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Analysis of the Aerosol Optical Characteristics in the African Urban Ecosystems - A Review

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Abstract

Understanding the trend and magnitude of aerosol-climate interaction has been identified as a source of uncertainty globally. The study reviewed the scientific approaches for the precise quantification of direct, indirect and semi-direct impacts of aerosol on climate. This includes the evolutionary development of aerosol optical properties observation, methods of calibration of sun photometers, mechanism of aerosol-radiation interaction, distribution of aerosol particles and component retrieval methods, aerosol properties, modelling and reanalysis, and aerosol radiative effects. The study identified the limited spatial extent of the ground-based measurement approach and the scarcity of remote sensing data in many climate hotspots of Africa. The study acknowledges the opportunities for the reduction of uncertainties due to calibration errors and unstable weather conditions when using the ground-based approach; however, complementing the ground-based approach with remote sensing techniques produces more reliable results, as remote sensing provides a long-term, consistent observation of aerosol optical properties. The study, however, asserts that remote sensing infrastructures for aerosol optical properties in the West Africa sub-region are not adequate to address the uncertainties in the aerosol-climate interactions.

Keywords: Aerosol; climate; effects; modelling; radiative

1. Introduction

Aerosol particles are a mixture of carbon, organic, inorganic solid or liquid substances of different optical properties suspended in the atmosphere over a particular time and space. In the context of climate change, aerosol optical properties are measured by aerosol particles' interaction with solar radiation (Ma *et al.*, 2022). Aerosol properties encompass a variety of variables, including aerosol optical depth (AOD), which is a measure of the magnitude of aerosol extinction due to scattering and absorption in the vertical column of the troposphere, or the extent of reach of the travelling solar radiation through the aerosol layer (Fountoulakis *et al.*, 2022). The single scattering albedo (SSA) is a measure of the relative value of scattering and absorption through the ratio of scattering and absorption coefficients, and the angstrom exponent (AE) is wavelength-dependent on the AOD, with higher values of AE >0.95 indicating fine particles and AE between 0.85 and 0.95 in indicating a coarse particle (Luo, et al, 2020). Aerosol properties are unevenly distributed on all scales as changes in radiative forcing of the atmosphere vary from place to place. Such differential characteristics of the atmosphere affect the climate and contribute to climate change risks, making understanding the trends and magnitude of radiative effects of aerosol absorption properties a critical challenge globally (Mao and Wan, 2022).

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Even though the aerosol-climate interactions are complex, aerosol particles influence the Earth`s radiation budgets directly and indirectly (Bellouin *et al.*, 2020). As a direct impact, aerosol particles may scatter or absorb solar radiation at varying degrees according to optical properties; as an indirect impact, aerosol particles may combine with clouds and cause changes in cloud properties, which may also affect the precipitation patterns (Chen *et al.*, 2023). While the absorbed aerosol particles, such as dust, may stop cloud formation but facilitate cloud evaporation, the non-absorbed aerosol, which includes sulphate salts, may extend the cloud lifetime and cloud cover (Stevens and Dastoor, 2019). The non-absorbing aerosol has been responsible for cross-equatorial sea surface temperature gradients, which have significantly contributed to changes in the low latitude cloud circulation and rainfall events (Ajoku et al, 2021). Although the Earth's radiation budget values at the top of the atmosphere (TOA) vary from negative to positive numbers at a certain single scattering albedo value contiguous upon local albedo, the net aerosol radiative forcing (ARF) at the TOA is generally negative at all spatial scales (Kumar and Devara, 2012).

Understanding the magnitude and trends of aerosol radiative forcing has been the source of uncertainties of climate effects of aerosol optical properties globally; however, the lack of adequate aerosol properties measuring stations in the West African sub-region has contributed to a poor understanding of the magnitude of aerosol -climate interactions (Chen *et al.*, 2023). This study intends to recommend important conceptual frameworks for a deeper understanding of the aerosol-climate interaction with particular reference to the Ilorin aerosol station as the only station for West African aerosol-climate studies. Aerosol optical properties are the capability of aerosols to scatter and absorb radiation at a varied wavelength. In terms of climate change, aerosol optical properties encompass a variety of concepts and parameters, including a model of atmospheric radiation forcing (ARF) (Gharibzadeh *et al.*, 2019). Such elements include the dimension of aerosol optical thickness (AOT), and angstrom exponent (α) at wavelength (λ), single scattering albedo (SSA), particle number, refractive index and sizes (Mukai *et al.*, 2021). Aerosol optical properties depend on activities involving simplicity against complexity, time resolution, and size resolution, also called bulk composition. Aerosol optical properties are unevenly distributed on all scales, as scattering and absorbing vary (Castellanos *et al.*, 2024). These dimensions of aerosol optical properties influence each other and contribute to climate change risk, making understanding the magnitude and trends in optical properties a critical dimension of climate change investigation. This study presents ground-based sun photometer observation of regional and local elaboration and critical reflection on the optical properties' characterisation (Chen *et al.* 2018).

2. Materials and Methods

The literature on aerosol sources and radiative and optical properties produced over three decades was assessed. A synthesis of the aerosol optical properties at regional scales was conducted, drawing on insights on aerosol optical properties across the sectoral chapters on cloud, rainfall and water availability, energy, and public health (Chen *et al.*, 2018). The article is subdivided into sections: Section 2.1 discusses the evolution of aerosol optical properties; Section 2.2 discusses calibration methods for sun photometer instruments; Section 2.3 explains the mechanisms of interactions between aerosol properties and air pollution; and Section 2.4 identifies the spatiotemporal distribution and components of aerosol retrieved from Remote Sensing data. Section 2.5 explains the long-term aerosol properties based on modelling, assimilation and reanalysis, while Section 2.6 discusses the evaluation of aerosol direct radiative forcing and radiative effects. The study further provided a conclusion.

3. Result and Discussion

3.1 Evolution of Aerosol Optical Properties Observation

The development of aerosol properties observation dates back to 1750, which represented the baseline upon which the anthropogenic radiative forcing is calculated through model simulation (Carslaw *et al.*, 2017). The model simulation was based on the assumption that aerosol properties before the preindustrial atmosphere were apparently not present in the atmosphere compared to the postindustrial atmosphere, which recorded changes in aerosol optical properties with a very large uncertainty of aerosol radiative forcing (Chen *et al.*, 2023). For example, the standard deviation of the cloud condensation nuclei (CCN) between the preindustrial atmosphere and the present-day ratio ranges between 0.35 and 0.75 (Carslaw *et al.*, 2017). The determination of aerosol optical properties began in the 20th century and was characterised by direct measurement of optical properties such as solar radiation, solar constant, irradiance, sunshine duration, and optical depth, as well as meteorological parameters through the ground-based sun photometer (Xun *et al.*, 2021). Subsequently, the photometer continued to progressively advance as other instruments, which include the Aerosol Robotic Network (AERONET) and subsets such as the photometric pour le Traitement Operation de normalisation satellite (PHOTONS), aerosol Canada (AEROCAN), Red Iberica de media fotometrica ´ de aerosols networks for aerosol measurements (RIMA), skyrad network (SKYNET), global atmosphere watch–precision filter radiometer network (GAWPFR), and global network of large-scale sun photometer stations developed (Giles *et al.*, 2019)

The scientific investigation of the aerosol optical properties began with an assessment of the background condition of the atmosphere in urban and rural areas of the world, followed by the global and regional analysis of the aerosol components and through the determination of size distribution, wavelength dependence of the complex refractive index, and SSA of aerosol optical products (Zhao *et al.*, 2020). Despite the present level of development of techniques for aerosol properties retrieval, there is difficulty in obtaining precise information in Africa, particularly in West Africa. However, a station has been established in Ilorin, Kwara State, which represents the whole West Africa sub-region. This is grossly inadequate compared to the adequate number of stations established in many other regions of the globe. In spite of that, many scholars still believe that the development of the ground-based observation of aerosol optical properties is a continuous process, and there is hope that other stations may be established in West Africa in the near future (Huang *et al.*, 2023). The aerosol optical properties have also changed according to its environmental systems, sources, and meteorological conditions, and identifying local factors driving climate change and linking the factors to air pollution will deepen understanding of air pollution emissions abatement measures (Zhang *et al.*, 2024) Scholars should therefore continue to extend their enquiry beyond the impacts of air quality on public health, and they should begin thorough investigation on the aerosol - climate relationship (Li *et al.*, 2017).

3.2 Calibration Methods between the Sun Photometer Instrument

The calibration of a sun photometer involves two known methods, namely: The Langley plot method and the comparison method. The Langley plot method is a calibration method whereby calibration is done on extraterrestrial irradiances, whereas the comparison method is an approach to comparing the calibration of a sun photometer to a spectro-photometer (Zhang *et al.*, 2024). The scientific underpinning of the standard of aerosol optical properties measurement is the calibration of a sun photometer, which requires that the Langley plot

method be used for the absolute solar calibration of sun photometers to obtain minimal uncertainty and reduce calibration error (Xun *et al.*, 2023). The calibration factors for both methods differ, ranging from the channel with the greatest sensitivity (0.13%, 500 nm) to the channel with the lowest signal (2%, 368 nm). The degrees of error for the Langley plot method are between 1.2% and 7%, while the accuracy levels for the comparison method are 2.9% and 5.3%, respectively. However, the accuracy of these methods may be affected by unstable weather conditions, few measurements and limited spectral bands on only the ultraviolet and near-infrared radiation (Zhang *et al.*, 2024).

CARSNET, the development of which was made by the Chinese, can be used to calibrate the sun`s photometer. Experimental investigations involving observation of the sun photometer under a set of meteorological conditions are numerous. High elevation, stable atmospheric conditions, calibration coefficients, master instruments, solar aureole and sky radiance calibration could form the basis of accurate aerosol optical characteristics, as absolute solar calibration of sun photometers implies that the result of observation was obtained at significantly reduced uncertainties (Pietras *et al.*, 2001). For example, the solar disk scan method was used for the calibration of radiance, while the uncertainty was estimated at less than ±0.01 (Campanelli *et al.*, 2023). Recently, a sphere calibration method for sky radiance observation has been developed, which was reported to be an improvement over the China aerosol remote sensing network because of its higher measurement accuracy, but these field observations of the global and regional perspectives of the aerosol optical properties were not suited to precision comparison measurements at local scales (Xia *et al.*, 2021). A station's aerosol optical properties data have been observed directly producing characteristic radiative and optical properties through the global networks of the station data (Boiyo *et al.,* 2018).

3.3 Mechanism of interactions of aerosol properties and pollution

Central to the observations reported here is the ground-based LIDAR designed to: provide accurate vertical spatiotemporal distribution of aerosol optical properties; investigate the transport processes of atmospheric aerosols, and examine the influence of aerosols on climate (Zhang *et al.*, 2023). This information can be obtained by LIDAR measurement of the detailed process of fog–haze events, and change processes. During the haze fronts, long-range transport of aerosols from other regions may also constitute an influencing mechanism of aerosol characteristics (Bhattacharyya et al., 2023). The mechanism is further influenced by the meteorological parameters, which include temperature, wind, the atmospheric boundary layer, and relative humidity. The LIDAR was set such that the increasing temperature during the dry season reduces soil moisture content (Li *et al.*, 2021). The dryness condition may facilitate the transportation of soil particles to the atmosphere through the action of winds. Diurnal and seasonal variation, which is a predominant feature in the atmospheric boundary layer, may set in, and it may worsen the increasing aerosol particles, particularly during the night of the dry season, as the height is usually shallower, compared to the days of the rainy season (Tastassa et al. 2024). Also, aided by higher relative humidity, the hygroscopic growth of atmospheric particles may lead to more scattering of solar radiation, and scattering of radiation may change the existing properties of aerosol particles at all geographic scales (Ying *et al.*, 2021). Therefore, during a pollution event, the mechanisms of anthropogenic activities on the optical properties of aerosols are determined through a ground-based observation system (Zheng *et al.*, 2019). For example, in a recent 16-year study analysing the spatiotemporal variability of aerosol particles over the United Arab Emirates using MODIS data, although temperature, relative humidity and wind speed were identified as interacting species with the aerosol particles in the atmosphere. However, the development of models, including SARIMA models,

has helped to reduce the influence of the interacting factors to the barest minimum. Similar studies have been successful in many regions of West Africa.

The evidence on optical properties was then assessed by considering the factors exacerbating spatiotemporal changes in optical properties across African contexts using categories of aerosol optical thickness and angstrom exponent at a given wavelength, data of approximate reduction in solar radiation, and size distribution dimensions of optical properties (Zhang *et al.*, 2023). Studies have shown that there were existing gaps and uneven research resources, as the analysis of the optical characteristics of aerosol particles at global scales has highlighted how the interaction of aerosol-solar radiation behaves in the atmosphere through natural and anthropogenic processes, which contributed to the negative aerosol radiative forcing (ARF) and ultimately climate change risk (Papachristopoulou *et al.*, 2022). For example, the 2021 IPCC report has shown that aerosols have contributed to a cooling of between 0.0°C and 0.8°C due to warming by well-mixed greenhouse gases (GHGs) by 1°C to 2°C, and from 1850 to 2019 (Connors *et al.*, 2022). Aerosol optical properties are therefore both a major contributor to direct and indirect climate effects globally, and reducing uncertainties in aerosol absorption is an urgent and effective means for reducing climate impacts (Chen et al., 2023).

3.4 Aerosol Spatiotemporal Distribution and Components Retrieved from Remote Sensing Data

Satellite remote sensing, based on the principle of electromagnetic radiation, provides an excellent description of high-quality aerosol products derived from satellite retrievals ranging from MODIS for the study of global aerosol optical properties to generalized retrieval of atmosphere and surface properties (GRASP) algorithm for the retrieval of aerosol components (Dubovik *et al.*, 2019). Over the last few decades, it has become increasingly clear that there were several cases in which the ground-based method failed. Among these are a lack of spatial and temporal capabilities. A common characteristic of the ground-based method is the lack of flexibility in providing a real-time spatiotemporal distribution of aerosol optical properties (Chevalier *et al.*, 2020). Although many explanations have been put forward for these limitations, it is still possible that satellite remote sensing might overcome the challenges (Xiaodan *et al.*, 2019). Studies have demonstrated that many satellite sensors have been designed to provide global high-quality aerosol products for the analysis of aerosol optical properties (Li *et al.*, 2022).

MODIS, MISR, OMI, CALIPSO, TOMS, AVHRR, and VIIRS, for example, have some of the same peculiarities as the more advanced algorithm, including the generalised retrieval of atmosphere and surface properties (GRASP), a new module for the estimation of aerosol components (Wong et al*,* 2011). The GRASP is situated coaxially with different remote sensing radiance measurements, which include AERONET radiance measurements, POLDER/PARASOL, and DPC/GF-5 satellite observation, to produce more accurate aerosol optical characteristics (Wang *et al.* 2024). This implies that, to obtain a more accurate spatiotemporal distribution of aerosol optical properties, the ground-based method alone cannot work effectively without applying the latest satellite remote sensing technologies (Yuan *et al.*, 2023). For example, atmospheric aerosol component retrieval based on satellite remote sensing can reveal the spatiotemporal variability in aerosol absorbing types during haze pollution episodes in many parts of the globe (Yuan *et al.*, 2023). Specifically, when comparing the ground-based measurement approach and remote sensing approach for urban studies in Africa, many scholars have noted that both methods are effective for measuring: total aerosol particles at a wavelength of 550nm and spectral dependence of optical properties

However, the ground-based measurement approach has limited spatial capability and a high frequency of missing long-term data compared to the remote sensing approach. On the other hand, while remote sensing data for most nations are richly available, comprehensive aerosol optical properties data for many African nations are not presently available for scientific studies. Several studies have identified ground-based in situ monitoring techniques, satellite remote sensing, and modelling for the estimation of aerosol absorption properties. Apart from complexity, a feature shared by all three existing methods of measurement of the aerosol absorption properties is large uncertainties, that is, limited understanding of the interaction between aerosol and cloud properties, aerosol-climate interaction, and the indirect and semi-direct effects of aerosol particles (Senf et al, 2021). A unique point is where the errors vanish. Combining ground-based in situ monitoring techniques, satellite remote sensing, and modelling, rather than A single method, fills in the missing data beyond the current confidence level (Balsamo *et al.*, 2018). For example, satellite aerosol retrievals produce an overestimate of AOD by about 0.02 ± 0.005 due to cirrus contamination; combining modelling for the same study may reduce the errors to the barest minimum (Li *et al.*, 2020).
However, the accuracy of combining modelling and remote sensing may be marred by factors such as land surface properties and meteorology; the result of the combination may be worse than using a single technique of measurement (Yang *et al.*, 2023). Therefore, the choice of method(s) to adopt depends largely on the study objectives. The current climate models have been widely noted for not being able to represent the exact aerosol absorption in many regions. Because of the growing economic activities and introduction of air pollution control regulations, aerosol emissions have drastically changed in terms of geographical distribution over the last few decades in Ilorin (Dilawar *et al.*, 2023). Scientists have not only raised concerns about ground-level aerosol pollution but also asked questions about the impacts of air pollution on public health in Ilorin (Ake *et al.*, 2022).

3.5 Long-term Aerosol Properties based on Modelling, Assimilation and Reanalysis

Despite the spatiotemporal capability of satellite remote sensing for the analysis of Aerosol optical properties, there remain more challenges and difficulties in obtaining high-quality aerosol properties under cloudy conditions as well as on bright surfaces (Yuan *et al.*, 2023). Interestingly, both the ground-based method and the satellite remote sensing technologies have been assimilated into models, thanks to the rapid development of atmospheric chemical transport models and numerical assimilation techniques, which have helped to produce long-term, high spatiotemporal resolution gridded aerosol optical property reanalysis products (El Amraoui et al, 2022). While common examples, such as the modern-era retrospective analysis for research and applications, version 2 (MERRA-2), Copernicus atmosphere monitoring service (CAMS) reanalysis, and Japanese reanalysis for aerosol (JRAero), coupled with ground-based observations, can be used to test aerosol optical characteristics at the regional scales (Buchard *et al.*, 2017). Variability inaccuracies may occur due to a lack of chemical modules, inadequate capability in characterising the AOD of coarse-mode and fine-mode aerosol particles, and uncertainties in the sources of emissions at different geographic regions (Zhang *et al.*, 2022).

Nevertheless, aerosol reanalysis products can provide a reasonable representation of regional AOD variability on all temporal scales. Despite the above advantages of the reanalysis products, future technologies must be improved to overcome possible sources and factors contributing to uncertainties inherent in the current studies (Xian *et al.*, 2023). Studies comparing the ground-based measurement approach with the remote sensing method have been undertaken in several parts of the world. For example, developed a high-resolution aerosol assimilation system, also known as a non-hydrostatic icosahedral atmospheric model, to obtain

a data reanalysis dataset. The result of the study has shown that combining both the ground-based measurement approach and the remote sensing method produces a higher correlation and minimal errors than when calculated separately. For example, a recent study in Japan developed a 2-dimensional variational method in a non-hydrostatic icosahedral atmospheric model of aerosol optical depth that was assimilated through the remote sensing techniques, and the result was compared with the ground-based approach. The result of the study shows that the correlation coefficient value involving the 2-dimensional variational method increased between 0.44 and 0.65, whereas the result may not provide a forecast result without the 2-dimensional variational method. However, the correlation coefficient value of the analysis aerosol particles and the 1-day forecast aerosol particles result especially in a high peak area of yellow sea may range between 0.05 and 0.1. On the other hand, findings may differ in Africa and other regions where the aerosol optical depth different is positive, correlation coefficient value of analysis aerosol particles and the 1-day forecast aerosol particles result may range between 0.15 and zero similar to the 3-day forecast aerosol optical depth, subject to degree of offset of the eastward spread of negative between any two geographical locations (Senf *et al*., 2021).

However, despite the consistent spatial data that the remote sensing technique may produce, a more comprehensive long-term data covering most parts of Africa is currently unavailable, and this is contributing to the uncertainties recorded in the previous years. Therefore, the provision of reliable modelling assimilation reanalysis results is contingent on the availability of remote sensing facilities.

3.6 Evaluation of Aerosol Direct Radiative Forcing and Radiative Effects

The difference in the absorbing potential of aerosol particles may be responsible for the heating or cooling effect in the Earth–atmosphere system witnessed in recent years. A combination of factors has been reported in the literature as the drivers of aerosol loadings on aerosol direct radiative forcing at the bottom and top of the atmosphere (Ramachandran et al, 2023). Such factors, which include haze pollution and frequent dust events, have shown the spatial distribution of aerosol direct radiative forcing under different aerosol types, aerosol concentrations, cloud types, atmospheric thermodynamics, and meteorological conditions. The aerosol increase may directly and indirectly affect cloud cover, the vertical thermal structure of the atmosphere, and the Earth–atmosphere radiation balance (Chen et al, 2022).

Apart from naturally-induced aerosol particles such as desert dust, which contributed at least between -0.6Wm^{-2} and +0.1Wm^{-2} direct radiative forcing, sulphates, organic carbons and other anthropogenic aerosol particles may produce direct radiative forcing between -0.9Wm-2 and -0.1Wm^{-2} (Xian *et al.*, 2023). In addition, the indirect effects due to the changing properties of the cloud may vary between -0.8Wm^{-2} and -0.3Wm^{-2} climate. Thus, the global rise in biomass-burning aerosol particles has suggested that anthropogenic activities are increasing in many parts of the world, which may further worsen global warming and climate risks shortly (Luo *et al*, 2020). For example, a recent study analysed the shortwave radiative forcing and radiative forcing efficiency of natural and anthropogenic aerosols through the use of top-of-the-atmosphere as well as the bottom-of-the-atmosphere (BOA) radiation models of the AERONET retrieval system and found that the shortwave radiative forcing was between -122±37Wm^{-2}. and −6±3 Wm^{-2}. was obtained for both desert mineral dust and biomass burning aerosol particles over the West Africa sub-region at the top of the atmosphere (TOA), while shortwave radiative forcing of between −42±22Wm^{-2}. and -4±2Wm^{-2} was obtained for mineral dust at the top of the atmosphere (Holanda *et al.*, 2019). This clearly indicates that the West African region is at a high climate risk. Further studies are needed to have a deeper

understanding of the relationship between the magnitude and trends of direct radiative forcing and other meteorological factors.

Recent studies have shown how different aerosol types have significantly contributed to the negative net ARF globally. For example, the biomass burning (BB) and desert dust aerosol types found in many sub-tropics were found to emanate from the North African region and Asia through the jet stream (Holanda *et al.*, 2019). Because industrialisation has largely favoured the increasing frequency of sulphates and other non-absorbing carbons, wind speed played a significant role in their transportation, but desert dust may be highly attributed to the trade winds (Holanda *et al.*, 2019). Despite these common similarities, aerosol particles mask a large amount of atmospheric greenhouse gases (GHG) on the earth's surface and combine to influence the negative cooling effects at the TOA. Since the mid-19th century to the present day, aerosol accounted for (TOA) cooling between 0 °C and 0.8 °C due to GHG-induced temperature increase by between 1 °C and 2 °C, but there were uncertainties in the annual global mean temperature change.

4. Conclusion

Because of the observed shift in the column of the aerosol optical properties in recent times, several scholars have warned that more than 95% of residents may be at higher climate risks, considering the intricate links between aerosol optical properties and climate (Mao *et al.*, 2023). The rapid change in aerosol emission and the non-availability of accurate observation-based trend analysis information imply that systematic and continuous monitoring of such changes is important so as to update our knowledge of the changing patterns of aerosol-climate interaction (Quaas *et al.*, 2022). Such an approach will help to reduce the uncertainties involved in the use of models to estimate aerosol absorption characteristics (Zhang *et al.*, 2022). The Intergovernmental Panel on Climate Change (IPCC) have noted that the African region had the worst scenario of climate impacts due to uncertainties in magnitude and trends in absorbed aerosol particles, and the region was characterised by inadequate ground-based observation instruments for scientific investigation (Fawzy et al, 2020).

Consequently, the assessment of aerosol optical properties constitutes a major challenge in Africa. Although the complementary roles played by remote sensing have enabled scholars to produce a significant number of scientific studies involving the optical properties of aerosol, in more than several other regions of the globe (Ranaivombola *et al.*, 2023). Yet, the spatial distribution of the studies was highly uneven, which may be due to a disproportionate estimate of optical properties, rather than the point-based distribution of the optical characteristics (O'Shea *et al.*, 2023). Certainly, regional studies may be regarded as a rough estimate of the aggregated aerosol optical properties of several local scales, but such an assumption may be highly liable to several omissions, and so could increase uncertainties in aerosol optical characteristics by several factors (Nabavi *et al.*, 2018). The study identifies the need to provide more aerosol infrastructures in African countries to complement the only existing one, which is currently used for West African studies.

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