air quality monitoring networks are relatively more developed compared with many other African countries, GIS and remote sensing have been used alongside ground measurements to assess industrial emissions, mining-related pollution, and urban air quality. Satellite observations have supported the monitoring of NO_2 and SO_2 emissions from industrial regions and energy production activities (Waldner et al., 2012).

Despite increasing applications, many African countries still face challenges including inadequate validation data, limited technical expertise, and restricted access to high-resolution environmental datasets. Strengthening collaboration between research institutions, government agencies, and international organizations remains essential for expanding geospatial air quality monitoring capacity across the continent.

Applications in Asia

Asia contains some of the most densely populated urban regions globally and has experienced rapid economic growth accompanied by increased emissions from transportation, industries, and energy production. As a result, GIS and remote sensing have become important tools for monitoring and managing air pollution across many Asian developing countries.

In India, satellite-based observations have been extensively applied to study $PM_{2.5}$ pollution due to limited availability of ground monitoring stations in many regions. Researchers have combined satellite-derived AOD, meteorological data, and statistical models to estimate particulate matter concentrations and evaluate long-term exposure patterns (Dey et al., 2012; van Donkelaar et al., 2016). These studies have provided valuable information for understanding regional pollution trends and supporting public health assessments.

China has also extensively applied remote sensing and GIS technologies for monitoring atmospheric pollution. Satellite observations have been used to analyse spatial patterns of $PM_{2.5}$, NO_2, and other pollutants, while GIS-based approaches have supported hotspot identification and emission source analysis. These methods have contributed to evaluating the effectiveness of pollution control policies and understanding changes in air quality over time (Zhang et al., 2017).

Other Asian developing countries, including Bangladesh, Pakistan, and Indonesia, have adopted satellite-based approaches to investigate urban pollution, industrial emissions, and biomass burning impacts. For example, remote sensing has been used to monitor pollution episodes associated with crop residue burning, which contributes significantly to seasonal increases in particulate matter concentrations in parts of South Asia (Cusworth et al., 2018).

The widespread application of GIS and remote sensing in Asia demonstrates the potential of geospatial technologies for improving air quality assessment in regions experiencing rapid environmental change.

Applications in Latin America

Latin American countries have also adopted GIS and remote sensing approaches to address increasing air quality concerns associated with urban growth, transportation emissions, industrial activities, and biomass burning. Large metropolitan areas such as Mexico City, São Paulo, and Santiago have used geospatial technologies to monitor pollution patterns and support environmental management.

In Mexico, satellite observations and GIS analyses have contributed to understanding urban air pollution trends, particularly for particulate matter and gaseous pollutants. Remote sensing data have been combined with ground observations and atmospheric measurements to evaluate pollution distribution and identify pollution patterns (Massie et al., 2006).

Brazil has applied remote sensing techniques extensively to investigate atmospheric pollution associated with biomass burning in the Amazon region. Satellite fire detection products have been used to monitor burning activities and evaluate their contribution to aerosol emissions and regional air quality changes (Andreae et al., 2015). GIS-based approaches have supported the analysis of fire locations, land-use changes, and environmental impacts.

In Chile and other South American countries, satellite observations have been integrated with ground measurements to assess particulate pollution in urban areas. These applications demonstrate the value of combining multiple data sources to overcome limitations associated with traditional monitoring systems.

Lessons from Developing Country Applications

The reviewed applications demonstrate that GIS and remote sensing provide important opportunities for improving air quality assessment in developing countries. Their major advantages include:

- Wide spatial coverage: Satellite observations allow assessment of pollution patterns over large regions, including areas without monitoring stations.
- Cost-effectiveness: Remote sensing provides environmental information without requiring extensive networks of ground instruments.
- Historical analysis: Satellite archives allow researchers to examine long-term pollution trends.
- Integration capability: GIS enables combination of pollution data with demographic, health, meteorological, and land-use information.

However, successful application requires adequate validation using ground measurements, technical expertise, reliable data processing capacity, and institutional support. Developing countries can maximize the benefits of these technologies by strengthening monitoring networks and improving access to geospatial data resources.

Challenges and Limitations of GIS and Remote Sensing Applications in Air Quality Assessment

Although GIS and remote sensing technologies have significantly improved the capacity for air quality assessment, their application in developing countries is associated with several technical, institutional, and methodological challenges. Understanding these limitations is essential for improving the reliability of geospatial air quality assessments and ensuring that results can effectively support environmental management and public health decisions.

Limited Availability of Ground-Based Validation Data

One of the major challenges affecting satellite-based air quality assessment is the limited availability of reliable ground monitoring data for validation. Satellite observations provide information about atmospheric conditions over large areas; however, they often require comparison with surface measurements to ensure accuracy and reliability (Snyder et al., 2013).

Many developing countries have inadequate air quality monitoring networks due to financial limitations, high equipment costs, and insufficient maintenance capacity. The lack of continuous ground observations makes it difficult to evaluate satellite-derived pollutant estimates and develop locally calibrated models (Amegah & Agyei-Mensah, 2017).

For example, satellite-derived $PM_{2.5}$ estimates require validation using ground-level measurements because relationships between aerosol optical depth (AOD) and surface particulate concentrations vary depending on meteorological conditions, atmospheric composition, and geographical characteristics (van Donkelaar et al., 2016). Strengthening ground monitoring networks is therefore necessary to improve the accuracy of remote sensing applications.

Spatial and Temporal Resolution Limitations

Satellite data provide extensive geographical coverage, but their usefulness may be affected by limitations in spatial and temporal resolution. Different satellite sensors have varying levels of resolution, which may influence their ability to detect pollution variations at local scales.

For instance, coarse-resolution satellite products may not accurately represent pollution variations within highly urbanized areas, industrial zones, or locations affected by localized emission sources. A pollution hotspot near a factory, highway, or mining operation may not be adequately captured if the satellite resolution is too broad (Martin et al., 2019).

Similarly, satellite observations are often collected at specific times during satellite overpasses, which may not represent daily or hourly pollution variations. Since pollutant concentrations can change rapidly due to traffic patterns, weather conditions, and emission activities, combining satellite observations with ground measurements and atmospheric models is often necessary.

Atmospheric and Environmental Factors Affecting Data Accuracy

Remote sensing measurements can be influenced by atmospheric and environmental conditions. Factors such as cloud cover, humidity, surface reflectance, atmospheric scattering, and seasonal variations can affect satellite observations and introduce uncertainties into pollution estimates (Gupta et al., 2006).

Cloud contamination remains a major limitation for optical satellite sensors because cloud-covered areas may prevent accurate retrieval of atmospheric information. This challenge is particularly important in tropical and humid regions where frequent cloud cover can reduce the availability of usable satellite observations.

In addition, the relationship between satellite measurements and surface pollutant concentrations can vary depending on meteorological conditions. For example, aerosol characteristics, atmospheric mixing height, and humidity levels influence the conversion of satellite-derived aerosol information into ground-level $PM_{2.5}$ estimates (van Donkelaar et al., 2016).

Technical Capacity and Expertise Requirements

The effective use of GIS and remote sensing for air quality assessment requires specialized knowledge in spatial analysis, satellite data processing, statistical modelling, and environmental interpretation. Many developing countries face shortages of trained personnel with expertise in advanced geospatial techniques.

Although satellite datasets are increasingly becoming freely available, processing and interpreting these datasets require appropriate software skills, computational resources, and technical training. Limited institutional capacity can restrict the adoption of advanced geospatial methods in environmental agencies and research institutions (Pinder et al., 2019).

Capacity building through training programmes, research collaborations, and investment in geospatial education is necessary to improve the application of GIS and remote sensing technologies in developing regions.

Data Accessibility and Financial Constraints

Although many satellite datasets are freely available, access to high-resolution environmental data, advanced computing resources, and specialized software can remain challenging for researchers in developing countries. Some air quality modelling approaches require significant computational capacity and technical infrastructure.

Financial limitations may also affect the establishment of integrated monitoring systems that combine satellite observations, ground measurements, and modelling approaches. Sustainable funding is required to maintain monitoring networks, support research activities, and develop environmental information systems.

Open-access satellite platforms and cloud-based geospatial tools, such as Google Earth Engine, have reduced some barriers by providing access to large environmental datasets and processing capabilities. However, continued investment in digital infrastructure and research capacity remains necessary.

Uncertainty in Modelling and Data Integration

The integration of GIS, remote sensing, and modelling approaches introduces uncertainties that must be carefully considered. Different datasets may have variations in spatial resolution, measurement techniques, and accuracy levels, which can affect final pollution estimates.

Machine learning and statistical models have improved air quality predictions; however, their performance depends on the quality and representativeness of input data. Models developed using data from highly monitored regions may not perform equally well when applied to developing countries with different emission characteristics, climate conditions, and environmental factors (Di et al., 2019).

Therefore, locally developed models and region-specific calibration approaches are important for improving the reliability of air quality assessments.

Institutional and Policy Challenges

Beyond technical limitations, institutional and policy challenges also influence the effective use of GIS and remote sensing for air quality management. In some developing countries, limited coordination between environmental agencies, research institutions, and policymakers reduces the application of scientific findings in decision-making.

Improving air quality management requires stronger institutional frameworks, data-sharing mechanisms, and collaboration among stakeholders. The integration of geospatial information into environmental policies can support evidence-based planning and improve pollution control strategies.

Summary

GIS and remote sensing have significantly expanded opportunities for air quality assessment in developing countries; however, challenges related to data availability, technical capacity, resolution limitations, and institutional support must be addressed. Improving the integration of satellite observations with ground monitoring networks, advanced modelling approaches, and local expertise will be essential for maximizing the benefits of geospatial technologies in future air quality management.

Emerging Trends and Future Directions in GIS and Remote Sensing for Air Quality Assessment

Advances in geospatial technologies, computational methods, and environmental monitoring systems are creating new opportunities for improving air quality assessment, particularly in developing countries. While traditional GIS and remote sensing approaches have significantly improved understanding of pollutant distribution, emerging technologies are providing more accurate, timely, and integrated solutions. Future developments are expected to focus on combining multiple data sources, improving prediction capabilities, and increasing accessibility of air quality information for environmental management and public health applications.

Artificial Intelligence and Machine Learning Applications

Artificial intelligence (AI) and machine learning (ML) techniques have become increasingly important in air quality assessment due to their ability to analyse large and complex environmental datasets. Unlike traditional statistical approaches, machine learning algorithms can identify complex relationships between air pollutants and influencing factors such as meteorological conditions, land-use characteristics, emission sources, and satellite observations (Di et al., 2019).

Machine learning models, including random forests, support vector machines, artificial neural networks, and deep learning algorithms, have been applied to improve predictions of pollutants such as $PM_{2.5}$, PM_{10}, NO_2, and ozone. These approaches can integrate satellite-derived data with ground observations and environmental variables to produce high-resolution pollution estimates (Li et al., 2020).

In developing countries, machine learning offers significant potential because it can help overcome limitations caused by sparse monitoring networks. By using satellite observations and available environmental datasets, predictive models can generate air quality information for areas where direct measurements are unavailable. However, successful application requires locally representative datasets and adequate technical expertise.

Cloud-Based Geospatial Platforms

The emergence of cloud-based geospatial platforms has transformed the accessibility and processing of environmental data. Platforms such as Google Earth Engine (GEE) provide researchers with access to extensive satellite archives and computational resources without requiring high-performance local computer systems (Gorelick et al., 2017).

Google Earth Engine has been increasingly applied in environmental studies involving land-use change, climate monitoring, and atmospheric pollution assessment. Its ability to process large satellite datasets enables researchers to analyse long-term pollution trends, monitor environmental changes, and develop spatial models more efficiently.

For developing countries, cloud-based platforms provide opportunities to overcome some barriers associated with limited computing infrastructure and expensive software. They also support collaboration among researchers, government agencies, and environmental organizations by improving access to geospatial information.

Integration of Low-Cost Air Quality Sensors with Remote Sensing

Low-cost air quality sensors represent another emerging approach for improving pollution monitoring, particularly in regions with limited conventional monitoring stations. These sensors are relatively affordable, portable, and capable of providing high-frequency measurements of pollutants such as particulate matter, carbon monoxide, and nitrogen dioxide (Snyder et al., 2013).

When integrated with GIS and satellite observations, low-cost sensors can improve spatial coverage and provide additional validation data for remote sensing products. Networks of low-cost sensors can support community-based monitoring and provide real-time air quality information.

However, challenges remain regarding sensor calibration, accuracy, long-term performance, and data quality control. Standardization and validation procedures are necessary before low-cost sensor data can be widely used for regulatory applications.

Application of Unmanned Aerial Vehicles (UAVs)

Unmanned aerial vehicles (UAVs), commonly known as drones, have emerged as useful tools for environmental monitoring because they provide high-resolution observations at local scales. UAV-based monitoring can capture spatial variations in pollution that may not be detected by satellites due to differences in resolution.

In air quality studies, UAVs equipped with environmental sensors have been used to investigate emissions from industrial facilities, transportation corridors, agricultural burning, and other localized sources. Their ability to operate at flexible altitudes and locations makes them valuable for targeted investigations (Villa et al., 2016).

For developing countries, UAV technology offers opportunities for monitoring pollution in areas where fixed monitoring stations are unavailable. However, challenges related to equipment costs, regulatory approval, technical expertise, and data processing need to be addressed.

Integration of Air Quality, Climate, and Health Data

Future air quality assessment is expected to increasingly integrate environmental, climate, and health datasets. Combining GIS-based pollution maps with population information, healthcare data, and socioeconomic indicators can provide improved understanding of pollution-related health risks.

This integrated approach supports exposure assessment and helps identify vulnerable communities affected by air pollution. It also contributes to evidence-based public health policies and environmental justice initiatives (Beelen et al., 2013).

In developing countries, where health impacts of air pollution may be underreported, integrating geospatial pollution information with health studies can provide valuable evidence for improving air quality regulations and intervention strategies.

Development of Localized Air Quality Monitoring Frameworks

A major future direction is the development of locally adapted air quality monitoring frameworks that combine GIS, remote sensing, ground measurements, and modelling approaches. Many existing global models are developed using data from regions with extensive monitoring networks and may not fully represent environmental conditions in developing countries.

Future research should focus on developing region-specific models that consider local emission sources, climate characteristics, land-use patterns, and socioeconomic conditions. Strengthening collaboration between universities, environmental agencies, and international research institutions will be essential for building sustainable air quality monitoring systems.

Policy and Decision-Support Applications

The ultimate goal of applying GIS and remote sensing in air quality assessment is to support effective environmental decision-making. Geospatial information can assist policymakers in identifying pollution sources, evaluating emission control strategies, planning urban development, and protecting vulnerable populations.

Developing countries can benefit from incorporating geospatial air quality information into national environmental policies and climate action plans. Improved communication of air quality information through maps, dashboards, and public information systems can also increase awareness and encourage pollution reduction measures.

Summary

Emerging technologies such as artificial intelligence, cloud computing, low-cost sensors, UAVs, and integrated environmental-health databases are expected to further enhance GIS and remote sensing applications in air quality assessment. For developing countries, these innovations provide opportunities to overcome monitoring limitations and develop more comprehensive, affordable, and sustainable approaches to managing air pollution.

CONCLUSION

Ambient air pollution remains a major environmental and public health concern, particularly in developing countries where rapid urbanization, industrial activities, transportation growth, and limited monitoring infrastructure continue to challenge effective air quality management. The lack of adequate ground-based monitoring networks has created significant gaps in understanding the spatial and temporal distribution of atmospheric pollutants.

This review has demonstrated that Geographic Information Systems (GIS) and remote sensing technologies provide valuable approaches for improving ambient air quality assessment in developing countries. GIS enables the integration, analysis, and visualization of spatial environmental information, supporting pollution mapping, hotspot identification, exposure assessment, and environmental decision-making. Remote sensing technologies, through satellite-based observations, provide large-scale information on particulate matter and gaseous pollutants, including $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3, thereby extending air quality assessment beyond the limitations of conventional monitoring systems.

The integration of satellite observations with GIS, ground-based measurements, meteorological information, and modelling approaches has improved the accuracy and reliability of pollution assessments. Applications across Africa, Asia, and Latin America demonstrate the usefulness of geospatial technologies in identifying pollution hotspots, evaluating emission sources, monitoring urban air quality, and supporting public health assessments.

Despite these advantages, several challenges remain, including limited ground validation data, differences between satellite-derived and surface measurements, inadequate technical capacity, restricted access to high-resolution datasets, and financial constraints. Addressing these challenges requires strengthening air quality monitoring networks, improving technical expertise, promoting data sharing, and encouraging collaboration between research institutions, government agencies, and international organizations.

Future developments involving artificial intelligence, machine learning, cloud-based geospatial platforms, low-cost sensor networks, unmanned aerial vehicles, and integrated environmental-health datasets provide promising opportunities for advancing air quality assessment. These technologies can help developing countries establish more cost-effective, reliable, and sustainable monitoring systems.

Overall, GIS and remote sensing should be considered complementary tools rather than replacements for conventional monitoring approaches. Their successful application depends on effective integration with ground observations, local knowledge, and appropriate environmental policies. By improving access to accurate air quality information, these technologies can support evidence-based decision-making, reduce exposure risks, and contribute to sustainable environmental management in developing countries.

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Conflict of Interest

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