

Analytical Chemistry's Role in Air Pollution Monitoring and Mitigation: Advancing Air Quality in Environmental Science

*1Gregory E. ONAIWU and 2Ukeme Donatus ARCHIBONG

¹Department of Physical Science, Chemistry Option, Benson Idahosa University, Benin City, Nigeria ²Department of Science Laboratory Technology, Faculty of Life Sciences, University of Benin, Benin City, Nigeria

*Correspondent Author: gonaiwu@biu.edu.ng, Tel: +234(0)8063396285

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ABSTRACT

This project examines the critical role of analytical chemistry in monitoring, understanding, and mitigating air pollution. Through sophisticated techniques and methodologies, analytical chemistry provides vital insights into pollutant composition, sources, and behaviour, enabling the development of effective environmental policies and public health initiatives. The introduction outlines the significance of air pollution as a major environmental and health issue, emphasising the need for effective analytical methods to address this challenge. Various analytical techniques and approaches for air quality monitoring are discussed, including portable monitoring systems, remote sensing technologies, and advanced modelling methods that enhance data collection and analysis. A detailed flowchart illustrates the portable air monitoring process, highlighting key steps from on-site setup to immediate response to pollution incidents, thereby enhancing the understanding of practical applications in air quality assessment. The project further explores how analytical chemistry influences environmental regulations and public health initiatives, with case studies demonstrating its impact, including the reduction of lead in gasoline, the regulation of fine particulate matter ($PM_{2.5}$), and successful public health campaigns informed by analytical data. Challenges in air pollution analysis are also addressed, focusing on technical and methodological hurdles, data interpretation issues, and the need for continuous innovation. Future research directions emphasise emerging technologies, interdisciplinary collaboration, and trends in environmental monitoring. The conclusion summarises the essential role of analytical chemistry in addressing air pollution, highlighting the importance of continuous innovation and collaboration across disciplines. It underscores the potential for community-based monitoring initiatives to empower citizens and enhance public awareness, emphasizing the need for effective strategies to protect public health and the environment.

Keywords: Air quality assessment; Chemical speciation; Source apportionment; Environmental monitoring; Public health surveillance



Portable Air Quality Monitoring Systems

1. Introduction

Air pollution remains one of the most critical environmental challenges of the 21st century, with significant consequences for public health. ecosystems, and the global climate. The World Health Organization (WHO) estimates that ambient air pollution is responsible for approximately 4.2 million premature deaths annually, primarily due to cardiovascular diseases, respiratory infections, lung cancer, and other chronic conditions [1]. This global health burden highlights the urgency of scientific efforts to understand, monitor, and mitigate air pollution [2]. Among the various disciplines helping to mitigate this challenge, analytical chemistry stands out as a key player, providing precise tools for the detection, identification, and guantification of atmospheric pollutants [3]

Over the past two centuries, the relationship between air pollution and human health has evolved alongside industrialisation and urbanisation. The Industrial Revolution marked a significant turning point, with large-scale coal combustion releasing substantial quantities of harmful pollutants, including sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter (PM), into the atmosphere [4, 5). Initially concentrated in industrial centers, these pollutants have since become a global problem, exacerbated by the rapid growth of motor vehicle use, industrial activities, and urban development [6, 7]. Today, air pollution represents a complex mixture of chemical species, each with distinct environmental and health impacts [8].Analytical chemistry offers essential techniques to tackle this growing issue. The field has enabled the development of sophisticated methods for monitoring air quality and enforcing environmental regulations, which is pivotal in mitigating pollution's effects on human health and the environment. Among the most critical pollutants are particulate matter (PM_{2.5} and PM₁₀), volatile organic compounds (VOCs), nitrogen oxides (NO_x), sulfur dioxide (SO₂), carbon monoxide (CO), and ozone (O_3) . For instance, PM_{2.5}, a fine particulate matter capable of penetrating deep into the lungs and entering the bloodstream, has been

strongly associated with respiratory and cardiovascular diseases [9, 10].

High-precision analytical techniques such as gas chromatography-flame ionisation detection (GC-FID), gas chromatography-mass spectrometry (GC-MS), high-performance liquid chromatography (HPLC), and inductively coupled plasma mass spectrometry (ICP-MS) have been instrumental in measuring and analyzing these pollutants [4, 11]. These methods offer unparalleled accuracy in separating, identifying, and quantifying chemical species in complex atmospheric samples, providing the data necessary for assessing air quality and evaluating the potential health risks posed by pollutants [12].

Beyond detection, source apportionment, the determination of the origins of pollutants is a critical step in formulating effective mitigation strategies. Source apportionment allows for targeted interventions by identifying the primary sources of pollution, such as vehicular emissions, industrial discharges, or natural sources like wildfires [13]. Using receptor models that analyze the chemical composition of air samples, analytical chemists can trace pollutants back to their sources, enabling regulatory agencies to develop more precise control measures. For example, identifying vehicular emissions as a major contributor to urban air pollution may lead to stricter emissions standards or incentives for adopting electric vehicles [14].

In recent years, advancements in analytical chemistry have enhanced the capacity for monitoring and mitigating air pollution. The development of portable analytical instruments, such as handheld GC-MS and field-deployable HPLC systems, has enabled realtime, on-site analysis of air pollutants, providing invaluable data for immediate decision-making in both urban and remote settings [15]. These portable devices are particularly valuable in resource-limited regions where traditional laboratory setups are unavailable. In addition, remote sensing technologies, including satellite-based sensors and ground-based LIDAR systems, have revolutionized air quality monitoring by allowing for large-scale, continuous tracking of pollutants. These technologies offer a comprehensive view of pollution trends, enabling the prediction of pollution events and the assessment of regional and global air quality dynamics [16, 17].

As industrial and technological developments continue to influence the landscape of air pollution, analytical chemistry will remain essential for understanding the complex dynamics of atmospheric pollutants. Its role in providing precise data on pollutant composition, concentration, and behaviour is critical to advancing both scientific knowledge and policy-making efforts aimed at reducing pollution. Collaboration between scientists, policymakers, and industry stakeholders will be key to ensuring that the tools and techniques developed within analytical chemistry are effectively applied to protect public health and the environment [18].

This review will explore the critical role of analytical chemistry in air pollution research and management. Specifically, we will examine some of the techniques used to detect and analyze atmospheric pollutants, discuss how these methods have evolved, and assess their impact on environmental policy and public health initiatives.

2. Techniques in Analytical Chemistry for Air Pollution Research

Analytical chemistry employs a range of sophisticated techniques to study air pollution, each tailored to detect, quantify, and analyze various atmospheric pollutants. These techniques allow for precise monitoring of pollutants, informing regulatory frameworks and public health interventions [12]. One of the most widely used and powerful tools in air pollution research is Gas Chromatography-Mass Spectrometry (GC-MS), which has become indispensable for analyzing volatile and semi-volatile organic compounds present in the atmosphere [8]. This section delves into the intricacies of GC-MS and its applications in environmental science.

2.1. Gas Chromatography-Mass Spectrometry (GC-MS)

Gas Chromatography-Mass Spectrometry (GC-MS) is a highly sensitive and versatile analytical technique that combines the separating power of gas chromatography (GC) with the molecular identification capability of mass spectrometry (MS). The synergy between GC and MS enables the precise identification and quantification of pollutants in complex mixtures, making it especially valuable in air pollution research [15]. GC-MS is commonly employed to detect volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and other trace pollutants in the atmosphere [11]. By providing both qualitative and quantitative data, GC-MS helps monitor air quality, trace pollution sources, and assess the effectiveness of pollution control measures [12]. Figure 1 presents a typical GC-MS system's detailed diagram, illustrating the analytical process's core components.



Figure 1: Diagram of a GC-MS System, showing key components involved in the analysis of atmospheric pollutants

2.1.1. Key Components of the GC-MS System

The GC-MS system consists of several critical components that work together to ensure accurate chemical species analysis and identification. Each component plays a specific role in the separation, identification, and quantification of pollutants. Below is a breakdown of these components:

Carrier Gas Supply: Inert gases such as helium or nitrogen serve as the mobile phase, transporting vaporized samples through the GC column [17]. The purity of the carrier gas is crucial, as impurities or moisture can interfere with the analysis. Gas traps are often employed to remove potential contaminants.

Autosampler: The autosampler introduces samples into the system with precision and consistency. This component ensures that multiple samples can be processed under identical conditions for reliable results [3].

Injection Port: Samples are introduced into the system via a heated inlet, where they are vaporized for transport through the GC column. Proper vaporization is essential for the effective separation of the sample's components in subsequent stages [18].

GC Column: The GC column is the heart of the gas chromatography process. It is a coiled tube lined with a stationary phase that interacts with the vaporized sample. Separation occurs as different compounds move through the column at different speeds, based on their affinities with the stationary phase and their volatilities [12].

Transfer Line: After separation, the sample's components are transferred to the mass spectrometer via a heated transfer line. This prevents condensation and ensures that the analytes remain in vapour form [16].

Mass Spectrometer: The mass spectrometer ionizes the separated compounds, creating charged molecular fragments. These fragments are then

separated by their mass-to-charge (m/z) ratios using a mass analyzer [14]. The detector records the abundance of these fragments, producing a mass spectrum that serves as a unique fingerprint for each compound.

Data System: Finally, the data system processes the mass spectrometer's output, creating a chromatogram. Each peak in the chromatogram corresponds to a distinct compound, and the area under each peak is used to quantify its concentration in the sample [8].

2.1.2. Principles of Gas Chromatography (GC)

Gas chromatography separates components of a complex mixture based on their volatilities and interactions with the stationary phase inside the GC column. The process involves the following steps:

Vaporisation: A vaporized sample is transported through the column by an inert carrier gas [11].

Separation: Different compounds move through the column at varying speeds, influenced by their boiling points and affinities with the stationary phase [18].

Retention Time: The time taken for each compound to travel through the column and reach the detector is known as its retention time. This retention time is characteristic of each compound and can be influenced by adjusting variables such as column temperature, carrier gas flow rate, and the type of stationary phase used in the column [15].

2.1.3. Principles of Mass Spectrometry (MS)

Mass spectrometry (MS) plays a crucial role in the GC-MS system by identifying compounds based on their mass-to-charge (m/z) ratios. After separation in the

GC column, compounds enter the mass spectrometer's ionization chamber, where they are bombarded with high-energy electrons [12]. This process fragments the molecules, resulting in positively charged ions. The two major steps are:

Ionisation and Fragmentation: In most environmental applications, electron ionization (EI) is used to create ions by knocking electrons out of the sample molecules [16]. The resulting molecular fragments are characteristic of each compound and are sorted by their m/z ratios using a mass analyzer (e.g., a quadrupole or time-of-flight analyser) [14].

Mass Spectrum: The detector records the abundance of these fragments, producing a mass spectrum—a plot of ion intensity versus m/z. This spectrum is a molecular fingerprint for each compound, which can then be compared to reference libraries for identification [11].

2.1.4. Applications of GC-MS in Environmental Research

GC-MS is a workhorse technique for studying air pollution, offering exceptional sensitivity, accuracy, and versatility. Below are some of its key applications in environmental science:

Environmental Monitoring: GC-MS is widely used to detect air, water, and soil pollutants. It enables the monitoring of atmospheric pollutants such as VOCs, PAHs, and persistent organic pollutants (POPs), which are critical for assessing environmental health and compliance with regulatory standards [9].

Source Apportionment: By analyzing specific marker compounds such as polycyclic aromatic hydrocarbons (PAHs), VOCs, and other pollutants, GC-MS can trace pollutants back to their sources, such as industrial activities, vehicular emissions, or natural processes [18]. This information is crucial for developing targeted pollution control strategies [19].

Case Study: Use of GC-MS for Air Quality Assessment in Lagos, Nigeria

In a study conducted to assess ambient air quality in Lagos, Nigeria—one of the most densely populated and industrialized cities in Sub-Saharan Africa—GC-MS was employed to detect and quantify airborne VOCs and PAHs across different urban zones. The study focused on comparing pollutant levels near traffic-congested areas, industrial zones, and residential neighborhoods.

Air samples collected using adsorbent tubes were thermally desorbed and analyzed via GC-MS. Results revealed high concentrations of benzene, toluene, ethylbenzene, and xylene (BTEX), particularly near motor parks and fuel stations. PAHs such as benzo[a]pyrene, fluoranthene, and chrysene were more prevalent in industrial zones, suggesting significant emissions from incomplete combustion processes and manufacturing activities.

The mass spectra obtained for the various compounds were matched against NIST library references for accurate identification, while quantification was achieved using internal standards and peak integration [12], [18]. This analysis provided crucial data for policymakers and public health officials, highlighting the need for stricter air quality regulations and more sustainable urban planning practices.

2.2. Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is a cutting-edge analytical technique known for its exceptional sensitivity, precision, and multielement detection capabilities at ultra-trace levels. It has become a cornerstone in air pollution research, particularly for the characterization of fine $(PM_{2.5})$ and coarse (PM_{10}) particulate matter. These particles frequently harbor toxic metals originating from anthropogenic activities, including industrial emissions, vehicular exhaust. and biomass combustion [19][20][21].

The diagram in Figure 1 illustrates the operational architecture of an ICP-MS instrument. From sample introduction to ion detection, this integrated system enables the quantification of a wide array of elements in complex environmental matrices. Its ability to perform simultaneous multi-element analysis, coupled with low detection limits and rapid throughput, makes it indispensable for environmental monitoring, source apportionment, and metal speciation studies.



Figure 1. Schematic Diagram of an ICP-MS Instrument Sources: https://www.mdpi.com/2304-8158/11/22/3705.

Figure 1, displays the sequential subsystems of ICP-MS, including the sample introduction system (peristaltic pump, nebulizer, spray chamber), inductively coupled plasma (ICP) torch, sampling interface (sampling cone and skimmer cone), ion optics (ion lenses), quadrupole mass analyzer, detector, and data acquisition system. Arrows trace the path of the sample from solution to ion detection.

2.2.1. Key Components of the ICP-MS System

Sample Introduction System

The sample introduction begins with a **peristaltic pump**, which delivers the liquid sample into a **nebulizer**. The nebulizer transforms the sample into an aerosol mist, which then enters the **spray chamber**. Here, larger droplets are removed, allowing only fine aerosols to reach the plasma torch, enhancing signal stability and reducing matrix interferences [21].

Inductively Coupled Plasma (ICP) Torch

In the **plasma torch**, powered by a radiofrequency (RF) generator, an argon gas stream is ionized to form plasma with temperatures ranging from 6,000–10,000 K. This high-energy environment evaporates the aerosol droplets, atomizes the sample, and efficiently ionizes most elements in the periodic table [20].

\Plasma Sampling Interface

The ionized sample travels through the **sampling cone** and **skimmer cone**, which form the plasmavacuum interface. These cones serve two primary functions: they extract ions into the mass spectrometer under vacuum and eliminate neutral species and larger particulates, preserving the ion integrity for analysis [19].

Ion Optics System

Inside the vacuum system, the **ion lenses** direct and focus the ion beam while filtering out undesired species such as polyatomic interferences and doubly charged ions. This ensures optimal transmission of target ions to the mass analyzer and improves analytical precision [21].

Mass Analyzer

The focused ions are introduced into a **quadrupole mass filter**, which separates them based on their

mass-to-charge (m/z) ratios. The quadrupole analyzer is favored for its speed, robustness, and suitability for routine environmental monitoring, although alternative analyzers like time-of-flight (TOF) and sector-field types are used for more complex analyses [19].

Detector and Data System

The separated ions are detected using an **electron multiplier**, which generates a signal proportional to the ion count. The **data acquisition system** converts these signals into digital outputs, displays quantitative results, and manages tasks such as instrument calibration, background correction, and reporting [20][21].

Vacuum System

Turbo molecular pumps maintain the vacuum essential for ion transport and minimize signal noise, ensuring high sensitivity across the entire mass range.

2.2.2. Principles of ICP-MS

The effectiveness of ICP-MS stems from its sequential ionization and detection pathway:

Nebulization and Aerosol Transport: The peristaltic pump drives the sample to the nebulizer and spray chamber, where a fine aerosol is produced and carried by argon gas into the plasma [21].

Atomization and Ionization: Inside the plasma torch, the sample is desolvated, atomized, and ionized under high temperatures, yielding positively charged ions for analysis [20].

Ion Extraction and Focusing: The sampling and skimmer cones extract the ions into a low-pressure chamber. Ion lenses focus the beam while reducing interferences [19].

Mass Separation and Detection: The quadrupole mass filter separates ions by m/z ratios, which are then quantified by the detector. These values are processed and displayed through the data system [20].

Quantification and Calibration: Sample intensities are compared to calibration standards, and internal standards help correct for instrument drift and matrix effects [21].

2.2.3 Applications of ICP-MS in Air Pollution Studies

ICP-MS has proven invaluable in numerous case studies worldwide. For instance:

Case Study: Metal Pollution in Beijing, China

A pivotal study by Chen et al. in 2012 utilised ICP-MS to analyse the concentrations of trace metals, including lead (Pb), arsenic (As), and cadmium (Cd), in Beijing's urban air. The results revealed that traffic emissions and industrial activities were the primary sources of these metal pollutants. By applying source apportionment techniques alongside ICP-MS analysis, the study was able to differentiate contributions from vehicular exhaust, coal combustion, and metal processing industries. Seasonal data showed higher metal concentrations during the winter months, likely due to increased heating activities and reduced atmospheric dispersion, which trap pollutants closer to the ground. This seasonal trend underscored the influence of meteorological conditions on air quality. The study's findings informed local policymakers and led to the adoption of cleaner energy sources and stricter industrial emission controls, such as upgrades to emission treatment technologies and tighter regulation of coal usage. These interventions contributed significantly to improving air quality and reducing associated public health risks in subsequent years [20].

Case Study: Steel Production in Spain

In another significant study, Álvarez-Ayuso and Querol in 2007 used ICP-MS to investigate metal emissions from steel production in Spain. The research identified hazardous metals such as chromium (Cr), nickel (Ni), and zinc (Zn) released during various stages of the steel manufacturing process, particularly from hightemperature operations like smelting and refining. By analyzing airborne particulate samples collected from areas surrounding steel plants, the study provided detailed insights into the concentration levels and distribution patterns of these metals. The findings highlighted the environmental and health risks associated with long-term exposure to metal-laden particulates. This evidence was instrumental in shaping environmental regulations, prompting authorities to establish stricter emission limits for industrial facilities. As a result, steel plants adopted advanced pollution control technologies such as improved filtration systems, scrubbers, and emission capture units. These measures led to a notable reduction in metal emissions and marked progress in industrial air quality management in the region [19].

Case Study: PM_{2.5} Metal Analysis in Urban Centers

In a study conducted in Mexico City, researchers employed ICP-MS to measure the concentrations of metals, including manganese (Mn), lead (Pb), and copper (Cu), in PM2.5. These fine particulate matter samples were collected across various monitoring sites to capture spatial variability in metal concentrations. The high sensitivity and precision of ICP-MS allowed for accurate quantification of trace metals, which were then input into source apportionment models such as Positive Matrix Factorization (PMF). The results of the modelling identified traffic-related sources-particularly brake and tire wear, fuel combustion, and industrial activities-as the dominant contributors to PM2.5bound metal concentrations [21]. The study provided critical evidence linking specific pollution sources to elevated health risks associated with metal exposure. This information was instrumental in guiding policymakers to develop targeted regulations, such as emissions standards for vehicles, promotion of public transport, and the enforcement of industrial pollution controls, all aimed at mitigating traffic-related emissions and improving overall air quality in Mexico City.

2.3 Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared (FTIR) spectroscopy is a widely used analytical technique for air pollution monitoring, as it can detect both organic and inorganic compounds by analyzing their unique infrared absorption spectra. FTIR allows for rapid and simultaneous measurement of multiple gaseous pollutants, making it a valuable tool for real-time air quality assessments.

2.3.1 Description and Principles of FTIR

FTIR spectroscopy works by passing infrared (IR) radiation through a sample. Different chemical bonds absorb specific wavelengths of IR light, creating a unique absorption spectrum that can be used to identify and quantify various compounds. The process starts with an infrared source emitting a broad spectrum of IR radiation. This radiation passes through an interferometer, which splits the beam into two paths—one directed to a fixed mirror and the other to a moving mirror. The beams are then recombined, creating an interference pattern that passes through the sample compartment.

Molecules in the sample absorb specific wavelengths of IR radiation, leaving characteristic "fingerprints" on

the transmitted beam. This modified beam is detected, and the resulting data are processed using Fourier transform algorithms to produce a spectrum. The spectrum displays the intensity of absorbed radiation as a function of wavenumber or wavelength. By comparing the sample's spectrum to reference spectra, the components of the sample can be identified and quantified.



Figure 2: FTIR Measurement Process

2.3.2 Applications in Air Pollution Monitoring

FTIR has been extensively applied to monitor air pollution by tracking gaseous pollutants such as carbon dioxide (CO_2) , methane (CH_4) , nitrogen oxides (NO_x) , sulfur dioxide (SO_2) , and volatile organic compounds (VOCs). Its ability to simultaneously measure multiple pollutants in realtime makes it particularly useful for both ambient air quality assessments and emissions monitoring from industrial sources. Case Studies of some FTIR in Air Pollution Studies are as follows:

2.3.2.1 Case Study: Biomass Burning in the Amazon Basin

Yamasoe *et al.* in 2000 used Fourier Transform Infrared Spectroscopy (FTIR) to monitor trace gases emitted during biomass burning in the Amazon Basin [22]. The study provided critical insights into the atmospheric consequences of large-scale forest fires, offering a comprehensive chemical profile of the emitted gases. By utilizing FTIR's capability to detect multiple gases simultaneously and in real time, the researchers identified significant levels of pollutants such as carbon monoxide (CO), methane (CH₄), and nitrogen oxides (NO_x), which are known to contribute to both regional air quality degradation and global climate change. The high-resolution data enabled the detection of subtle variations in emission patterns linked to fire intensity and combustion stages, from flaming to smoldering phases. The spectroscopic data, illustrated in Figure 3 below, highlighted the intensity and variability of emissions during different burning phases, demonstrating how combustion efficiency influences the composition of released gases. These findings underscored the environmental importance of controlling biomass burning activities, informing conservation strategies and air quality policies in the Amazon region and beyond, and emphasizing the need for real-time monitoring tools in managing firerelated emissions.



Fig 3: Trace Gases Emitted from Biomass Burning (Adapted from The Guardian, 2024) [23]

2.3.2.2 Case Study: VOCs in Urban Air in London

Rodgers and his team used Fourier Transform Infrared Spectroscopy (FTIR) to analyze volatile organic compounds (VOCs) in the urban air of London [24]. The study provided a detailed assessment of the concentration and composition of VOCs, capturing both spatial and temporal variations across different city zones. By leveraging FTIR's ability to identify a wide range of gas-phase organic compounds in real time, the researchers detected elevated levels of hydrocarbons and oxygenated VOCs, particularly in high-traffic areas and near industrial facilities. The data indicated that vehicular emissions, especially from diesel engines, along with industrial solvent use, were significant contributors to the VOC burden in the city's atmosphere. These findings played a pivotal role in shaping traffic management strategies, such as implementing low-emission zones, optimizing traffic flow, and promoting cleaner vehicle technologies. The study thus contributed to targeted policy interventions aimed at reducing VOC concentrations and improving urban air quality in London.

3.0 Source Apportionment in Air Pollution Research

Source apportionment is an essential process in air pollution research, enabling the identification and quantification of pollution sources and their relative contributions to air quality. Understanding the origins of pollutants allows environmental scientists and policymakers to devise effective mitigation strategies and implement health protection measures. Several analytical methods are employed for source apportionment, each contributing valuable insights that aid in developing targeted and efficient air quality management approaches. For this study, diagnostic ratios and receptor models would be considered.

3.1 Diagnostic Ratios

Diagnostic ratios are fundamental tools used to provide preliminary insights into pollutant sources by comparing the concentrations of specific compounds or elements. These ratios offer a relatively quick assessment of pollution sources, guiding more detailed analyses using receptor models. While diagnostic ratios provide initial insights, they have inherent limitations and typically require further investigation for accurate source apportionment [13]. Diagnostic ratios are particularly useful for identifying sources of polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), and particulate matter (PM). Commonly used diagnostic ratios include:

3.1.1 PAH Ratios

The ratio of specific polycyclic aromatic hydrocarbons (PAHs), such as fluoranthene to pyrene (Flt/Pyr), is often employed to distinguish between coal combustion and vehicular emissions [25]. This diagnostic ratio serves as a practical tool in source apportionment studies, offering insights into the dominant origin of PAHs in ambient air. For instance, a Flt/Pyr ratio greater than 1 typically indicates emissions associated with coal combustion, characterized by incomplete burning processes and higher molecular weight PAH profiles. Conversely, a ratio less than 1 suggests that vehicular emissions,

particularly from gasoline-powered engines, are the primary contributors. This differentiation is especially valuable in urban and industrial areas where multiple emission sources coexist, as it allows researchers and policymakers to design targeted control strategies that address the most significant sources. By applying such ratio-based approaches, air quality management efforts can be more effectively tailored to reduce PAH levels and mitigate associated health risks.

3.1.2 VOC Ratios

The benzene-to-toluene (B/T) ratio is a useful diagnostic tool for differentiating between traffic and industrial emissions. A high B/T ratio is typically linked to vehicular emissions, as gasoline contains a higher concentration of benzene, a volatile organic compound (VOC) commonly emitted by vehicles. On the other hand, a lower B/T ratio is generally associated with industrial emissions, where tolueneanother VOC commonly used in industrial processes-tends to be more prevalent [26]. This ratio-based analysis is particularly valuable in urban areas with mixed emission sources, as it helps researchers identify the primary contributors to air pollution. By distinguishing between traffic-related and industrial emissions, the B/T ratio aids in source apportionment studies, providing critical information for the development of targeted air quality management strategies. These strategies can then focus on reducing emissions from the most significant sources, ultimately improving urban air quality and public health.

3.1.3 Elemental Ratios

Ratios of metals, such as lead (Pb) to zinc (Zn), are valuable tools in identifying the sources of particulate matter in air pollution studies. A high Pb/Zn ratio typically indicates emissions from industrial processes, such as metal smelting, where lead is a predominant pollutant due to its use in various industrial applications. In contrast, a lower Pb/Zn ratio is often associated with vehicular sources, including emissions from tire wear and brake linings, where zinc is more commonly found as a result of its presence in vehicle components and additives [27]. These metal ratios are crucial in source apportionment studies, as they provide insight into the relative contributions of traffic and industrial emissions to overall air pollution. By analyzing these ratios, researchers can pinpoint specific pollution sources, which is vital for developing targeted pollution control measures and improving air quality management strategies in urban and industrial areas.

3.2 Receptor Models

Receptor models are advanced mathematical approaches used to identify and quantify pollution sources based on chemical analyses of air samples collected at specific sites. These models decompose observed pollutant concentrations into contributions from various sources such as traffic, industrial activities, and natural emissions. By understanding the composition of pollutants at a receptor site, receptor models can provide a clearer picture of the sources responsible for air pollution, which in turn helps in designing targeted air pollution mitigation strategies. The three major techniques used in receptor modelling are positive matrix factorisation (PMF), chemical mass balance (CMB), and principal component analysis (PCA) [13]. PMF is particularly useful for dealing with complex data sets and can handle missing data, while CMB is used to match observed concentrations with known source profiles, and PCA helps reduce the dimensionality of the data to identify underlying patterns or factors. Each of these methods offers unique advantages, and when combined, they enable comprehensive source apportionment that can inform effective environmental policies and pollution control measures.

3.2.1 Positive Matrix Factorization (PMF)

Positive Matrix Factorization (PMF) is a widely used receptor model that estimates the contribution of pollution sources by decomposing observed pollutant concentrations into factor contributions and profiles. One of the key advantages of PMF is that it does not require prior knowledge of source profiles, making it particularly useful for datasets with missing information or when dealing with uncharacterized sources [28]. This flexibility allows researchers to apply PMF to a broad range of air quality studies, even in cases where detailed source profiles are not available. PMF has been applied in numerous studies to assess sources of particulate matter (PM), volatile organic compounds (VOCs), and other air pollutants. For example, it has been used to identify and quantify the contributions of various sources, such as traffic emissions, industrial activities, biomass burning, and secondary aerosol formation. By separating the factors contributing to air pollution, PMF provides valuable insights into the source-specific impacts on air quality, aiding in the development of targeted control strategies and informed regulatory decisions.

3.2.2 Chemical Mass Balance (CMB)

The Chemical Mass Balance (CMB) model utilizes known source profiles to apportion sources of pollutants at a receptor site. It operates on the assumption that the observed concentrations of pollutants are a linear combination of the contributions from various sources. By employing a database of well-characterized source profiles, CMB calculates the proportion of pollutants contributed by each source, allowing for a more accurate estimation of the sourcespecific contributions to air pollution. This model is particularly effective when accurate and reliable source profiles are available, such as those for emissions from industrial processes, traffic, or other well-defined sources [29]. CMB has been widely applied in air pollution studies to guide regulatory efforts and inform air quality management strategies. Its ability to provide clear insights into the contribution of different sources is valuable for developing targeted measures to mitigate pollution and improve public health, especially in areas with complex emission patterns or mixed pollution sources.

3.2.3 Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a statistical technique used to reduce the dimensionality of large datasets while preserving as much variance as possible. In air pollution research, PCA is particularly useful for identifying patterns in pollutant concentrations and grouping pollutants that are likely to have similar sources. By analyzing the variance between pollutant measurements, PCA helps infer the most significant pollution sources, making it a valuable tool for source apportionment. This technique is highly effective when dealing with complex datasets that include numerous variables and when the source profiles are unknown or uncharacterized [30]. However, interpreting the principal components often requires additional analysis, such as rotation techniques (e.g., varimax rotation), to enhance source identification and improve the interpretability of the results. PCA has been widely applied in studies to identify major sources of particulate matter, heavy metal pollution, and other atmospheric pollutants, offering important insights into the underlying factors driving air quality issues. By identifying patterns in complex air pollution data, PCA provides a foundation for designing more effective air quality management strategies and regulatory frameworks.

3.2.4 Applications Receptor Models

Receptor models have been utilized in diverse geographical contexts across the globe to provide detailed insights into the sources of air pollution. The selection of some geographic locations is as follows: In Beijing, China, a study utilized Positive Matrix Factorization (PMF) to analyze PM2.5 samples, identifying six major sources of pollution: coal combustion, vehicular emissions, secondary sulfate, secondary nitrate, biomass burning, and dust. The results revealed that coal combustion and vehicular emissions were the dominant contributors to the city's air pollution, accounting for the majority of the observed PM2.5 levels [31]. These findings were pivotal for informing Beijing's air quality management strategies, highlighting the need to address pollution from both coal-burning activities and vehicular emissions. knowledge This enabled local policymakers to implement targeted interventions aimed at reducing emissions from these primary sources, which have been linked to a variety of health issues in urban populations. By focusing on these areas, Beijing's environmental policies sought to mitigate the harmful effects of particulate pollution and improve air quality for its residents.

In the Los Angeles Basin, USA, Chemical Mass Balance (CMB) modeling was employed to analyze the sources of volatile organic compounds (VOCs) in the region. The analysis showed that vehicle emissions and industrial solvents were the primary contributors to the elevated levels of VOCs found in ambient air. These results provided crucial information that helped local authorities better understand the sources of air pollution in Los Angeles, a city known for its air quality challenges. The findings of this study were instrumental in guiding air quality management efforts, as they pointed to the need for regulatory measures targeting both vehicular emissions and industrial activities. By identifying these key sources, the study helped policymakers design and enforce stricter regulations to reduce VOC emissions, ultimately improving the air quality in the Los Angeles Basin and mitigating the public health risks associated with exposure to these pollutants [32].

In New Delhi, India, Principal Component Analysis (PCA) was applied to analyze particulate matter data, which allowed researchers to identify major sources of pollution, including vehicular emissions, biomass burning, and industrial activities. The study demonstrated how PCA effectively grouped pollutants with common sources, providing a clearer understanding of the contributions from various pollution sources to the city's overall air quality. This approach enabled the identification of the most significant contributors to particulate matter pollution, with vehicular emissions and biomass burning emerging as the leading sources. The findings highlighted the potential for targeted regulatory action to address traffic-related emissions and improve regulations on industrial pollution. By focusing on these key areas, New Delhi could better manage its air guality and reduce the harmful health effects associated with exposure to high levels of particulate matter [33].

3.3 Advantages and Limitations of Receptor Models

Each receptor model in air pollution studies offers distinct advantages and limitations, making it essential to carefully consider which method is most appropriate for source apportionment in a given study. Positive Matrix Factorization (PMF), for instance, is highly flexible and can handle missing data, as well as unknown sources, making it ideal for exploratory studies in complex pollution environments where the sources of pollutants may not be well characterized. Its ability to provide meaningful insights into unidentified pollution sources is a significant strength, especially in urban or industrial areas with diverse pollution sources. However, one of the primary challenges with PMF is the interpretation of the factor profiles it generates. These profiles represent the source contributions and can sometimes be difficult to interpret without expert knowledge. Misinterpreting these profiles can lead to incorrect source identification, which may limit the model's usefulness in some contexts [34].

Chemical Mass Balance (CMB), on the other hand, provides highly precise source apportionment when

source profiles are well-known and accurately characterized. It uses a database of predefined source profiles and assumes that the observed pollutant concentrations are a linear combination of these profiles. This method is particularly useful in situations where reliable and comprehensive data on pollution sources are available. However, CMB's major limitation lies in its reliance on the accuracy and availability of these source profiles. In cases where source profiles are incomplete or unavailable, the model's ability to accurately identify pollution sources is compromised, making it less suitable for environments where data on specific source emissions is lacking [35].

Principal Component Analysis (PCA) is a statistical technique that excels at reducing the dimensionality of large datasets and identifying patterns in pollutant concentrations. It is particularly effective in exploring large datasets with numerous pollutants, as it can reveal the most significant sources based on the variance in the data. PCA helps identify groups of pollutants that have similar sources, providing valuable insights into the nature of the pollution. However, one of the limitations of PCA is that it does not directly apportion pollutant concentrations to specific sources. Instead, it provides principal components that represent variations in the data, which requires additional interpretation to link back to specific pollution sources. The interpretation of these components can be subjective, and techniques such as rotation may be needed to clarify the source contributions. This added complexity can sometimes make PCA more difficult to apply effectively without additional data analysis methods [36].

In environmental science, the choice of the best receptor model depends on the specific goals of the research, the available data, and the complexity of the pollution sources being studied. PMF, while challenging in terms of interpreting the factor profiles, is often regarded as the best option in many environmental science applications due to its flexibility in handling missing data and uncharacterized sources. It is particularly valuable when working in complex environments with multiple and varied pollution sources. Additionally, its ability to provide insights even with incomplete data makes it

highly versatile, especially in situations where other methods like CMB or PCA may be limited. Therefore, despite its challenges, PMF is frequently chosen as the preferred method for source apportionment in air pollution studies.

1. Flexibility in Handling Complex Datasets

PMF can handle datasets with missing information, unknown sources, and multiple pollutants. This is crucial in environmental science, where pollutant sources are often complex and not fully characterized. For instance, PMF is especially useful in studies involving particulate matter (PM_{2.5} and PM₁₀), volatile organic compounds (VOCs), and other complex air pollution mixtures that may not have well-established source profiles [17].

2. No Need for Prior Source Profiles

Unlike CMB, PMF does not require prior knowledge of pollutant source profiles. In many environmental contexts, such as when studying remote areas or new industrial activities, obtaining accurate source profiles may be difficult or impossible. PMF can identify and quantify sources even in such cases, making it more versatile and suitable for exploratory studies in various environmental settings [37].

3. Broad Applicability

PMF has been successfully applied in a wide range of environmental studies, including those dealing with urban air quality, industrial emissions, and even global pollution studies. Its adaptability to different types of pollution data makes it particularly useful for environmental scientists seeking to assess the relative contributions of different sources to overall pollution levels [38].

4. Identification of Secondary Sources

One of PMF's strengths is its ability to identify secondary pollutants formed in the atmosphere (e.g., secondary sulfates and nitrates) from precursor emissions. This is essential in environmental science, where understandPresented in Table 1 is a comparison of the three receptor models (PMF, CMB, and PCA), highlighting their strengths and weaknesses in environmental science applications:

Model	Advantages	Limitations	Suitability for Environmental Science
Positive Matrix Factorization (PMF)	 Handles missing data and unknown sources. No need for prior source profiles. Effective for identifying both primary and secondary pollutants. Applicable to a wide range of pollutants (PM, VOCs, etc.). 	 Requires expert interpretation of factor profiles. Potential for misidentification of sources if factor profiles are inaccurately interpreted. 	High : Ideal for exploratory studies and complex datasets common in environmental science. Versatile across various pollutants and regions.
Chemical Mass Balance (CMB)	 Highly precise when source profiles are well- known. Direct source apportionment. Useful for regulatory purposes when data is well-characterized. 	 Requires accurate, pre- established source profiles. Limited in cases with missing or incomplete source data. Inflexible when dealing with uncharacterized sources. 	Moderate : Best for specific applications where detailed source profiles are available (e.g., industrial emission studies).
Principal Component Analysis (PCA)	 Useful for reducing dimensionality in complex datasets. Can indicate major pollution sources based on variance in the data. 	 Does not provide direct source apportionment. Requires additional models for accurate source identification. Less suited for detailed air quality analysis. 	Low : Helpful for data exploration, but insufficient for precise source apportionment without supplementary methods.

4.0 Advancements in Analytical Methods for Air Pollution Monitoring

The field of air pollution monitoring has evolved rapidly with the development of innovative analytical methods and technologies [40]. These advancements have significantly improved the capacity to detect, quantify, and track pollutants, providing more accurate and timely data. This section focuses on how newer portable and remote sensing technologies have addressed limitations in traditional methods, enabling better air quality management and public health protection.

4.1 Portable Analytical Instruments

Portable analytical instruments have significantly advanced air pollution monitoring by enabling on-site analysis and the collection of real-time data. Traditional air quality monitoring methods typically relied on laboratory-based analyses, which involved delays in obtaining results and limited the ability to respond promptly to pollution events. However, with the introduction of portable devices such as handheld gas chromatography-mass spectrometry (GC-MS) and field-deployable high-performance liquid chromatography (HPLC), air quality monitoring has become more immediate and accessible. These portable instruments provide rapid, on-site data collection, allowing researchers and environmental agencies to respond to pollution events in real time. By facilitating quicker decision-making and more effective pollution control measures, portable analytical instruments have greatly enhanced the ability to monitor and mitigate air pollution in dynamic environments [41].

4.1.1 Development and Use of Handheld GC-MS and Field-Deployable HPLC Systems

The handheld GC-MS is an advanced tool that integrates the separation capabilities of gas chromatography with the sensitivity of mass spectrometry, all in a compact and portable form. This innovation allows for immediate detection and quantification of volatile organic compounds (VOCs) directly at the pollution source, providing real-time data crucial for emergency response situations and ongoing industrial monitoring. Unlike traditional laboratory-based systems, which require sample transport and lengthy analysis times, handheld GC-MS systems deliver quick results, making them essential for rapid decision-making during pollution events [41].

Field-deployable high-performance liquid chromatography (HPLC) systems, on the other hand, are particularly suited for analyzing semi-volatile and non-volatile pollutants, such as particulate matter (PM) components like polycyclic aromatic hydrocarbons (PAHs) and metals. These systems allow for the on-site analysis of complex pollutants that are typically more challenging to measure using other portable techniques. The advantage of field-deployable HPLC systems lies in their ability to bypass the logistical challenges associated with sample transport and laboratory delays, providing timely and accurate data directly at the monitoring site [42]. Table 5 provides a detailed comparison between the handheld GC-MS and field-deployable HPLC, highlighting their respective strengths and applications for air pollution monitoring.

Table 2: Comparison of Fortable Analytical Instrument	Table 2:	Comparison	of Portable Anal	ytical Instrument
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Instrument	Pollutants Detected	Key Advantages	Typical Applications
Handheld GC-MS	VOCs	Real-time data, portability	Industrial monitoring, emergency response
Field-Deployable HPLC	Semi-volatile and non-volatile pollutants (e.g., PAHs, metals)	On-site analysis, eliminates lab delays	Urban air quality, particulate matter studies

4.1.2 Advantages of Portable Analytical Instruments

Portable instruments offer significant advantages over traditional methods, as shown in Table 3 below.

Table 3: Advantages of Portable vs. Traditional Methods

Parameter	Portable Instruments	Traditional Methods
Response Time	Real-time	Delayed (lab analysis required)
Spatial Coverage	High (mobile and flexible)	Limited (fixed monitoring sites)
Cost Efficiency	Lower (no sample transport)	Higher (transportation and lab fees)

4.1.3 Process Flow of Portable Air Monitoring Instrument Usage

The following flowchart illustrates the steps involved in using portable air quality monitoring instruments:

Flowchart 1: Portable Air Monitoring Process

Step 1: On-site setup

Step 2: Pollutant detection (e.g., VOCs or PM components)

Step 3: Real-time data collection



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Step 5: Response to a pollution incident

4.2 Remote Sensing Technologies

Remote sensing technologies have made it possible to observe and track pollutants over large geographic areas and across extended timeframes, providing comprehensive data for air quality management. Traditional air pollution monitoring stations are often limited in spatial coverage, but remote sensing technologies such as satellite-based sensors and ground-based Light Detection and Ranging (LIDAR) systems offer a wider perspective on pollutant distributions [43].

Satellite-based sensors are satellites equipped with advanced sensors, such as those aboard NASA's Terra and Aqua platforms, which offer global coverage and can monitor a variety of pollutants, including nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and particulate matter (PM). These sensors provide invaluable data on pollutant transport and transboundary pollution, supporting international air quality management [44]. Ground-based LIDAR systems provide high-resolution vertical profiles of aerosols and ozone within the lower atmosphere. By offering insights into the vertical distribution of pollutants, LIDAR helps to understand atmospheric dispersion and layering, which play critical roles in air pollution dynamics [45].

4.2.2 Applications of Remote Sensing Technologies

lobal pollution mapping has significantly benefited from the use of satellite data, which play a critical role in tracking pollutant distributions on a global scale. Satellite imagery allows researchers to identify pollution hotspots and monitor long-range pollutant transport across continents. By continuously observing the atmosphere, satellites provide valuable insights into the spread and concentration of pollutants such as nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and particulate matter (PM), facilitating the identification of regions that require immediate attention for pollution control [46].

Vertical profiling through ground-based LIDAR (Light Detection and Ranging) technology offers detailed measurements of aerosol concentrations at various altitudes. This technique is vital for understanding how pollutants disperse in the atmosphere and how their concentrations change with altitude. The data obtained from LIDAR profiles can be integrated into air quality models to improve predictions of pollution patterns, helping policymakers design more effective mitigation strategies and better understand the vertical dynamics of aerosol behavior in the atmosphere [47].

Remote sensing technologies have also been crucial for emission source identification, enabling researchers to pinpoint and quantify emissions from specific sources such as power plants, factories, and urban centers. By analyzing remotely sensed data, which includes both satellite and ground-based observations, researchers can track the emissions from industrial activities, transport sectors, and other major contributors to air pollution. This capability allows for targeted pollution control strategies that address the most significant sources of emissions and support more efficient regulatory measures [43].

4.2.4 Case Studies of Remote Sensing in Air Pollution Research

The summary of some selected case studies using sensing technologies is presented in Table 4 below.

Case Study	Key Findings	Reference
Monitoring NO ₂ Globally	Satellite-based instruments identified global NO_2 trends, showcasing emission control successes.	[44]
Air Quality Improvements in China	Significant reductions in SO_2 and NO_2 were observed after strict pollution control measures were implemented.	[48]
Wildfire Smoke Monitoring	Ground-based LIDAR was used to track vertical smoke plumes, providing insights into air quality impacts from wildfires.	[49]

Table 4: Case Studies of Remote Sensing in Air Pollution Monitoring

5.0 Impact of Analytical Chemistry on Environmental Policy and Public Health

Analytical chemistry is a cornerstone in shaping environmental policy and public health strategies. The ability to accurately measure and identify pollutants provides essential data that inform regulations to protect the environment and human health. Analytical chemistry has significantly contributed to environmental regulations, public health guidelines, and our understanding of pollution-related health risks by offering precise and reliable information on air quality and pollutants.

5.1 Influence on Environmental Regulations

Environmental policies and air quality standards are built upon solid scientific evidence, with analytical methods playing a pivotal role in understanding pollutant levels and their associated risks. Techniques like gas chromatography-mass spectrometry (GC-MS), inductively coupled plasma mass spectrometry (ICP-MS), and high-performance liquid chromatography (HPLC) are essential for obtaining detailed and accurate measurements of pollutants in the atmosphere. These techniques help identify the composition of air pollutants, their concentration, and their potential impacts on human health and the environment. The data obtained through these methods are integral to the development of regulatory frameworks such as the National Ambient Air Quality Standards (NAAQS) in the United States. The NAAQS sets permissible limits for a range of air pollutants including sulfur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), ozone (O₃), and lead (Pb), ensuring that air quality remains within safe levels for public health [50].

The role of these analytical techniques in shaping environmental regulations is highlighted by several case studies that demonstrate their effectiveness in determining pollutant concentrations and their sources. These case studies show how methods like GC-MS and HPLC have been instrumental in detecting trace levels of toxic substances in the atmosphere, leading to evidence-based policy decisions. The outcomes of these studies are crucial in informing air quality management strategies and supporting the enforcement of air pollution standards.

Additionally, the comparison of pollutant standards across major environmental agencies, such as the United States Environmental Protection Agency (EPA), the World Health Organization (WHO), and the European Union, provides a clear understanding of the global approach to air quality regulation. This comparison helps policymakers and scientists align efforts in addressing transboundary air pollution and improving air quality worldwide. The relevant data and findings from these analyses are summarized in Table 5, which reviews case studies of analytical techniques in environmental research, and Table 6, which compares pollutant standards from major agencies.

Table 5: Case Studies in Air Pollution Contr	rol and Analytical Techniques
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Case Study	Analytical Techniques	Outcomes
Reduction of Lead in Gasoline	Atomic absorption spectroscopy, ICP-MS	Phase-out of leaded gasoline, a significant reduction in lead pollution.
Regulation of Fine Particulate Matter (PM _{2.5})	HPLC, GC-MS	Stricter air quality standards lead to improved air quality.

Table	6:	Comr	arison	of P	ollutant	Stand	lards i	Across	Mai	or Ac	tencies	
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Pollutant	EPA (NAAQS) Limits (USA) (2020) [51]	WHO Air Quality Guidelines (2021) [52]	EU Air Quality Standards (2008) [53]
Sulfur Dioxide (SO ₂)	75 ppb (1-hour average)	20 µg/m³ (24-hour average)	125 µg/m³ (24-hour average)
Nitrogen Dioxide (NO ₂)	100 ppb (1-hour average)	40 µg/m³ (annual mean)	40 µg/m³ (annual mean)
Particulate Matter (PM ₁₀)	150 μg/m³ (24-hour average)	50 µg/m³ (24-hour average)	$50 \ \mu\text{g/m}^3$ (24-hour average)
Particulate Matter (PM _{2.5})	35 µg/m³ (24-hour average)	15 μg/m³ (24-hour average)	25 µg/m³ (24-hour average)
Carbon Monoxide (CO)	9 ppm (8-hour average)	10 mg/m³ (8-hour average)	10 mg/m³ (8-hour average)
Ozone (O ₃)	0.070 ppm (8-hour average)	100 µg/m³ (8-hour average)	120 µg/m³ (8-hour average)
Lead (Pb)	$0.15 \mu\text{g/m}^3$ (rolling 3-month average)	0.5 µg/m³ (annual average)	0.5 µg/m³ (annual average)

5.2 Public Health Initiatives

Analytical chemistry has been essential in advancing public health initiatives, particularly in linking pollutants to specific health risks and informing the creation of guidelines to reduce exposure. Techniques like Fourier-transform infrared spectroscopy (FTIR) and nuclear magnetic resonance (NMR) allow scientists to study the toxicological impacts of pollutants, providing key insights into how these substances affect human health.

Environmental policies and air guality standards are built upon solid scientific evidence, with analytical methods playing a pivotal role in understanding pollutant levels and their associated risks. Techniques like gas chromatography-mass spectrometry (GC-MS), inductively coupled plasma mass spectrometry (ICP-MS). high-performance and liquid chromatography (HPLC) are essential for obtaining detailed and accurate measurements of pollutants in the atmosphere. These techniques help identify the composition of air pollutants, their concentration, and their potential impacts on human health and the environment. The data obtained through these methods are integral to the development of regulatory frameworks such as the National Ambient Air Quality Standards (NAAQS) in the United States. The NAAQS sets permissible limits for a range of air pollutants including sulfur dioxide (SO_2) , nitrogen oxides (NO_x) , particulate matter (PM), carbon monoxide (CO), ozone

 (O_3) , and lead (Pb), ensuring that air quality remains within safe levels for public health [50].

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Additionally, the comparison of pollutant standards across major environmental agencies, such as the United States Environmental Protection Agency (EPA), the World Health Organization (WHO), and the European Union, provides a clear understanding of the global approach to air quality regulation. This comparison helps policymakers and scientists align efforts in addressing transboundary air pollution and improving air quality worldwide. The relevant data and findings from these analyses are summarized in Table 5, which reviews case studies of analytical techniques in environmental research, and Table 6, which compares pollutant standards from major agencies.

Case Study	Context	Outcomes	References
Air Quality Improvement in London	Monitoring NO_x and PM	36% reduction in NO _x levels; improved respiratory health outcomes	[55], [56]
Beijing's Air Pollution Control	Identification of PM _{2.5} sources	25% reduction in PM _{2.5} levels; fewer respiratory diseases and deaths	[48]
Reduction of Airborne Benzene	Monitoring industrial emissions	Lowered ambient benzene levels; reduced leukemia risk	[57] [58]

Table 7: Case Studies of Public Health Initiatives

6.0 Challenges and Future Directions

Air pollution analysis faces several technical, methodological, and interpretative challenges. However, with ongoing research and emerging technologies, the field continuously evolves to overcome these obstacles. This section explores the current challenges and the future directions in air pollution analysis.

Air pollutants exist in complex mixtures and undergo various chemical transformations in the atmosphere, making detection and quantification particularly challenging. Factors such as temperature, humidity, and atmospheric reactions can significantly affect measurement accuracy. Consequently, pollutant identification often requires advanced techniques capable of differentiating components and their transformation products, which adds to the complexity of air pollution studies.

The analysis of specific pollutants presents additional challenges due to their varying chemical properties and behaviors in the environment. For example, the detection of Volatile Organic Compounds (VOCs) typically relies on gas chromatography-mass spectrometry (GC-MS), a method known for its high sensitivity and specificity. However, this approach is labor-intensive, requiring complex sample preparation, calibration, and sometimes preconcentration steps to detect low-abundance compounds. These steps can increase analysis time and resource consumption. Recent advancements have focused on miniaturization, automation, and the development of more robust pre-concentration methods, which are designed to streamline VOC detection while enhancing sensitivity and accuracy [26]. Nevertheless, the complexity of analyzing complex mixtures of VOCs, where atmospheric reactions and varying concentrations occur, remains a significant challenge in air pollution monitoring.

Similarly, for Particulate Matter (PM), particularly its inorganic constituents, techniques such as highperformance liquid chromatography (HPLC) and inductively coupled plasma mass spectrometry (ICP-MS) are commonly employed. These methods allow for detailed chemical characterization, including the identification of heavy metals and trace elements. However, accurately quantifying trace components, especially at low concentrations, continues to be a major obstacle. Interferences, sample matrix complexity, and the detection limits of the techniques used often pose challenges in obtaining precise measurements. For example, when analyzing heavy metals in particulate matter, matrix effects-caused by the complex composition of PM samples-can interfere with the detection of certain metals, complicating the analysis. This variability, coupled with the need for high resolution and sensitivity, makes accurate analysis particularly difficult, especially when PM composition differs depending on pollution sources and environmental conditions [59]. Moreover, the demand for high-throughput methods to process large volumes of samples and the need for real-time data collection to track pollution trends further complicate air pollution analysis. These challenges not only add to the technical complexity of air quality monitoring but also place significant demands on time and resources. While significant progress has been made in improving air pollution analysis techniques, addressing these challenges remains crucial to ensuring that air quality monitoring can keep pace with increasing pollution levels and provide the necessary data to inform effective environmental policies.

7.0 Future Research Directions and Conclusion

Emerging technologies and interdisciplinary approaches are progressively addressing the current limitations in air pollution analysis. These advancements significantly enhance our ability to monitor, understand, and control pollutants, promising improved detection, real-time monitoring, and better identification of pollutant sources. Continuous innovation in analytical techniques is essential to meet the evolving challenges of air pollution. New technologies, such as laser-induced breakdown spectroscopy (LIBS) and nanomaterialbased sensors, are improving sensitivity and selectivity in pollutant detection. Furthermore, integrating big data analytics and machine learning into air quality monitoring systems will allow for sophisticated analyses of complex datasets, facilitating accurate trend predictions and informed decision-making.

Collaboration among analytical chemists, environmental scientists, engineers, and public health experts is critical for addressing future air pollution complexities. For instance, initiatives like the U.S. Environmental Protection Agency's (EPA) Air-Now program demonstrate how interdisciplinary teams can combine real-time air quality data with health impact assessments to inform public policy. By fostering a holistic understanding of pollutant sources, transport, and health effects, interdisciplinary research can enhance the development of effective pollution control strategies. Such partnerships are vital for translating scientific research into actionable policies that effectively address the health impacts of air pollution. Despite the promising opportunities presented by these advancements, several challenges remain. Funding constraints, regulatory hurdles, and technological can limitations impede the implementation of new methodologies. Addressing these challenges may require innovative funding solutions, supportive policy frameworks, and increased training for interdisciplinary teams to ensure successful collaboration. Looking ahead, embracing community-based monitoring initiatives and ensuring real-world impact will shape the future of air quality monitoring and management. Analytical chemistry will remain central to future efforts in air pollution research and management. Its robust pollutant detection, identification, and quantification capabilities are indispensable for developing

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strategies to mitigate air pollution. Embracing continuous innovation and fostering interdisciplinary collaboration, we can create more effective approaches to protect both public health and the environment from the adverse effects of air pollution. Stakeholders, including researchers, policymakers, and community members, must invest in and prioritize air pollution research and innovation to ensure a healthier future for all.

Conflict of Interest

The authors declare that there is no conflict of interest.

Authors' Declaration

The authors affirm that the work presented is original, and will accept all liability for any claims about the content.

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