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Advances in Aerosol Characterization and Analytical Instrumentation: Measurement Traceability, Standardization, and Environmental Applications

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ABSTRACT

Atmospheric aerosols influence climate processes, air quality, ecosystem health, agricultural productivity, and human exposure, making reliable particle characterization essential for environmental research and regulatory decision-making. Despite substantial progress in aerosol science, uncertainties remain in the measurement of particle number and mass concentrations, size distributions, optical properties, and chemical composition. This review examines recent developments in aerosol characterization with particular emphasis on analytical instrumentation, measurement traceability, standardized procedures, and cross-platform comparability. Advanced gas-phase techniques, including proton-transfer-reaction time-of-flight mass spectrometry (PTR-ToF-MS) and gas chromatography–mass spectrometry (GC-MS), provide complementary capabilities for real-time monitoring and detailed identification of volatile organic compounds and their oxidation products. Particle-phase properties can be evaluated using high-resolution time-of-flight aerosol mass spectrometry (HR-ToF-AMS), aerosol chemical

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speciation monitoring (ACSM), condensation particle counting (CPC), and scanning mobility particle sizing (SMPS). Emerging approaches such as chemical ionization mass spectrometry coupled with filter inlet for gases and aerosols (FIGAERO-CIMS) and extractive electrospray ionization time-of-flight mass spectrometry (EESI-ToF-MS) further enable molecular-level investigation of complex gas–particle systems and secondary organic aerosol formation. Alongside instrumental advances, robust calibration, metrological traceability, and harmonized measurement protocols are necessary to ensure that aerosol datasets obtained across laboratories, monitoring networks, and application sectors remain comparable. The review also considers documentary standards and regulatory measurement requirements relevant to ambient air and particle emissions from transportation and stationary sources. Remaining challenges associated with methodological differences, instrument-specific uncertainties, and data harmonization are critically discussed, together with opportunities for improving measurement consistency and supporting reliable aerosol monitoring across environmental and regulatory applications.

Keywords: Atmospheric aerosols; Aerosol characterization; Analytical instrumentation; Measurement traceability; Secondary organic aerosols; Measurement standardization

Highlights

- Reviews advances in aerosol physical and chemical characterization.
- Examines analytical tools for resolving complex gas–particle systems.
- Evaluates calibration, traceability, and aerosol measurement standardization.
- Identifies challenges affecting cross-instrument and cross-sector data comparability.
- Highlights future needs for harmonized and reliable aerosol monitoring frameworks.

1.Introduction

Atmospheric aerosols are an important component of the Earth system because of their influence on climate, air quality, human health, ecosystems, and agricultural productivity (Arfin et al., 2023; Davidson et al., 2005; Li et al., 2022; Liu et al., 2021). Their effects are governed not only by atmospheric abundance but also by particle size, number and mass concentration, chemical composition, morphology, and optical properties. These characteristics influence atmospheric residence time, transport and deposition, radiative interactions, cloud processes, and human exposure. Consequently, the reliable characterization of airborne particles has

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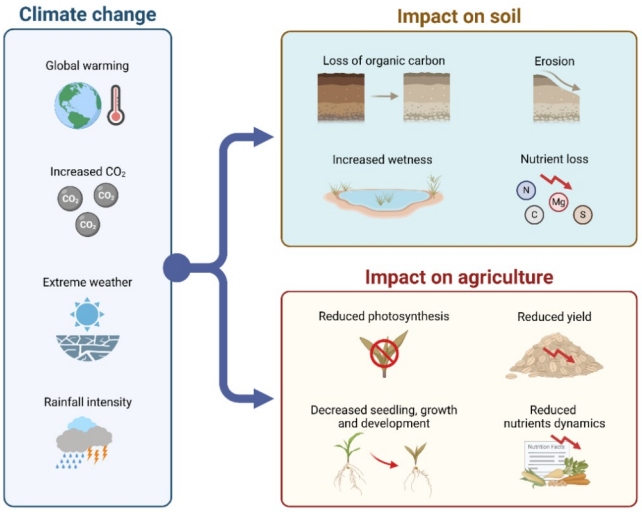


Figure 1. Effects of climate change on soil properties and agricultural productivity. Schematic representation of how climate-related drivers, including global warming, increased atmospheric CO_2, extreme weather, and changes in rainfall intensity, affect soil and agricultural systems

become increasingly important for atmospheric research, emission control, environmental monitoring, and regulatory decision-making. Experimental measurement remains fundamental to understanding aerosol behavior and evaluating its environmental consequences. Reliable measurements provide the evidence required to examine atmospheric processes, validate mechanistic hypotheses, constrain numerical and climate models, evaluate emission-control strategies, and assess changes in air quality. Nevertheless, every aerosol measurement carries a degree of uncertainty arising from instrumental response, calibration procedures, sampling conditions, particle characteristics, environmental variability, and data-processing approaches. These challenges become particularly important when measurements obtained using different instruments, laboratories, monitoring networks, or regulatory protocols are compared. The rapid development of aerosol instrumentation has further increased the need for robust calibration and measurement traceability. Current technologies range from relatively inexpensive particulate matter (PM) sensors used in distributed air-quality networks to particle-number (PN) instruments employed for emission monitoring and sophisticated analytical platforms capable of resolving particle composition at high temporal and chemical resolution. Although this technological diversity has substantially expanded aerosol-monitoring capabilities, differences in operating principles, detection limits, calibration procedures, sampling configurations, and quality assurance/quality control (QA/QC) can introduce variability among datasets. Establishing traceability to recognized measurement standards is therefore essential for generating measurements that are reproducible and comparable across instruments and applications.

Aerosol metrology provides the framework needed to establish this measurement confidence. Calibration links the response of an instrument under specified conditions to a reference quantity with a defined measurement uncertainty (JCGM, 2012). Importantly, calibration represents the establishment of this quantitative relationship and does not necessarily imply subsequent adjustment of the instrument. Measurement

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uncertainty may be expressed as a combined standard uncertainty or as an expanded uncertainty using an appropriate coverage factor. Guidance relevant to uncertainty estimation and the evaluation of measurement accuracy is provided through established standards such as ISO 20988 and the ISO 5725 series (ISO 20988, 2007; ISO 5725-1, 2023; ISO 5725-2, 2019). Within the metrological hierarchy, primary, secondary, working, and travelling standards serve different functions. Primary standards establish measurement values independently of another standard for the same quantity, whereas secondary standards derive their traceability through calibration against a primary reference (JCGM, 2012). For aerosol particle number concentration, for instance, a Faraday Cup Aerosol Electrometer (FCAE), when appropriately linked to primary electrical-current and aerosol-flow standards, can provide a primary measurement reference. A Condensation Particle Counter (CPC) calibrated against such a reference can subsequently function as a secondary standard. Interlaboratory comparisons provide an additional mechanism for evaluating measurement consistency and identifying systematic or random differences that may not be fully captured through individual uncertainty assessments. Such comparisons are therefore increasingly important for strengthening confidence in aerosol measurements across institutions and monitoring systems. Alongside physical aerosol measurements, understanding particle formation and transformation requires detailed chemical characterization. Secondary organic aerosol (SOA) is particularly challenging because it develops through complex atmospheric oxidation of volatile and semi-volatile precursors. Biogenic volatile organic compounds (VOCs) include important classes such as monoterpenes and sesquiterpenes, whereas anthropogenic sources contribute a broad range of aromatic and aliphatic hydrocarbons (Gu et al., 2021; Srivastava et al., 2022). A substantial fraction of SOA precursors and transformation products remains incompletely characterized, contributing to uncertainties in atmospheric aerosol budgets and climate predictions (Figure 1). Changes in temperature, humidity, oxidant availability, precursor composition, and atmospheric aging further influence SOA formation and chemical evolution. Biomass burning represents an important source of primary and secondary organic aerosol and releases numerous compounds capable of undergoing atmospheric oxidation (Shrivastava et al., 2015). Emissions can include aromatic and aliphatic hydrocarbons, phenolic compounds, carbonyls, and other oxygenated species that contribute to subsequent SOA formation (Tipayarom and Kim Oanh, 2020; Tsiligiannis et al., 2019; Kiland et al., 2023; Zarzana et al., 2018). Agricultural residue burning is particularly relevant in regions where crop residues are routinely burned as an inexpensive method of field clearance. Such practices can release substantial quantities of particulate matter and VOCs and have been widely reported across Asian regions, including India and China (Bansal et al., 2019; Chantara et al., 2019; Devaprasad et al., 2023; Satish et al., 2020; Singh et al., 2016). Although emission profiles and emission factors from biomass and agricultural-residue burning have been extensively investigated (Dhammapala et al., 2007; Stockwell et al., 2014, 2015; Zhang et al., 2011, 2017), uncertainties remain regarding the chemical evolution of these emissions and the contribution of unidentified precursors to SOA production.

Advances in analytical instrumentation are increasingly helping to address these knowledge gaps. Real-time gas-phase measurements using proton-transfer-reaction time-of-flight mass spectrometry (PTR-ToF-MS) can resolve rapid variations in VOCs and their oxidation products, while gas chromatography–mass spectrometry (GC-MS) provides detailed chemical identification of collected compounds. Particle-phase

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composition can be investigated using high-resolution time-of-flight aerosol mass spectrometry (HR-ToF-AMS) and aerosol chemical speciation monitoring (ACSM), while CPC and scanning mobility particle sizing (SMPS) provide complementary information on particle number and size distributions. More advanced approaches, including chemical ionization mass spectrometry coupled with a filter inlet for gases and aerosols (FIGAERO-CIMS) and extractive electrospray ionization time-of-flight mass spectrometry (EESI-ToF-MS), offer molecular-level information on gas- and particle-phase compounds and can improve understanding of SOA formation and atmospheric aging.

Instrumental capability alone, however, does not guarantee comparability. Documentary standards provide agreed procedures and technical requirements that support consistent measurement practices across research, industrial, and regulatory environments. Such documents may be developed internationally through organizations such as the International Organization for Standardization (ISO), regionally through bodies such as the European Committee for Standardization (CEN), nationally, or through specialized organizations including SAE International. While many documentary standards are voluntary, they may become incorporated into regulatory frameworks when measurements are used for emission compliance, environmental protection, or public-health assessment. Differences among standards and protocols can therefore have practical consequences when aerosol measurements from air-quality monitoring, road transportation, aviation, shipping, and stationary emission sources are compared. Against this background, the present review critically examines advances in aerosol characterization, analytical instrumentation, measurement traceability, calibration, and documentary standardization. Particular attention is given to particle number and mass concentration, particle size, black-carbon-related measurements, and analytical approaches for investigating aerosol composition and SOA evolution. The review further evaluates differences among measurement approaches used across environmental monitoring and emission-control applications and identifies remaining metrological and methodological gaps. By integrating physical characterization, advanced chemical analysis, calibration principles, and documentary standards within a common framework, this review seeks to highlight opportunities for greater harmonization and to support more accurate, reproducible, and comparable aerosol measurements across scientific and regulatory disciplines.

2. Analytical Instrumentations

The characterization of SOA formation and evolution within environmental chambers require advanced analytical instrumentation capable of resolving complex gas-particle mixtures. Gas-phase analysis commonly employs instruments such as Proton-Transfer-Reaction Time-of-Flight Mass Spectrometry (PTR-ToF-MS) and gas Chromatography-Mass Spectrometry (GC-MS). PTR-ToF-MS enables high-sensitivity, real-time monitoring of VOCs and their oxidation products, whereas GC-MS provides detailed offline chemical specification from collected samples. Particle-phase characterization is achieved using instruments such as the High-Resolution Time-of-Flight Aerosol Mass Spectrometer (HR-ToF-AMS) and the Aerosol Chemical Speciation Monitoring (ACSM), which measure aerosol mass, composition, and size distributions. Particle number concentration and size are determined using the Condensation Particle Counter (CPC) and Scanning Mobility Particle Sizer (SMPS). Advanced dual-phase systems, including Chemical Ionization Mass Spectrometry (CIMS) with FIGAERO inlets and Extractive

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Electrospray Ionization Time-of-Flight Mass Spectrometry (EESI-ToF-MS), provide molecular-level insights into both gas and particle phase without fragmentation. Collectively, these instruments enable comprehensive assessment of SOA formation composition, and transformation under controlled experimental conditions (Joshi et al., 2024).

2.1. GC and LC-MS for molecular analysis

Gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-mass spectrometry (LC-MS) are two widely employed analytical techniques for the molecular-level characterization of atmospheric organic aerosols (Oas). Since the 1970s, GC-MS has been extensively applied to identify volatile and semi-volatile organic compounds in aerosols, particularly in source apportionment studies. This technique relies on volatility-driven separation and is especially effective for thermal stable compounds with low to moderate polarity. It has successfully identified source-specific tracers such as polycyclic aromatic hydrocarbons (PHAs) originating from fossil fuel combustion and levoglucosan derived from biomass burning. However, GC-MS exhibits limitations in analysing highly polar or thermally unstable compounds, which often require chemical derivatization for detection. Advances such as comprehensive two-dimensional gas-chromatography (GCxGC) have significantly enhanced its resolving capability, enabling the identification of hundreds of compounds in a single analysis. In contrast, LC-MS is better suited for analysing polar, non-volatile, and high molecular weight species, including dimers and oligomers of secondary organic aerosols (SOAs). This method employs soft ionization techniques-such as electrospray ionization (ESI), atmospheric pressure chemical ionization (APCI), and photoionization (APPI)-which minimize fragmentation and facilitate more detailed molecular identification (IPCC, 2021; IREA, 2023; Kumler et al., 2019; Craig et al., 2019). When coupled with high-resolution mass spectrometry (e.g., Orbitrap or FT-ICR-MS), LC-MS enables near-complete molecular characterization through precise molecular formula assignment and isomer differentiation. Although GC-MS remains advantageous due to its robustness and separation efficiency, LC-MS has become indispensable for investigating complex aerosol chemistry, particularly where soft ionization and detection of high molecular weight compounds are required (Hildmann et al., 2024).

2.2. Analytical approaches and resulting analytical conditions

Three principal analytical strategies are employed in the study of organic aerosols (OAs): targeted analysis (TA), non-targeted analysis (NTA), and semi-targeted analysis (STA), each characterized by distinct capabilities and requirements. Targeted analysis is applied when specific, well-characterized compounds-often serving as markers for particular sources or processes-are of interest. This approach provides high sensitivity, accuracy, and precision, and depends on the availability of authentic reference standards. Techniques such as tandem mass spectrometry (e.g., triple quadrupole MS) and reversed-phase liquid chromatography (RPLC) are commonly utilized in TA. In contrast, non-targeted analysis aims to detect and characterize all measurable organic compounds, including unknown species. This approach facilitates the investigation of complex and poorly understood atmospheric processes, such as cloud formation, aerosol ageing, and the discovery of novel chemical markers. Semi-targeted analysis serves as an intermediate approach, enabling the quantification of compound classes for which only limited representative standards exist. This method is particularly valuable when accurate standard generation is difficult, as is often the case for

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complex SOA constituents or organosulfates. Although STA may not yield absolute concentration values, it provides insight into relative trends and guides further investigation. The selection of an appropriate analytical strategy must align with the research objectives, and in many cases, a combination of approaches is employed to achieve a comprehensive understanding of OA composition and transformation (Hildmann et al., 2024).

2.3. Instrumental approaches

Advancements in instrumentation have played a pivotal role in improving the chemical characterization of organic aerosols. Traditional one-dimensional liquid chromatography (LC) and mass spectrometry (MS) systems have evolved into more advanced configurations, including multidimensional LC and tandem MS techniques. Liquid chromatography coupled with ultraviolet/visible detection (LC-UV/Vis) has long been used to detect compounds with strong chromaphoric properties, such as PAHs and derivatized carbonyl compounds. While UV/Vis detection lacks specificity, its integration with MS (LC-UV/Vis-MS) enhances selectivity and compound identification, particularly for optically active species like brown carbon. More advanced approaches, such as LC-MSn (tandem mass spectrometry), provide structural information by inducing fragmentation of selected ions. Techniques including product ion scanning and multiple reaction monitoring (MRM) are widely applied in studies of SOAs and biomass burning aerosols, offering high specificity for target compound identification and quantification. Two-dimensional liquid chromatography (2D-LC) techniques have emerged as powerful tools for resolving complex aerosl mixtures. In heart-cut (LC-LC) and multiple heart-cut (mLC-LC) configurations, selected fractions from the first chromatographic dimension undergo further separation in a second dimension, thereby enhancing resolution and reducing co-elution. Comprehensive LC (LCxLC) extends this approach by transferring the entire effluent from the first dimension into the second, providing maximum analytical coverage and making it particularly for non-targeted analyses. However, these techniques face practical challenges, including reduced sensitivity at trace concentrations, complex system configurations, and issues related to solvent compatibility (Hildmann et al., 2024).

2.4. Instruments for Particle-Phase Measurements

2.4.1. Aerosol Mass Spectrometer (AMS)

Aerosol mass spectrometry is widely used for real-time characterization of atmospheric particle composition and mass loading. The high-resolution time-of-flight aerosol mass spectrometer (HR-ToF-AMS) is particularly useful for analyzing non-refractory submicron particles and provides information on their chemical composition, size, and mass concentration. Aerosol mass is quantified from ion signals detected at specific mass-to-charge ratios (m/z) (Jimenez, 2003). The high sensitivity and mass resolution of HR-ToF-AMS also facilitate assessment of the elemental composition and oxidation state of organic aerosols. However, electron-impact ionization can cause substantial molecular fragmentation, which may limit identification of individual organic compounds. Complementary analytical techniques are therefore useful when more detailed molecular characterization is required (Wang et al., 2019).

2.4.2. Aerosol Chemical Speciation Monitor (ACSM)

The aerosol chemical speciation monitor (ACSM) is based on analytical principles similar to aerosol mass spectrometry but is primarily designed for routine and extended monitoring of aerosol composition. It provides quantitative measurements of major non-refractory particulate components,

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including organics, sulfate, nitrate, ammonium, and chloride. ACSM has also been employed to investigate SOA formation associated with biomass-burning emissions under controlled chamber conditions (El Mais et al., 2023). Compared with HR-ToF-AMS, ACSM generally provides lower sensitivity and resolution but offers advantages for continuous, long-term measurements. HR-ToF-AMS is more appropriate when detailed chemical characterization and higher mass resolution are required.

2.4.3. Particle Number Concentration and Size Distribution

Particle number concentration and size distribution are important parameters for evaluating aerosol formation, growth, and atmospheric transformation. Electrical-mobility-based techniques are commonly employed for this purpose. The scanning mobility particle sizer (SMPS) characterizes particle size distributions based on electrical mobility, whereas the condensation particle counter (CPC) measures particle number concentrations after increasing the detectable size of small particles through vapor condensation (Engelhart et al., 2012). These measurements can be combined with online monitoring of gaseous species such as NOx, O_3, and SO_2 to provide a more comprehensive understanding of aerosol evolution during chamber experiments (Ahern et al., 2019). Measurement configurations may also vary depending on whether experiments are performed using indoor or outdoor atmospheric chambers. Chemical ionization mass spectrometry (CIMS) is an advanced analytical technique capable of characterizing compounds involved in SOA formation while preserving considerable molecular information. Coupling CIMS with a Filter Inlet for Gases and AEROsols (FIGAERO) enables sequential characterization of compounds present in both gas and particle phases (Lopez-Hilfiker et al., 2014). FIGAERO-CIMS has been used in atmospheric studies to investigate VOC oxidation products, oxygenated organic compounds, and other species associated with SOA formation and chemical aging (Buchholz et al., 2020). Compared with the electron-impact ionization employed in HR-ToF-AMS, the relatively soft ionization used in CIMS can reduce fragmentation and retain more information about the molecular characteristics of detected compounds.

2.4.3. Extractive Electrospray Ionization Time-of-Flight Mass Spectrometry (EESI-ToF)

Extractive electrospray ionization time-of-flight mass spectrometry (EESI-ToF) provides high-time-resolution characterization of organic aerosols at near-molecular detail. Its relatively soft ionization approach limits extensive fragmentation, allowing chemically complex and low-volatility organic species to be investigated with greater molecular specificity. EESI-ToF can therefore be used to follow changes in SOA composition and provide insights into atmospheric aging and transformation processes (Lopez-Hilfiker et al., 2019).

Dual-phase configurations further extend EESI-ToF measurements to both gaseous and particulate compounds using a common analytical platform (Lee et al., 2022). Together, EESI-ToF and CIMS complement conventional aerosol characterization techniques by providing molecular information that may not be retained using harder ionization approaches. Their integration with AMS, ACSM, SMPS, and CPC measurements can provide a broader understanding of aerosol concentration, particle size, chemical composition, and molecular evolution during SOA formation.

3. Methods to collect and analyses individual fog/cloud residual particles

To investigate individual fog or cloud residual particles, researchers commonly employ Counter-Flow Virtual Impactors (CVI) or

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ground-based CVI (GCVI) systems to separate activated cloud droplets from non-activated interstitial particles. These instruments selectively admit droplets from non-activated interstitial particles. These instruments selectively admit droplets exceeding a defined size threshold (typically 6-10 μm), which are subsequently evaporated at elevated temperatures (~40°C), leaving residual particles for analysis. These residues provide critical insight into particle transformation processes occurring during cloud interactions. For real-time (online)analysis, techniques such as Single Particle Mass Spectrometry (SPMS), including ATOFMS and SOAMS, are used to determine particle size and chemical composition at the individual particle level. The Single Particle Soot Potometer (SP2) is specifically employed to analyses black carbon and its associated coating. Offline analytical methods include Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM), often combined with Energy-Dispersive X-ray Spectroscopy (EDS), to characterize particle morphology and elemental composition. Additional advanced techniques-such as micro-PIXE, STXM/NEXAFS, NanoSIMS, and ToF-SIMS-provide detailed chemical and spatial information on particle structure and surface chemistry. These methods collectively enable comprehensive analysis of particle size, morphology, internal mixing states, and the formation of secondary species resulting from cloud processing. However, potential artefacts-such as the loss of volatile components and complex transformations during droplet activation and evaporation-must be carefully considered when interpreting results (Zhang et al., 2025).

4. Compositions of individual fog/cloud droplets residual particles in different environments

The chemical composition of individual fog or cloud droplet residual particles varies significantly across different environments due to their differences in emission sources and atmospheric processing mechanisms (Sun et al., 2018). In urban and industrial regions, these particles are typically dominated by soot; ammonium sulphate, fly ash, and metal-rich constituents (e.g., Pb, Fe, Zn), often exhibiting complex internal mixing with secondary species such as nitrate and sulphate, indicative of strong internal mixing with secondary species such as nitrate and sulphate, indicative of strong anthropogenic influence (Sunder et al., 1996; SuYing et al., 2010). In costal environments, residual particles are primarily composed of sea salt and aged sea salt, frequently mixed with sulphates, organic matter, and nitrogen-containing organic compounds formed through interactions between marine emissions and anthropogenic pollutants (Takemura et al., 2004). Dust-dominated regions are characterized by mineral particles such as quartz, aluminosilicates, calcite, and gypsum. Their effectiveness as cloud condensation nuclei (CCN) is enhanced when coated with soluble substances, including sulphates and organic compounds formed through atmospheric reactions (Tao et al., 2007). In remote background regions, particles are typically highly aged and internally mixed with sulphate, nitrate, and organic components due to long-range transport and extensive atmospheric processing. These particles often exhibit complex morphologies and modified microphysical properties resulting form in-cloud chemical transformations, such as the formation of sulphate and oxalate. Such changes influence their cloud-forming ability and optical properties relevant to climate processes (Zhang et al., 2018, 2020, 2024).

5. Conclusion

Advances in aerosol characterization and analytical instrumentation have substantially improved our ability to understand the physical and chemical properties, sources, formation, and atmospheric transformation of

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aerosols. Modern analytical platforms, including PTR-ToF-MS, GC-MS, LC-MS, HR-ToF-AMS, ACSM, CPC, SMPS, FIGAERO-CIMS, and EESI-ToF-MS, provide complementary information on particle number, size distribution, chemical composition, and molecular-level changes in complex gas–particle systems. The integration of targeted, non-targeted, and high-resolution analytical approaches has further expanded the characterization of secondary organic aerosols and their transformation products.

Despite these advances, differences in instrument response, sampling procedures, calibration methods, detection limits, and data-processing approaches continue to affect the comparability of aerosol measurements. Therefore, measurement traceability, robust QA/QC procedures, standardized calibration practices, and harmonized analytical protocols are essential for producing reliable and reproducible datasets across laboratories and monitoring networks. Established metrological frameworks and documentary standards can play an important role in reducing measurement uncertainty and improving cross-instrument and cross-sector comparability. Future research should focus on integrating complementary analytical platforms, improving molecular-level characterization of complex and previously unresolved aerosol components, and developing standardized procedures for emerging instrumentation. Greater harmonization between analytical innovation, metrological traceability, and environmental monitoring will strengthen the interpretation of aerosol measurements and their application to air-quality assessment, atmospheric research, climate studies, emission control, and environmental and public-health decision-making. Ultimately, combining advanced instrumentation with rigorous measurement standards will be critical for developing reliable and comparable aerosol monitoring frameworks across scientific and regulatory applications.

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References

Bansal, O., Singh, A., Singh, D., 2019. Characteristics of black carbon aerosols over Patiala northwestern part of the IGP: source apportionment using cluster and CWT analysis. Atmos. Pollut. Res. 10, 244–256. https://doi.org/10.1016/j.apr.2018.08.001.

Canagaratna, M.R., Jayne, J.T., Jimenez, J.L., Allan, J.D., Alfarra, M.R., Zhang, Q., Onasch, T.B., Drewnick, F., Coe, H., Middlebrook, A., Delia, A., Williams, L.R., Trimborn, A.M., Northway, M.J., DeCarlo, P.F., Kolb, C.E., Davidovits, P., Worsnop, D.R., 2007. Chemical and microphysical characterization of ambient aerosols with the Aerodyne aerosol mass spectrometer. Mass Spectrom. Rev. 26, 185–222. https://doi.org/10.1002/mas.20115.

Chantara, S., Thepnuan, D., Wiriya, W., Prawan, S., Tsai, Y.I., 2019. Emissions of pollutant gases, fine particulate matters and their significant tracers from biomass burning in an open-system combustion chamber. Chemosphere 224, 407–416. https://doi.org/10.1016/j.chemosphere.2019.02.153.

Craig, M.T., Carreño, I.L., Rossol, M., Hodge, B.M., Brancucci, C., 2019. Effects on power system operations of potential changes in wind and solar generation potential under

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climate change. Environ. Res. Lett. 14, 034014.

Devaprasad, M., Rastogi, N., Satish, R., Patel, A., Singh, A., Dabhi, A., Shivam, A., Bhushan, R., Meena, R., 2023. Characterization of paddy-residue burning derived carbonaceous aerosols using dual carbon isotopes. Sci. Total Environ. 864, 161044. https://doi.org/10.1016/j.scitotenv.2022.161044.

Dhammapala, R., Claiborn, C., Jimenez, J., Corkill, J., Gullett, B., Simpson, C., Paulsen, M., 2007. Emission factors of PAHs, methoxyphenols, levoglucosan, elemental carbon and organic carbon from simulated wheat and Kentucky bluegrass stubble burns. Atmos. Environ. 41, 2660–2669. https://doi.org/10.1016/j.atmosenv.2006.11.023.

Eichler, P., Müller, M., D'Anna, B., Wisthaler, A., 2015. A novel inlet system for online chemical analysis of semi-volatile submicron particulate matter. Atmos. Meas. Tech. 8, 1353–1360. https://doi.org/10.5194/amt-8-1353-2015.

Engelhart, G.J., Hennigan, C.J., Miracolo, M.A., Robinson, A.L., Pandis, S.N., 2012. Cloud condensation nuclei activity of fresh primary and aged biomass burning aerosol. Atmos. Chem. Phys. 12, 7285–7293. https://doi.org/10.5194/acp-12-7285-2012.

Gu, S., Guenther, A., Faiola, C., 2021. Effects of anthropogenic and biogenic volatile organic compounds on Los Angeles air quality. Environ. Sci. Technol. 55, 12191–12201. https://doi.org/10.1021/acs.est.1c01481.

Hatch, L.E., Luo, W., Pankow, J.F., Yokelson, R.J., Stockwell, C.E., Barsanti, K.C., 2015. Identification and quantification of gaseous organic compounds emitted from biomass burning using two-dimensional gas chromatography-time-of-flight mass spectrometry. Atmos. Chem. Phys. 15, 1865–1899. https://doi.org/10.5194/acp-15-1865-2015.

Hildmann, S., Hoffmann, T., 2024. Characterisation of atmospheric organic aerosols with one- and multidimensional liquid chromatography and mass spectrometry: state of the art and future perspectives. TrAC Trends Anal. Chem. 175, 117698.

Intergovernmental Panel on Climate Change (IPCC), 2023. The Earth's energy budget, climate feedbacks, and climate sensitivity. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 923–1054. https://doi.org/10.1017/9781009157896.009.

International Renewable Energy Agency (IRENA), 2023. Renewable Capacity Statistics 2023. International Renewable Energy Agency, Abu Dhabi.

Jimenez, J.L., 2003. Ambient aerosol sampling using the Aerodyne aerosol mass spectrometer. J. Geophys. Res. 108, 8425. https://doi.org/10.1029/2001JD001213.

Kiland, K.J., Mahrt, F., Peng, L., Nikkho, S., Zaks, J., Crescenzo, G.V., Bertram, A.K., 2023. Secondary organic aerosol from biomass burning phenolics could increase brown carbon lifetimes, seed ice clouds, and transport pollutants. ChemRxiv. https://doi.org/10.26434/chemrxiv-2023-n4qvm.

Kumler, A., Carreño, I.L., Craig, M.T., Hodge, B.M., Cole, W., Brancucci, C., 2019. Inter-annual variability of wind and solar electricity generation and capacity values in Texas. Environ. Res. Lett. 14, 044032.

Lee, C.P., Surdu, M., Bell, D.M., Dommen, J., Xiao, M., Zhou, X., Baccarini, A., Giannoukos, S., Wehrle, G., Schneider, P.A., Prevot, A.S.H., Slowik, J.G., Lamkaddam, H., Wang, D., Baltensperger, U., El Haddad, I., 2022. High-frequency gaseous and particulate chemical characterization using extractive electrospray ionization mass spectrometry (dual-phase-EESI-TOF). Atmos. Meas. Tech. 15, 3747–3760. https://doi.org/10.5194/amt-15-3747-2022

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Lopez-Hilfiker, F.D., Mohr, C., Ehn, M., Rubach, F., Kleist, E., Wildt, J., Mentel, T.F., Lutz, A., Hallquist, M., Worsnop, D., Thornton, J.A., 2014. A novel method for online analysis of gas and particle composition: description and evaluation of a filter inlet for gases and AEROsols (FIGAERO). Atmos. Meas. Tech. 7, 983–1001. https://doi.org/10.5194/amt-7-983-2014.

Lopez-Hilfiker, F.D., Pospisilova, V., Huang, W., Kalberer, M., Mohr, C., Stefenelli, G., Thornton, J.A., Baltensperger, U., Prevot, A.S.H., Slowik, J.G., 2019. An extractive electrospray ionization time-of-flight mass spectrometer (EESI-TOF) for online measurement of atmospheric aerosol particles. Atmos. Meas. Tech. 12, 4867–4886. https://doi.org/10.5194/amt-12-4867-2019.

Satish, R., Rastogi, N., Singh, A., Singh, D., 2020. Change in characteristics of water-soluble and water-insoluble brown carbon aerosols during a large-scale biomass burning. Environ. Sci. Pollut. Res. 27, 33339–33350. https://doi.org/10.1007/s11356-020-09388-7.

Shrivastava, M., Easter, R.C., Liu, X., Zelenyuk, A., Singh, B., Zhang, K., Ma, P.L., Chand, D., Ghan, S., Jimenez, J.L., Zhang, Q., Fast, J., Rasch, P.J., Tiitta, P., 2015. Global transformation and fate of SOA: implications of low-volatility SOA and gas-phase fragmentation reactions. J. Geophys. Res. Atmos. 120, 4169–4195. https://doi.org/10.1002/2014JD022563.

Singh, A., Rastogi, N., Patel, A., Satish, R.V., Singh, D., 2016. Size-segregated characteristics of carbonaceous aerosols over the northwestern Indo-Gangetic Plain: year-round temporal behavior. Aerosol Air Qual. Res. 16, 1615–1624. https://doi.org/10.4209/aaqr.2016.01.0023.

Srivastava, D., Vu, T.V., Tong, S., Shi, Z., Harrison, R.M., 2022. Formation of secondary organic aerosols from anthropogenic precursors in laboratory studies. npj Clim. Atmos. Sci. 5, 22. https://doi.org/10.1038/s41612-022-00238-6.

Stockwell, C.E., Veres, P.R., Williams, J., Yokelson, R.J., 2015. Characterization of biomass burning emissions from cooking fires, peat, crop residue, and other fuels with high-resolution proton-transfer-reaction time-of-flight mass spectrometry. Atmos. Chem. Phys. 15, 845–865. https://doi.org/10.5194/acp-15-845-2015.

Sun, J., Zhi, G., Jin, W., Chen, Y., Shen, G., Tian, C., Zhang, Y., Zong, Z., Cheng, M., Zhang, X., Zhang, Y., Liu, C., Lu, J., Wang, H., Xiang, J., Tong, L., Zhang, X., 2018. Emission factors of organic carbon and elemental carbon for residential coal and biomass fuels in China—a new database for 39 fuel-stove combinations. Atmos. Environ. 190, 241–248. https://doi.org/10.1016/j.atmosenv.2018.07.032.

Sunder, A., Kliche, D., Chou, J., Welch, R., 1996. First estimates of the radiative forcing of aerosols generated from biomass burning using satellite data. J. Geophys. Res. 21, 265–273.

SuYing, Y., JianZhong, M., ZhiJin, H., Peng, Y., Yue, C., Wei, W., 2010. Influence of multi-chemical-component aerosols on microphysics of warm clouds in North China. Sci. China, 451–461.

Takemura, T., Nozawa, T., Emori, S., Nakajima, T., Nakajima, T., 2004. Simulation of climate response to aerosol direct and indirect effects with aerosol transport-radiation model. J. Geophys. Res. 109.

Tao, W.-K., Li, X., Khain, A., Matsui, T., Lang, S., 2007. Role of atmospheric aerosol concentration on deep convective precipitation: cloud-resolving model simulations. J. Geophys. Res. 112, D24S18.

Tipayarom, A., Kim Oanh, N.T., 2020. Influence of rice straw open burning on levels and profiles of semi-volatile organic compounds in ambient air. Chemosphere 243, 125379. https://doi.org/10.1016/j.chemosphere.2019.125379.

Tsiligiannis, E., Hammes, J., Salvador, C.M., Mentel, T.F., Hallquist, M., 2019. Effect of NOx on 1,3,5-trimethylbenzene (TMB)

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oxidation product distribution and particle formation. Atmos. Chem. Phys. 19, 15073–15086. https://doi.org/10.5194/acp-19-15073-2019.

Zarzana, K.J., Selimovic, V., Koss, A.R., Sekimoto, K., Coggon, M.M., Yuan, B., Dubé, W.P., Yokelson, R.J., Warneke, C., de Gouw, J.A., Roberts, J.M., Brown, S.S., 2018. Primary emissions of glyoxal and methylglyoxal from laboratory measurements of open biomass burning. Atmos. Chem. Phys. 18, 15451–15470. https://doi.org/10.5194/acp-18-15451-2018.

Zhang, H., Hu, D., Chen, J., Ye, X., Wang, S.X., Hao, J.M., Wang, L., Zhang, R., An, Z., 2011. Particle size distribution and polycyclic aromatic hydrocarbons emissions from agricultural crop residue burning. Environ. Sci. Technol. 45, 5477–5482. https://doi.org/10.1021/es1037904.

Zhang, H., Hu, J., Qi, Y., Li, C., Chen, J., Wang, X., He, J., Wang, S., Hao, J., Zhang, L., Zhang, L., Zhang, Y., Li, R., Wang, S., Chai, F., 2017. Emission characterization, environmental impact, and control measure of PM2.5 emitted from agricultural crop residue burning in China. J. Clean. Prod. 149, 629–635. https://doi.org/10.1016/j.jclepro.2017.02.092.

Zhang, J., Cenci, J., Becue, V., Koutra, S., Ioakimidis, C., 2020. Recent evolution of research on industrial heritage in Western Europe and China based on bibliometric analysis. Sustainability, 1–15.

Zhang, T., Zhu, Z., Gong, W., Zhu, Z., Sun, K., Wang, L., Huang, Y., Mao, F., Shen, H., Li, Z., Xu, K., 2018. Estimation of ultrahigh resolution PM2.5 concentrations in urban areas using 160 m Gaofen-1 AOD retrievals. Remote Sens. Environ., 91–104.

Zhang, W., Wang, H., Zhang, X., Peng, Y., Liu, Z., Wang, D., Zhang, D., Han, C., Zhao, Y., Zhong, J., Jia, W., Ning, H., Che, H., 2025. Subgrid-scale aerosol–cloud interaction in the atmospheric chemistry model CMA_Meso5.1/CUACE and its impacts on mesoscale meteorology prediction. Atmos. Chem. Phys. 25, 9005–9023.

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