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In the Air tonight: Satellite-based Air Quality Data and Inclusive Development in Africa: a Scoping Review of the Literature

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Abstract

Climate change and inequality are the most pressing societal challenges of our time. Understanding these complex, interrelated and urgent problems requires interdisciplinary scientific collaboration. Air quality (AQ) is closely linked to climate and climate change as many of the drivers of air pollution (i.e. combustion of fossil fuels) are also sources of greenhouse gas emissions. AQ has been identified as the single largest environmental risk to public health and people's wellbeing. There is a robust and growing base of evidence that air pollution – a mixture of particulate matter and gases – negatively affects various dimensions of our health, our environment and socio-economic aspects of our lives. So far, the effects of air pollution are broadly studied in the 'global north'. Much less is known about the status and impact of air pollution in developing countries, particularly on the African continent.

The objective of this working paper is to review the existing academic and grey literature on the use of satellite-based air quality data as well as the inclusion of different socio-economic perspectives in this field of study. The paper also examines how researchers from diverse disciplines and geographies collaborate when it comes to a multidisciplinary problem like air quality in Africa.

After careful review of 88 publications published between 2000-2024, the main outcomes of the review indicate that the knowledge about air pollution on the African continent is growing, yet the evidence-base remains thin. While satellite measurements have the potential to provide a lot of information on air quality in Africa, there are very few publications using air quality data as measured by satellite instruments. Furthermore, even when such data are used, the lack of region-specific models for assessing African air quality typically results in less certain measures in comparison to other better validated parts of the world. However, despite these shortcomings, satellite-derived estimates of exposure can be leveraged in studies where ground-level measurements are not feasible. In addition, satellite measurement can be used to create so-called top-down emission estimates and inventories.

It can be observed that the debate on air quality in Africa is often led by natural scientists who use atmospheric chemical models to understand the atmospheric composition and how it changes over time by performing satellite-, aircraft-, and ground-based measurements to validated and improve their models and understanding. Complementary discussions bringing the social science perspective to light emphasizing spatial heterogeneity in the prevalence of air pollution, the resultant impacts on various population groups, and regional societal responses are underdeveloped. This observation points to the siloed approaches present in the mainstream of both natural and social sciences. These isolated silos lead to differences in how data is accessed to and used, which in turns hinders communication, co-creation, and cross-specialization learning around a common set of interdisciplinary data that could be utilized in both natural and social science domains.

In terms of links to inclusive development, the satellite-based air quality data, when used, is primarily to assess the impact of poor air quality on human health of a given population. Some studies link air quality to socio-economic status and exclusion (defined as low-income neighbourhoods or marginalized groups) but satellite-based data are not frequently used to establish such links. However, an analysis of the institutional

affiliations of the first and last authors of the reviewed articles revealed an increased number of publications led by African-based scholars in recent years. Even though the field remains dominated by scholars originating from non-African institutions, such a trend is bringing local and contextual voices to the global discussion, making the process more inclusive.

Finally, despite its potential, satellite data has had a very limited use in the policy making process on the African continent. Lack of capacity to work with the data as well as to adequately translate the data into a language relevant for policy-makers is one of the key challenges to be addressed in moving forward. As most of African countries are yet to establish air quality standards and legislation, the need for adequate measurements and contextualisation of data is great. Therefore, this paper urgently calls for building more inclusive scientific communities by developing a methodology for contextual and reciprocal learning between natural and social sciences through joint data generation and use with a focus on air quality in Africa.

Introduction

1.1 Rationale

Climate change and inequality are the most pressing societal challenges of our time. Understanding these complex, interrelated and urgent problems requires interdisciplinary scientific collaboration (Victor, 2015). Air quality (AQ) is closely linked to climate and climate change as many of the drivers of air pollution (i.e. combustion of fossil fuels) are also sources of greenhouse gas emissions (Akasha, Ghaffarpasand, & Pope, 2021). Air quality has been identified as the single largest environmental risk to public health and people's wellbeing (WHO, 2021). There is a robust and growing evidence base that air pollution – a mixture of particulate matter, metals, gases and compounds – negatively affects various dimensions of our health, our environment and socio-economic aspects of our lives (Box 1). So far, the effects of air pollution are broadly studied in the 'global north'. Much less in known about the status and impact of air pollution in developing countries, particularly on the African continent.

Regarding **health**, the effects of air pollution increase the risk of lung cancer, heart disease, bronchitis, and other cardiorespiratory conditions (Kelly & Fussell, 2015). Children and elderly are particularly at risk (Rees, Wickham, & Choi, 2019), so are poor people who are more likely to live in a polluted environment and suffer the adverse impacts of air pollution (World Bank, 2021). Globally, air pollution accounts for an estimated 6.7 million deaths and it is the 4th leading risk factor for early death worldwide (2019) (Awe, Kleiman, & Sánchez-Triana, 2022; Health Effects Institute, 2020). In addition, it harms cognitive functioning across all life stages and is associated with depression, schizophrenia, and autism. Recent studies also identified air pollution as an important contributing factor increasing the risk of mortality from COVID-19 (Austin, Carattini, Mahecha, & Pesko, 2020; Pozzer et al., 2020).

Regarding **impact on environment, climate change, ozone depletion and a number of other environmental ills**, such as degradation of ecosystems and decreased agricultural productivity are probably the most discussed effects of air pollution. Finally, the **impact on socio-economic aspects of our lives**: breathing polluted air negatively predicts people's life satisfaction and well-being. Some research suggests that air pollution reduces work productivity (increase absenteeism and decrease general individual employee productivity), thus one's income, as well as increases criminal and unethical behaviour (United Nations Environment Programme, 2023b).

Box 1
Impact of air pollution on human lives

Despite urgency, the scientific community remains hermetic, including funding opportunities, as well as siloes created along disciples' lines. Research by Overland & Sovacool (2020) revealed that between 1990 and 2018, the natural and technical sciences received 770% more funding than the social sciences for research on climate change ($40bln vs. $4.6bln for the social sciences and humanities). Moreover, the funding for climate-related research on Africa has always been small and the total sum dedicated between 1990 and 2020 was $620mln. That means that most funding goes to researchers outside the continent. Most of the relevant research projects are thus led by 'northern' scholars, which further translates into the unequal authorship opportunities and consequently promotes non- or less-inclusive science communities.

People in Africa bear a disproportionately heavy burden of air pollution and its associated impacts relative to other regions (State of Global Air, 2021). Air pollution is currently the second largest cause of death on the continent, exceeded only by AIDS (Fisher et al., 2021). Moreover, greenhouse gas emissions are expected to grow exponentially on the continent in the coming decades due to industrialization, urbanization and population growth. Majority of that increase will occur in cities (Narain et al., 2016). Sub-Saharan Africa (SSA) will host five of the world's 41 megacities by 2030; (Lagos, Kinshasa, Johannesburg, Dar es Salaam, and Luanda) (Marais et al., 2019). These structural and demographic transitions will inevitably worsen air quality on the continent, thus impact negatively on a the health, environmental and socio-economic aspects dimensions of development (Awe et al., 2022), and will have a considerable impact on global emissions and atmospheric composition. Interdisciplinary collaborations across geographies are thus equally essential to advance our understanding on the topic.

Poor air quality also jeopardises achievement of inclusive development. The concept of inclusive development promotes a perspective on development that goes beyond (a) economic growth and includes health, environment and other socio-economic dimensions, and (b) the average macro outcome of development indicators such as GDP per capita, and considers the (unequal) distribution of development outcomes and processes (Dekker, 2017). Current development processes in countries with significant macro-economic growth, leave large segments of the population behind. Inclusive development indicators and perspectives explicitly also focus on the distribution of development outcomes (social and geographical inequalities) and the participation in development processes, or inclusive governance (Dekker & Pouw, 2022). Inclusive development is also a key to advancing the SDG Agenda[1] (INCLUDE, 2013; Islam, 2019; Rocha Menocal, 2017). Poverty, health, education, agriculture and exposure to risks are different lenses of inclusive development and link to environmental (in)justice.

Environmental (in)justice or environmental (in)equality refers to the phenomenon that the burden of air pollution not only falls disproportionately on poorer countries; but within countries, poorer and more marginalized communities, vulnerable groups, both in urban and rural settings, are most exposed to bad air and their negative effects (Ferguson et al., 2020). An estimated 75% of people in Sub-Saharan Africa depends on solid fuels such as coal, wood, charcoal, and dung as their primary cooking sources, exposes over 800 million people to hazardous pollutants within their homes daily (Health Effects Institute, 2022). This perilous situation is particularly pronounced among women and children, who typically spend more time in proximity to cooking areas as they most likely face higher exposure to pollutants and most probably experience more impact (Hajat, Hsia, & O'Neill, 2015; Mlambo, Ngonisa, Ntshangase, Ndlovu, & Mvuyana, 2023; Okello, Devereux, & Semple, 2018; Rentschler & Leonova, 2022). Moreover, risk exposure to air pollution in urban areas is not only a product of environmental hazards, but it is also shaped by socio-political processes including infrastructure and technological investment decisions (i.e., urban settlements, roads, highways, urban services, technology), as well as mitigation and adaptation decision-making. There is a subsequent need for a rapid political action based on robust air quality data, which will tackle air pollution related problems.

The economic repercussions of air pollution extend far beyond its severe human toll. Research indicates that the yearly financial burden arising from health damages linked to air pollution-related diseases averages an alarming 6.5% of Africa's GDP (World Bank,

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[1] Air quality (AQ) is linked to a number of SDGs, such as health and wellbeing (SDG 3), clean water (SDG 6), energy (SDG 7), inequalities (SDG 10), sustainable cities (SDG 11) or climate (SDG 13) (Rafaj et al., 2018).

2021). A recent study revealed that "[i]n 2019, Ethiopia's economy was significantly hit, suffering a loss of $3.0 billion, equating to 1.16% of its Gross Domestic Product (GDP). In the same vein, Ghana and Rwanda incurred losses of $1.6 billion (0.95% of GDP) and $349 million (1.19% of GDP) respectively, all due to illnesses caused by air pollution" (Health Effects Institute, 2022). These findings underscore the urgent necessity to address air quality issues and link them directly to public health and economic stability concerns in and beyond Africa.

However, a major challenge for AQ monitoring in Africa has been persistent data gaps (Hsu, Reuben, Shindell, de Sherbinin, & Levy, 2013). Among the most popular methods used to monitor air quality, we shall distinguish ground level air quality monitoring and satellite remote sensing. The former provides accurate local, granular measures of air quality, while the latter provides greater spatial, and often temporal, coverage. Although still in its infancy and with scattered coverage, ground level monitoring that uses lower-cost sensors is currently gaining popularity on the continent (see initiatives such as AirQo in Uganda or Ghana Urban Air Quality Project [GHAir]). Alternatively, harnessing the power of satellite data, especially high-resolution measurements from the TROPOMI satellite, can provide a continental coverage and lend new insights for regional to city-scale air quality issues and inform climate policies (Hsu et al., 2013; Revenga, 2005). These open-access air quality satellite data provide a hopeful solution for closing data and knowledge gaps about the current emissions. Once coupled with (quantitative and qualitative) socio-economic information, (quantitative) air quality satellite data has a potential to contribute to a better measuring and monitoring progress towards the Sustainable Development Goals (SDGs), as well as inform climate policies to be more inclusive. Despite these observations and opportunities that comes with the new and open-access technologies, cross learning between social and natural sciences is rare.

1.2 Objective and methodology

The objective of this working paper is to review the existing academic and grey literature on the use of satellite-based air quality data and their impact on different socio-economic domains of inclusive development in Africa. The literature review is therefore guided by the following research question:

Whether and how are the satellite air quality data used to assess inclusive development processes and outcomes in Africa?

The following sub-questions will further focus the review:

1. What are the characteristics of air quality and pollution in Africa?
2. What are the main methods to assess air quality on the continent?
3. What are the main policies and guidelines framing air quality in Africa?
4. How are satellite air quality data used in the African context?
5. If and how do satellite based studies use an inclusive development perspective on air quality in Africa?
6. If and how do the researchers from diverse disciplines and geographies collaborate when it comes to a multidisciplinary problem like air quality in Africa?

The literature review employed a convenient sampling technique, which involved selecting available literature sources based on their accessibility, ease of retrieval, and relevance to the research topic. The focus was on readily accessible sources such as academic journal articles, books, online databases, and reputable websites. The sources were identified by using search engines, academic databases, and citation networks to locate key literature and using the combination of key words like "satellite data", "remote sensing" "TROPOMI", "MODIS", "inclusive development", "vulnerability", "health", "socio-economic impact", "air quality", "air pollution", "Africa" (among others). The years 2000-2024 (January) were chosen as a cut-off dates for the search to include the latest available publications. The convenient sampling approach may not provide an exhaustive overview of the entire literature on the topic; however, it yields valuable insights and will serve as a starting point for further exploration.

After identifying literature that fitted the search criteria, the analysis of the institutional affiliations of the first and last authors of the reviewed literature was performed. Affiliations were taken from the publications directly and based on the location of their institutions, they were later classified into five categories: (i) non-African first author and non-African last author; (ii) African first and last author; (iii) African single author; (iv) African first author; non-African last author; and (v) non-African first author, African last author. No further 'career tracking' of the authors was undertaken to assess their actual affiliation. It is important to note as it is clear that there is high mobility of some of the scholars involved, which may have led to some small inaccuracies of their actual origins and current home institutions, but should be sufficient to indicate general trends.

Finally, it should be noted that the first draft of this paper was developed in preparation of the workshop in the Lorentz Center called "The Power of TROPOMI to bridge African science and policy" that took place in Leiden in April 2022. The aim of this meeting was to bring African scientists and policy-makers together with other international members of the environmental and socio-economic science communities to illustrate how powerful TROPOMI satellite data can be used in various ways to jointly address pressing air quality issues. This workshop served as an arena to establish a community of practice for researchers coming from different science domains, policymakers, and practitioners on the use of air quality and satellite data in Africa. Among the key conclusions of this workshop, there was a call for increased interdisciplinary collaboration on the topic and the need for a common set of interdisciplinary data that could be used in both natural and social sciences to further cross-fertilize and substantiate the global discussion on air quality.

1.3 Structure of the paper

This working paper frames the findings of the literature review in the context of background information on air quality and policy frameworks in Africa. It is organised as follows. Section two introduces air pollution in Africa from technical side. It reviews the main sources of air pollution and general air quality assessment methods. Section three touches upon the available policy framework on the continent (and globally). The main literature review section that links air quality satellite data with inclusive development outcomes can be found in the fourth section. It is followed by the paper's conclusions.

Air pollution in Africa

2.1 Main sources of air pollution in Africa

Despite evidence that air pollution impacts negatively on human health, the environment and socio-economic factors, air pollution remains an abstract concept for most people (Health Effects Institute, 2020). Globally, there are a large number of pollutants in the air, with many having multiple impacts (e.g. health & climate), and some react in the atmosphere to form other pollutants (i.e. act as precursors). Pollutants such as nitrotheir role as short-lived climate forcing pollutants (SLCPs). More than 45% of global warming is attributed to SLCPs, which makes them the second-largest anthropogenic climate change contributors behind carbon dioxide (CO_2) (Zaelke, 2013). Mitigating the impacts of SLCPs is essential to address the climate and health crisis.

The air quality in Africa is degraded not only by fossil fuels burning for activities such as power generation (including use of generators – a major source of black carbon) and road transport (especially highly polluting old vehicles and its heavy congestions), but also by natural sources such as desert dust particles from the Sahara and Namib Deserts. Other sources of air pollution on the continent include combustion from intense dry season savanna and woodland fires (biomass burning), domestic/household burning of coal, charcoal, kerosene and wood, agricultural practices to burn crop residue, and burning of waste at large landfills and domestic open trash burning (Marais et al., 2019). Biomass burning (BB) is one of the major sources of widespread natural aerosols after Saharan dust (Dajuma et al., 2021), while agricultural activities (particularly livestock) and decomposition of waste release important amount of methane - the second most important greenhouse gas which can cause climate change. Globally BB aerosol make up most primary combustion aerosol emissions with ~52% from Africa (Andreae, 2019; Bond et al., 2013; Brown et al., 2021; Isaxon et al., 2022). Africa accounts for about 72% of the total global burned area. Recent estimates show that Africans fires emission estimates are 31-101% higher than previous estimates (Ramo et al., 2021). This will not only impact Africa's population but will also have a global environmental impact. More details regarding the types of air pollutants in Africa are summarized in Annex 1.

From the above, two main pollutants are commonly considered key indicators of air quality: fine particulate matter (PM) and ground-level (tropospheric) ozone. Tropospheric ozone is one of the secondary pollutants from burning activities[2] and it is a major component of urban smog. It has a negative impact on vegetation and can decrease the efficiency of agriculture (Marais et al., 2019). PM in ambient air originates from natural sources (wind-born soil and sea spray), anthropogenic sources (combustion of fossil fuels, industry emissions, vehicle and road wear), and atmospheric transformation. Mechanical processes, such as resuspended road dust, abrasive mechanical processes in industry and agriculture, as well as some bioaerosols, are the primary sources of PM with a size ranging from 2.5 to 10 µm. Consequently, these particles are more enriched with metals, carbon, silica, and other constituents related to crustal materials, as well as biological species. In the context of Africa, it is important to distinguish between ambient (outdoor) and indoor air pollution. In ambient air pollution condition, PM with a mean aerodynamic diameter of 2.5 µm or less ($PM_{2.5}$) is commonly found in urban and industrial areas (Kim, Kabir, & Kabir, 2015; Tositti et al., 2018). Indoor PM is primarily from penetration from outdoor air, traditional cooking practices, and resuspension from house dust. The World Health Organization (WHO) has recognized PM as a major risk factor for health. Figure 1 below summarises the contribution of key sources to $PM_{2.5}$ exposure in five countries across Africa in 2019.

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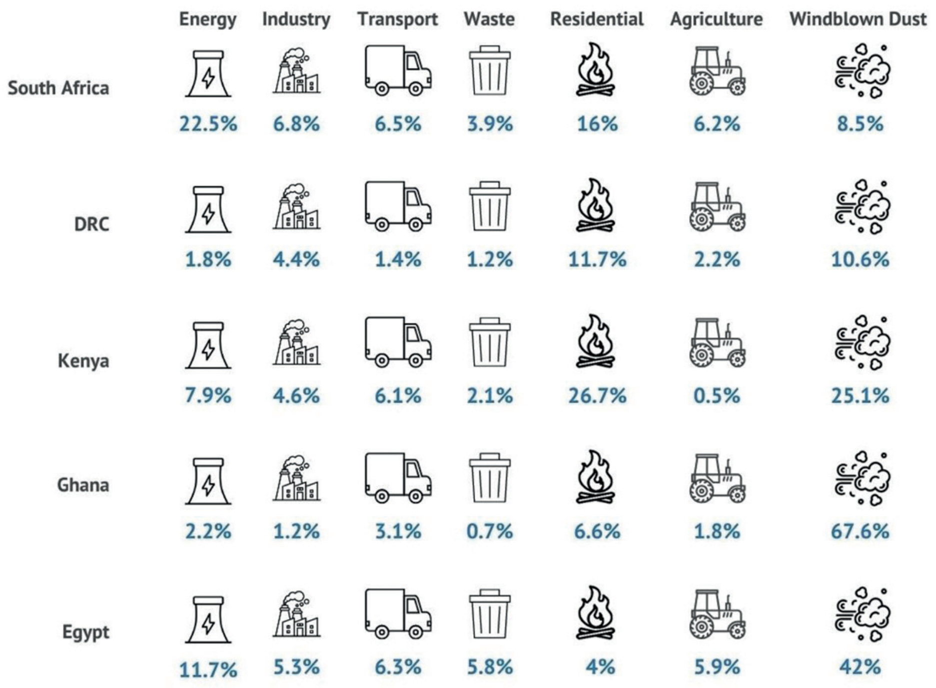
[2] Africa's wide scale burning of biomass produces large quantities of ozone precursors (NOx and volatile organic compounds [VOC]) (Langley Dewitt et al., 2019).



	Energy	Industry	Transport	Waste	Residential	Agriculture	Windblown Dust
South Africa	22.5%	6.8%	6.5%	3.9%	16%	6.2%	8.5%
DRC	1.8%	4.4%	1.4%	1.2%	11.7%	2.2%	10.6%
Kenya	7.9%	4.6%	6.1%	2.1%	26.7%	0.5%	25.1%
Ghana	2.2%	1.2%	3.1%	0.7%	6.6%	1.8%	67.6%
Egypt	11.7%	5.3%	6.3%	5.8%	4%	5.9%	42%

Figure 1

Contribution of key sources to PM2.5 exposure in five countries across Africa in 2019
Source: (State of Global Air, 2021)

PM plays a vital role in altering air quality, human health, and climate change. Notably, the concentration of PM$_{2.5}$ is alarmingly high in Africa, particularly in the northern, western, and central regions (see Figure 2). According to the WHO, more than half of the African continent surpasses the annual median concentration of 26 µg/m^3 for PM$_{2.5}$, significantly exceeding the recommended limit of 5 µg/m^3. A comprehensive review of studies on outdoor air pollution in eight African cities (covering seven countries), revealed PM$_{2.5}$ levels ranging from 40 to 260 µg/m^3, in contrast to the annual averages of 13 µg/m^3 in urban Europe and 9 µg/m^3 in urban United States in 2019 (Malmqvist, 2021). It should be noted that the information on air pollution in Africa shown here relies heavily on air quality modelling as monitoring data are limited. Despite the severe implications of air pollution in Africa, there remains a significant gap in the scientific, every-day, and political understanding of emissions, atmospheric processes, and the impacts of air pollutants in this region.

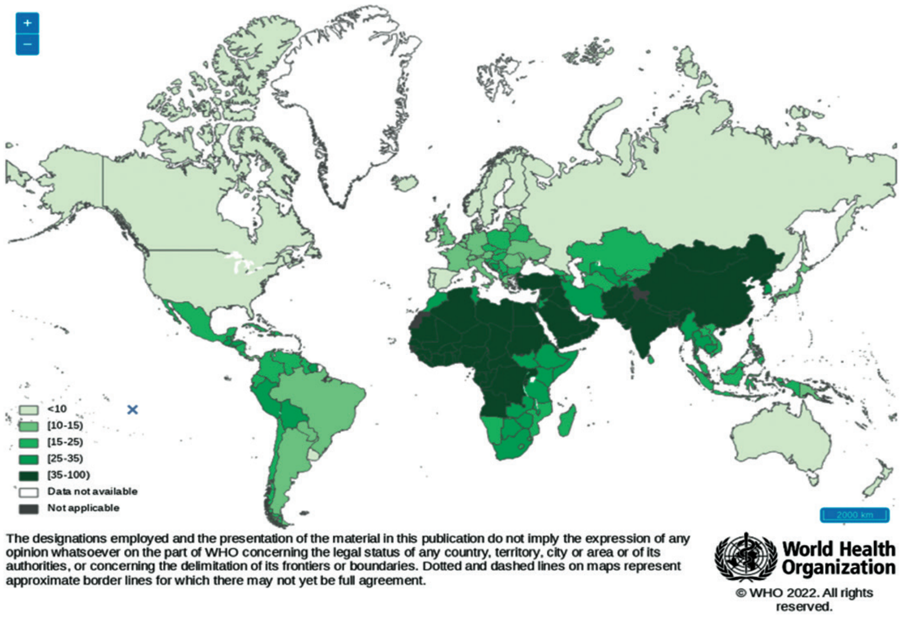


Figure 2

Annual average concentration (µg/m^3) of fine particulate matter (PM$_{2.5}$) (2019) Source: (WHO, 2023)

The ambient level of nitrogen oxides (NOx = NO2 + NO) is also a good indicator for air quality in urban and industrialized areas. NOx atmospheric concentrations over urban areas are directly linked to human activities (fuel combustion from road traffic, residential and tertiary sector, industrial activities). NOx species are produced during combustion processes and thus may serve as a proxy for fossil fuel-based energy usage as well as co-emitted greenhouse gases and other pollutants. NOx is a necessary ingredient for the formation of surface ozone that has a number of negative effects on human health and vegetation. For instance, several communications have associated a decrease in NO2 air pollution measured from space (by TROPOMI) with the lockdowns resulting from Covid-19 (Prunet, Lezeaux, Camy-Peyret, & Thevenon, 2020).

Poor air quality, with its impacts, is especially critical in developing nations in Africa, which have some of the highest estimated levels of ambient pollution, but the poorest infrastructure in place for monitoring and tracking air quality. The following section will introduce the most common methods of AQ assessment.

2.2 Air quality assessment methods

Understanding air pollution levels, sources, and impacts is a critical first step in addressing air pollution problems (Hsu et al., 2013). A number of methods of air quality monitoring are utilised to assess levels of air pollution.[3] This includes:

- Ground-level Monitoring:
  - Reference or regulatory grade monitoring stations: take accurate measurements, are used to build a long term understanding of air quality, and show compliance with national air quality standards. Given the size and cost of these devices most cities can only afford limited numbers. It is also a reason why ground level quality monitoring is well established in the global north, but has limited coverage in the global south.
  - Lower-cost sensor-based technology: an alternative for ground level air quality monitoring that is cost effective, mobile, and flexible. Such devices are proliferating, and have varying quality and accuracy. Furthermore, there are issues associated with their long-term durability, the technical skills required to use and maintain them, and the potential for erroneous monitoring. By calibrating and cross-referencing to reference/regulatory stations quality concerns can be addressed, but not fully overcome. Currently, the instruments do

[3] Depending on the types of pollutant, different assessment methods are used and further a (mix of) measurement method is applied. Currently, measuring atmospheric pollutants is done through automatic methods. For more detailed description of most common methodologies currently used for measuring atmospheric pollutants, please consult Annex 2.

focus on PM measurements and do not cover all criteria air pollutants (i.e. air pollutants regulated due to their health impacts).

- Satellite-based Remote Sensing: offers the prospect of daily observational information for most locations in the world. Satellite sensors measure interference in the light energy reflected or emitted from the Earth, which is used to calculate concentrations of air pollutants, such as particulate matter, nitrogen dioxide, carbon monoxide, and ozone. Challenges associated with this approach include lack of a universally applicable air quality model, the effect of humidity, the coarse spatial resolution, the effect of clouds, deserts, snow, dust, and complex topographies, and that the satellite measures the full column of air and not just ground-level concentrations. Furthermore, measurements cannot be taken at night.
- Air pollution modelling and model-data fusion: modelling air pollution over larger geographic domains as well as the combination of ground level monitoring data and the application of modelling systems. For Africa, the available information is often from global studies, uptake may be constrained by technical and infrastructure considerations (cloud-based computing may address some of these) and is dependent on the quality of other sources of data. Modelling is very advanced for some regions, but less so for others. In Africa, there is currently a lack of measurement data for model validation.
- Visibility as a proxy for air pollution: long-term visibility measurements can be used for a proxy for air pollution. Visibility data is routinely collected at airports globally (in some cases from the 1950s to present day). Historic visibility is inversely proportional to the amount of particulate matter present in the air i.e. declining visibility correlates closely with increasing levels of air pollution. This approach provides a sense of trends in air quality over time but is unable to provide insight into current levels, or within area variations (Avis & Bartington, 2020).
- A 'citizen science' bottom-up approach: a collaboration between community members and scientists facilitated through the use of novel technologies and IT infrastructures (such as LCS, mobile apps), as well as community engagement strategies to assess the quality of air in the given community (Sîrbu et al., 2015).

Satellite-based remote sensing of air quality, the main focus of this paper, offers the prospect of daily observational information for most locations in the world. More information about how satellite-based remote sensing of air quality works and details about the key AQ monitoring instruments can be found in Annex 3. With the use of public platforms such as Google Earth Engine (GEE), daily and even hourly air pollution data are available for research. More recent studies have utilized data from the Ozone Monitoring Instrument (OMI) or the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multiangle Imaging Spectroradiometer (MISR) instruments on NASA's Aqua and Terra satellites (Mcelroy, 2021).[4] The most recent and promising tool has been the Sentinel-5 TROPOMI instrument.

TROPOspheric Monitoring Instrument, TROPOMI, launched in October 2017 on board the Copernicus Sentinel-5 Precursor satellite, is considered roughly 20 times better than its predecessor OMI and the combined improvement of higher spatial resolution and measurement precision provides better delineation of air pollution sources in complex industrial or urban areas. It means that TROPOMI enables emission attribution of both natural (e.g., wetland and other biogenic emissions etc.) and anthropogenic sources from urban and industrial activities. Beyond this, strong anthropogenic point sources can be distinguished from regional background concentrations illustrating the emissions from individual power plants, industrial facilities, ships, as well as gas and oil exploration sites. Furthermore, TROPOMI data allows for detailed global tracking of desert dust outbreaks, volcanic eruptions (and related aviation safety planning and warnings), and trace gas and aerosol plumes co-emitted from biomass burning and wildfires. With a broader spectral range than its predecessor OMI, TROPOMI is not just relevant as an air quality mission but also useful for better understanding the emission of climate-relevant gases like the second most important greenhouse gas methane (CH_4) and tropospheric ozone. Carbon dioxide emissions can even be calculated for

[4] These instruments have provided global observations of aerosol optical depth (AOD), a measure of light extinction by aerosol in the atmospheric column above the earth's surface. AOD is tied to PM2.5 by an empirical formula, which can be affected by the AOD vertical profile, humidity, temperature, and wind speed (Mcelroy, 2021).

point sources and regions, based on the detailed mapping of nitrogen dioxide (NO_2). (Veefkind et al., 2012).

The scope of TROPOMI capabilities are now being realized along with essential open access cloud platform and service developments, ex. Google Earth Engine and the Copernicus Sentinel-5P Mapping Portal (S5P-PAL), thus making the data more accessible than ever for users with limited computing, bandwidth and storage resources. Both GEE and S5P-PAL are free to use for the research, educational and non-profit sectors and eliminate the need to download prohibitively large data files and store them locally. So far, TROPOMI data has contributed to policy debates for the US, Canada, India, China, and Europe. TROPOMI data were frequently used to visualize the decrease in air pollution for major European and global cities during the COVID-19 lockdown periods and they could help better understand future coronavirus outbreaks around the globe. Despite improved accessibility and the potential satellite data presents for visualizing numerous issues and shaping the socio-political agendas, their use in the context of Africa have so far been limited (i.e. Dasgupta, Lall, and Wheeler 2020; El-Nadry et al. 2019; Hu et al. 2018; Marais et al. 2019; Shikwambana, Mhangara, and Mbatha 2020).

However significant barriers to the use of satellite data for indicator development remain. These relate to difficulties in accessing and using the data, differences between what satellites actually measure and parameters of interest to decision-makers, limited collaboration between the atmospheric measurement and Earth observing satellite communities to develop robust satellite- based indicators, technical issues such as cloud cover interfering with satellite data collection, and a lack of cross-cutting technical and funding resources (Engel-Cox, Oanh, van Donkelaar, Martin, & Zell, 2013; Hsu et al., 2013; National Research Council, 2007). On top of these barriers are the gaps in the perception of 'readiness for use' and permissible levels of uncertainty between those in the remote sensing community who have the technical expertise to process remote sensing data, and those in the policy community who could benefit from the indicators (De Sherbinin, Levy, Zell, Weber, & Jaiteh, 2014).

Regardless the challenges, remote sensing data provide a valuable estimate of $PM_{2.5}$ measurements especially in the absence of extensive local ground-based monitor networks and poor general infrastructure for monitoring and tracking air quality, which is the case in Africa. Among the 47 countries comprising Sub-Saharan Africa, only 6 can provide long-term data on airborne particulate matter, spanning a total of 16 cities. Just seven of the 54 countries in Africa have "real-time air pollution monitors", while only 6% of children across Africa live within 50km of a reliable air-quality monitor (Narain et al., 2016).[5] Only South Africa[6] and Senegal, and more recently Ghana, Uganda and Rwanda have a continuous and real-time air quality monitoring network coverage with data available publicly and freely on-line[7] (Katoto et al., 2019; Okello et al., 2023). In spite of the global outcry for urgent action against air pollution, most African countries lack functional air quality monitoring stations and data there from; making air quality management difficult despite number of policies, guidelines and commitments made globally and on national levels (Agbo et al., 2021). The following section will briefly introduce such main frames.

[5] In contrast to the 72% of children in North America and Europe (Narain et al., 2016).

[6] Although the example of South Africa shows us that despite having advanced air quality policy and monitoring in place, the compliance is problematic (Marais et al., 2019).

[7] See www.saaqis.org.za and www.air-dakar.org .

African air quality policy and guidance

Efforts to significantly reduce the danger posed by air pollution to human health, cannot succeed without a legal and institutional foundation that establishes a robust system of air quality governance. Globally, a clear commitment to a certain level of ambient air quality that is compatible with human health and the natural environment does not yet exist in public international law (Scotford, Misonne, Tseng, McCarthy, & Rudko, 2021). However, as air pollution has no boarders, there are several commitments and initiatives in place to address air pollution and promote clean air.[8] Regulating air quality is complex, as air pollution results from a wide range of social and economic behaviours, combined with geographical, environmental and population conditions (Scotford et al., 2021). Therefore, policies addressing air quality need to regulate diverse sources of emissions (industry, private vehicles, public transport, power generation, ships etc.), and diverse behaviours that generate air pollution (through urban planning, control of individual pollution incidents, or other means). Below, a short elaboration can be found of some of the key policies and frameworks that address air quality on the continental, regional and national level.

Continental level

The key priority of the African Union Agenda 2063's goal on environmentally sustainable and climate resilient economies and communities in the context of sustainable development is to "develop/facilitate the implementation of Africa Quality Standards for air and other forms of pollution". The importance of improved assessment of air quality of the continent has been confirmed by African policymakers multiply times. At the 15th session of African Ministerial Conference on Environment (AMCEN) in 2015 in Cairo, Egypt, ministers called for enhanced air quality monitoring and modelling and the need to develop an Africa-wide air quality framework agreement on air quality management in their declaration. This issue was addressed again at the 16th session of AMCEN (2017), Libreville, Gabon, where ministers acknowledged the region was facing increasing levels of air pollution, which has a negative effect on the environment and social and economic development in the region, as well as on human health and the well-being of the African population. The 2019 17th AMCEN Session in Durban, South Africa concluded with the Decision 17/2 , which acknowledges the importance of SLCPs and the "need for an assessment of the linkage between policies to address air pollution and policies to address climate change". Finally, the AMCEN Decision 18/4 (2022) "urge African countries to support further development and implementation of the 37 recommended measures as a continent-wide Africa Clean Air Program, coordinated by strong country-led initiatives, cascaded to the Regional Economic Communities and higher levels of policy" (CCAC secretariat, 2021).

In terms of initiatives on the continental level, the Clean Air Initiative in Sub-Saharan Africa (CAI-SSA) and the Air Pollution Information Network for Africa (APINA) were launched by the World Bank and the Stockholm Environment Institute, respectively, in the late 90s in response to the deteriorating air quality situation in the region (CCAC secretariat, 2021). More recently, Clean Air for Africa: Partnership Forum for Integrated Action on Air Pollution and Climate Change was launched (2023), following the publication of the first Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa (United Nations Environment Programme, 2023a). The purpose of this Partnership Forum is to create awareness, partnerships and develop a road map for implementation of 37 measures across 5 key areas — transport, residential, energy, agriculture, and waste — to fight climate change, prevent air pollution, and

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8. A list and explanation of the key global AQ policy and guidance can be found in Annex 4.

protect human health and the environment simultaneously. The expected outcome of the Forum was the outline for developing Africa Clean Air Programme.[9]

Regional level

There has been significant regional development of treaties and agreements concerning air quality, motivated by shared transboundary air pollution problems. In Africa, three agreements call for regional cooperation on the harmonization of air quality standard, monitoring procedures and data management: The North African Framework Agreement on Air Pollution (2011), The Eastern Africa Regional Framework Agreement on Air Pollution (Nairobi Agreement; 2008); The Southern African Development Community (SADC) Regional Policy Framework on Air Pollution (Lusaka Agreement; 2008) and West and Central Africa Regional Framework Agreement on Air Pollution (Abidjan Convention; 2009). They also enhance stakeholder participation in air quality management (Scotford et al., 2021). An Air Pollution Information Network for Africa (APINA) played a leading role in the development and promulgation of regional framework agreements on air pollution. The short description of these agreements can be found in Table 1 below. These agreements are however yet to translate into actions in many signature countries. APINA is no longer operational, however, the African Group on Atmospheric Sciences (ANGA) working group has been established and operates on its basis.

National level

Air quality laws and regulations have been identified as one of the key policy actions to significantly improve air quality, yet in Africa, environmental regulation to reduce pollution is only recently developing and often inadequate or absent (Scotford et al., 2021). Majority of countries that do not have legislative instruments containing ambient air quality standards are in Africa (Figure 3) (Scotford et al., 2021). Different countries have different systems of law and different state constitutional structures, which can determine how air quality laws are devised and implemented. The enforcement and compliance of these laws are major issues.

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[9] The idea behind the Africa Clean Air Programme is that it would bring together Member States and all concerned stakeholders for the monitoring, modelling, sharing and evaluating of data on ambient air quality. It would like to establish and/or strengthen air quality monitoring networks using harmonized regional instrumentation and protocols and linking these to modelling efforts in the region. Finale, strengthen education and communication and promote participation and coordination of national and regional stakeholders in the development and implementation of air quality policies and management strategies (Tagwireyi, 2023).

Table 1

Regional agreements on air pollution in Africa

Declaration/ Resolutions/ Agreements	Region/ Regional Economic Communities	Focus	Status
North African Framework Agreement on Air Pollution 2011	North Africa	Unknown	Unclear[10]
Dakar Declaration 2002	Sub-Saharan countries ECOWAS	Elimination of leaded fuel in Sub-Saharan Africa	Agreed by participants from 25 Sub-Saharan countries; including representatives of government, industry and civil society, as well as from international organizations Achieved in 2021
Lusaka Agreement 2008	SADC	Regional policy framework on air pollution outlining multilateral cooperation for action on air pollution from transport, industry, open burning, household air pollution, national environmental governance, public awareness, education, development and capacity building	Adopted by 14 SADC countries, representing governments, industry, NGOs, civil society, international organizations and academia
Nairobi Agreement 2008	EAC	Eastern Africa Regional Framework Agreement on Air Pollution to develop actionable targets to address air pollution in the following key areas: transport; industry and mining; energy; waste; vegetation fires; household air pollution; urban planning and management; and regional and national environmental governance	Signed by 7 countries
The Libreville Declaration 2008	Continental	Health and environment in Africa with a policy statement that provides a cohesive and integrated framework to address human health and environment links on the continent	Signed by ministers of health and the environment from 52 African countries
Abidjan Agreement 2009	ECOWAS and ECCAS	Actionable targets to address air pollution issues in the following key areas: transport; industry and mining; household pollution; waste disposal; bush fires; uncontrolled burning and deforestation; urban planning and management; and national and regional environmental governance	Signed by 13 countries

Source: (United Nations Environment Programme, 2023b)

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[10] The Agreement is referred to in official documents of the United Nations Environmental Programme and NEPAD documents. Details about the focus and the status of this agreement were not found.

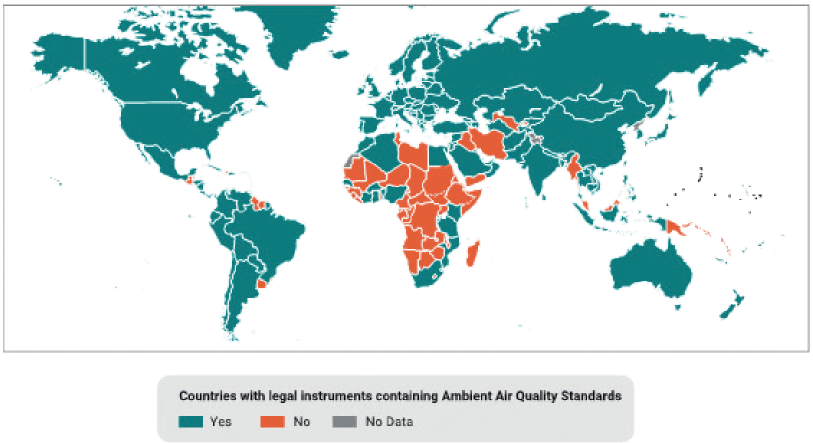

Figure 3
Countries with legislative instruments containing ambient air quality standards
Source: (Scotford et al., 2021)

Despite the political will, the lack of or insufficient air quality data means that many national and local governments do not have or only have partial knowledge of concentrations and trends, which makes it difficult to evaluate the effectiveness of the strategies and policies, select target values and set priorities that are adapted to the local context (Okello et al., 2023). The use of satellite data is "increasingly recognized as an essential tool for decision-making that can leapfrog African development" (Woldai, 2020). However, data literacy and capacity among the government officials are currently among the main barriers preventing policymakers from making data-driven decisions to improve policies and their outcome (Donback, 2020). Moreover, numbers, graphs, and pollution maps only tell half the story. The multi-scalar and interdependent nature of urban air pollution (indoor-outdoor) presents a complex landscape for air quality studies and has particularly significant impacts on certain vulnerable groups that face a higher risk of poverty and social exclusion than others (Avis & Bartington, 2020). Building a bridge between air quality data and inclusive development outcomes and processes would provide a much better visualisation of these impacts and tell a more holistic, thus convincing story. Therefore, there is a need for a much deeper cross-fertilisation between natural and social science discipline to make a real impact on policy and practice. The following section will review to what extent such interdisciplinary collaboration has already taken place in the context of air quality and inclusive development in Africa.

Literature review: Air quality satellite data and inclusive development in Africa

4.1 General trends in the literature

A number of global emission inventories have been published so far, and these have been used for air quality and climate change modelling in Africa (i.e. Fioletov et al. 2020; Lappen and Schumacher 2014). These works used detailed emissions available at the regional scale for North America, Europe and Asia, but not for Africa, for which there is a general lack of detailed anthropogenic inventories at the continental and regional scales. This means that the models that are used for air quality and climate change in Africa right now rely on global inventories that are primarily collected from outside Africa and based on generalized assumptions. It inevitably creates a bias and higher uncertainty in the assessment of AQ and its impacts. If these methods would like to be further used to better inform policy-making and monitoring processes on the continent, Africa needs to develop its own AQ assessment tools.

Two major review articles concerned air quality issues in Africa: Simwela et al. (2018) and more recently Agbo et al. (2021). Although the evidence base in Agbo et al. (2021) has substantially grown in comparison to the Simwela et al. (2018) publication (which also looked at the AQ literature more broadly), both reviews highlight the very serious situation related to air quality in Africa, lack of political responsiveness caused by a lack of available data, as well as call for more research. Moreover, Okello et al. (2023) undertakes a scoping review of strategies developed and/or implemented in Africa in improving air quality and/or health outcomes, co-benefits of the strategies, potential collaborators, and pitfalls of current air quality management strategies in Africa. None of the reviews explicitly analyse the data source of the articles under review. An analysis of the references used in these review articles indicate that only a handful of publications have used satellite data, basing their analysis on mostly temporarily ground measurements campaigns.

Excluding global studies, the literature focusing specifically on AQ in Africa is based predominantly on data coming from ground measurements, although increasing number of articles use satellite data or a combination of both data collection methods. Articles that use only ground measurements are excluded from this review. This section of the literature review will focus predominantly on the air quality research that is somehow based on the satellite data. This scoping of the literature conducted for the purpose of this working paper identified a total of 88 separate articles that uses satellite data to assess air quality (and its potential impacts) in Africa. The detailed table summarising the publications can be found in Annex 5. It can be observed that the first publication that fulfils the search criteria dates back only to 2006 and there is a long break afterwards until 2012. The number of reviewed publications has substantially increased as of 2020 (Figure 4). Most of the publications analyses the situation in the South Africa region (mostly in South Africa itself) and East Africa (Kenya and Uganda). A growing trend is observed in West Africa, especially publications from and about Nigeria (Figure 5). Data retrieved from MODIS were used most frequently, although a positive trend is also observed about the use of data derived from OMI and TROPOMI. Increasingly, remote-sensing retrievals of aerosol optical depth (AOD) are being combined with atmospheric chemistry models to produce accurate and fairly resolved estimates of ground-level concentrations of $PM_{2.5}$ (hence, the popularity of data derived from MODIS). However, an important limitation of these studies must be mentioned. Satellite information at the local level can be reliable only after calibration with referenced ground-level data, which are largely lacking on the continent. Some studies have explicitly shown that satellite data-modelled outputs are not always consistent with satellite observations over Africa (i.e. (Awe et al., 2022)). Consequently, there have been and still is very limited available (and reliable) data on African AQ to date.

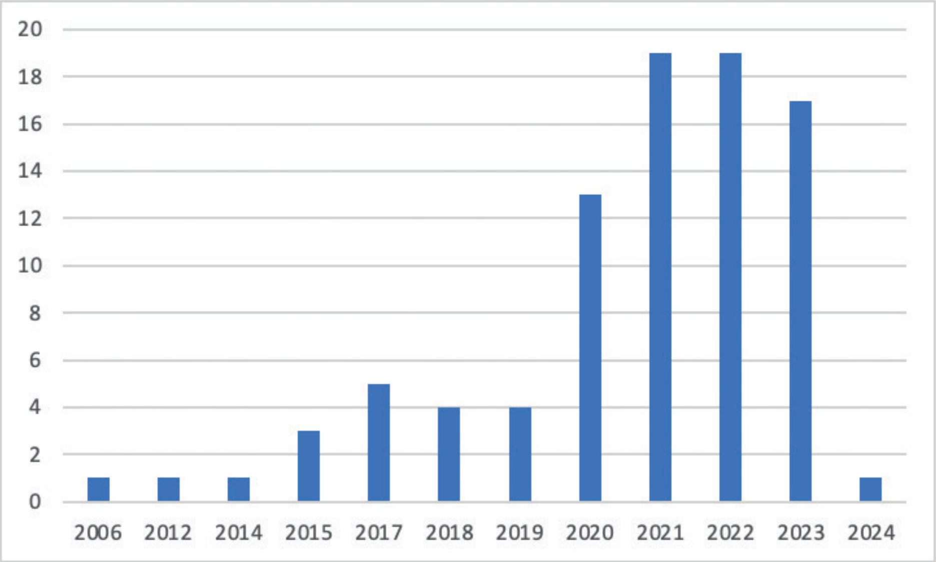

Figure 4
Number of reviewed publications by year
Source: Own calculations

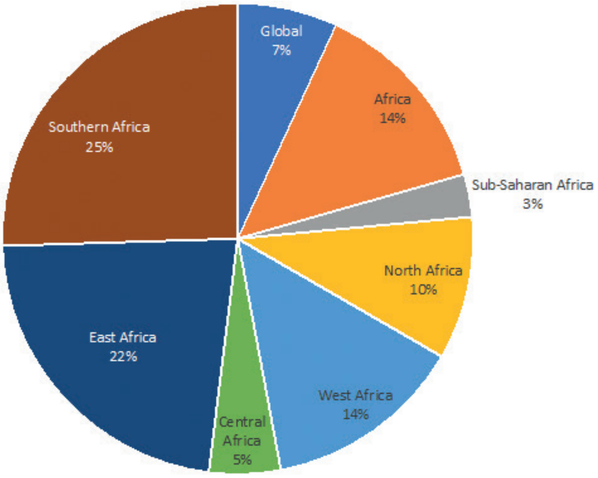

Figure 5
Regional distribution within the reviewed publications
Source: Own calculations

An increased number of articles that are authored by the African scholars (as the first and the last author) has been noted in the last years. Although the publications written by non-African (first and last) authors still constitute over 50% of all the reviewed articles, the remaining 48% involved African scholars in either lead-authorship (42%, including solo publications) or as the final author (6%) (Figure 6). Among the articles first-authored by the scientists affiliated to an African institute (37 in total), only three of them published research on another African country that the country of their official affiliation. That means that an important in-country expertise has been generated. Most 'non-African authors' (first and last ones) were affiliated with institutions in northern America (USA and Canada), Asia and Europe. It should be noted that some of these authors do have some links to Africa (i.e. published while affiliated with a foreign institution during his or her (temporary) PhD contract but would come back to the country of origin ever since. Tracking the career paths of the authors was out of scope of this research though. Despite this lack of precision, a small positive trend can be observed in increased capacity and interest in this climate change related topic among the locally-based scholars. An important observation, which would ideally lead to increased flow of research funding to the African institutions, locally-led research projects, increase in African-led scientific publications and finally, bringing local and contextual voices to the global discussion currently dominated by the 'northern' perspective (Overland & Sovacool, 2020). Ultimately, making the process much more inclusive.

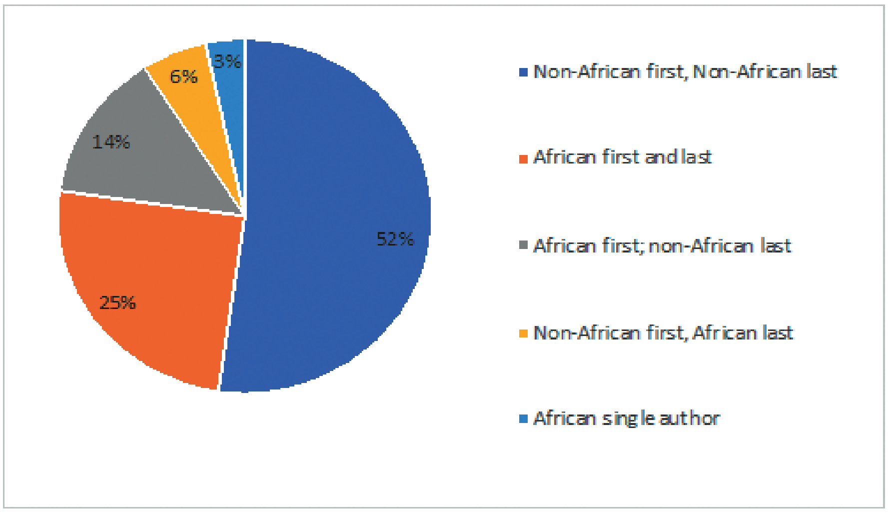

Figure 6
The affiliations of the reviewed articles' authors
Source: Own calculations

4.2 Siloed approach

While analysing the literature, it becomes clear that studies using AQ satellite data in Africa, are mainly natural sciences based, 76% of the reviewed articles taking a mono-disciplinary approach. These publications often apply generic and non-contextualised models based on satellite and ground-level AQ data. The remaining 24% of the articles takes, or attempts to take, an interdisciplinary approach using air quality satellite data with other types of data or studies in order to test potential impact of air quality on, most frequently, health (Bachwenkizi et al., 2021, 2022; Etchie et al., 2018; Fisher et al., 2021; Fleischer et al., 2014; Heft-Neal, Burney, Bendavid, & Burke, 2018; Kalisa, Clark, Ntakirutimana, Amani, & Volckens, 2023; Larson et al., 2022; Lelieveld, Evans, Fnais, Giannadaki, & Pozzer, 2015; Lin, Guo, Di, et al., 2017; Lin, Guo, Kowal, et al., 2017; Marais et al., 2019; Owili, Lien, Muga, & Lin, 2017). A limited number of the reviewed studies link air quality to some elements of the inclusive development (i.e. disability (Lin, Guo, Zheng, et al., 2017), community and occupational exposure (Kwarteng et al., 2020); exposure of vulnerable residents to air pollution (Dasgupta et al., 2020); economic growth (United Nations Environment Programme, 2023b); urbanization (Wei et al., 2021); link between socioeconomic development and air pollution (Hickman et al., 2021); agriculture activities and air pollution (Shikwambana, Mokgoja, & Mhangara, 2022); identifying areas facing both high social vulnerability and air pollution levels (Clarke, Ash, Coker, Sabo-Attwood, & Bainomugisha, 2022); assessing air quality trends with the climate factors, socio-economic indicators, and terrain characteristics (Ouma, Keitsile, Lottering, Nkwae, & Odirile, 2024). These studies though still somehow take a siloed approach. They often refer to potential inclusive development impacts but rarely test them using methods coming from both disciplines.

Although out of scope of this review, an observation was made about a growing body of literature that links vulnerability and some inclusive development lenses to air pollution in Africa among literature where the authors do not use satellite data to establish the links (among others: urban climate justice (Corburn, Njoroge, Weru, & Musya, 2022; Flanagan et al., 2021); risk exposure (Becerra, Belland, Bonnassieux, & Liousse, 2020; Ngo, Kokoyo, & Klopp, 2017); air quality and socio-economic status (John & Das, 2012; Manshur et al., 2023; Mutahi, Borgese, Marchesi, Gatari, & Depero, 2021; Ngo, Asseko, Ebanega, Allo'o Allo'o, & Hystad, 2019; Olaniyan et al., 2020; Rooney et al., 2012). The key methods of assessing air quality in the above mentioned literature are either analysis of data derived from (lower-costs) ground-level sensors or engaged citizen science. Alternatively, the air quality data is retrieved from the existing databases. This shows an increasing interest in establishing further evidence about the link between air quality and vulnerability but it also indicates that the social science community is not aware, or not able to use, available air quality satellite data. These observations point out to the siloed approaches in both the natural as well as the social sciences. These silos result in and are the result of differences in access to and use of data, and a lack of communication, co-creation and cross learning around a common set of interdisciplinary data that can be used in both natural and social sciences.

4.3 Satellite air quality data and inclusive development

A growing global evidence base highlights that the exposure to and impact of air pollution are not equally distributed, which calls for more attention being paid to the concept of inclusive development. Despite the fact that socio-economic marginalization makes people more exposed and vulnerable to air pollution, and apart from substantial evidence of this fact for the US, little evidence exists documenting the global scale of poor people's exposure to harmful air pollution, especially in Africa.

Inclusive development requires prioritizing the health and well-being of all citizens, particularly marginalized communities who are often disproportionately affected by air pollution. Research in Sub-Saharan Africa has shown that health risks from indoor air pollution exposures vary along socio-economic lines (Emmelin & Wall, 2007). Several factors are compounding so that this burden is disproportionately borne by low- and middle-income countries. Especially in the developing countries, large populations are located in densely populated urban areas. Less stringent air quality regulations, the prevalence of older polluting machinery and vehicles, subsidized fossil fuels, congested urban transport systems, rapidly developing industrial sectors, and cut-and-burn practices in agriculture are all contributing to heightened concentration levels. In addition, high proportions of physical and outdoor labour mean that more people are faced with heightened exposure. Constraints in terms of the accessibility, availability and quality of health care provision further increase air pollution related mortality in developing countries (Lelieveld et al., 2020).

Poor air quality, caused by factors such as industrial emissions, household cooking methods, wildfires and open burning, as well as transportation pollution, can lead to respiratory diseases, cardiovascular problems, and other illnesses. In 2023, WHO estimated that about 6.7 million premature deaths were attributed annually to the effects of ambient and household air pollution (World Health Organisation, 2023). Of the global deaths globally attributable to air pollution, 1.1 million (17%) were in Africa (Fisher et al., 2021). Interventions aimed at reducing air pollution and improving related health effects have been reported in Africa (Quansah et al., 2017; Quinn et al., 2018; Woolley et al., 2022). Most have largely focused on indoor air pollution though (which is out of scope of this review), such as the introduction of cleaner-burning fuels (Benka-Coker, Tadele, Milano, Getaneh, & Stokes, 2018; Bruce et al., 2018; Olopade et al., 2017) and improved stoves that burn solid fuels more efficiently (Mamuye, Lemma, & Woldeamanuel, 2018; Mortimer et al., 2017; Ochieng, Vardoulakis, & Tonne, 2017; Van Gemert et al., 2019). Nevertheless, the absence of long-term air quality data and a related monitoring network in most countries make it difficult to develop a complete assessment of the magnitude of the air pollution problem (Pope, Gatari, Ng'ang'a, Poynter, & Blake, 2018; Singh, Avis, & Pope, 2020; Singh et al., 2022).

In terms of links to inclusive development, the satellite data in the reviewed articles is mostly used, to assess the impact of poor air quality on population health (Bachwenkizi et al., 2021, 2022; Etchie et al., 2018; Fisher et al., 2021; Fleischer et al., 2014; Heft-Neal et al., 2018; Kalisa et al., 2023; Larson et al., 2022; Lelieveld et al., 2015; Lin, Guo, Di, et al., 2017; Lin, Guo, Kowal, et al., 2017; Marais et al., 2019; Owili et al., 2017). Although the adoption of satellite-based measures of air quality in health studies in Africa is in its infancy, it has been growing. A number of studies indicated that PM concentrations in urban centres were considerably higher than the WHO guidelines and were found to vary considerably temporarily and spatially. Among the vulnerable groups often referred to, new-born children, young mothers and elderly are mentioned most often. In recent years, there is increasing research interest in understanding air pollution trends and their associated health and environmental impacts in Sub-Saharan Africa using the available satellite data. For instance, Lelieveld et al. (2015) estimated, using satellite estimations of air pollution and pollutant-mortality risk models, the numbers of premature deaths attributable to air pollution globally (Figure 7). The authors suggested that ambient PM2.5 from commercial and domestic energy generation, agriculture and traffic sources contribute the most to premature deaths worldwide. They calculated that premature mortality could be reduced by 4.54 million each year by mitigating both ambient and household air pollution, mainly through changes in commercial and domestic energy use, especially in Africa where domestic energy mostly relies on solid fuels. Without concrete and appropriate mitigation plans and policies, the authors expect a doubling of mortality from air pollution by 2050 considering the projected rates of increase in population and air pollution levels. This study has therefore an important health- and climate- policy-related recommendations.

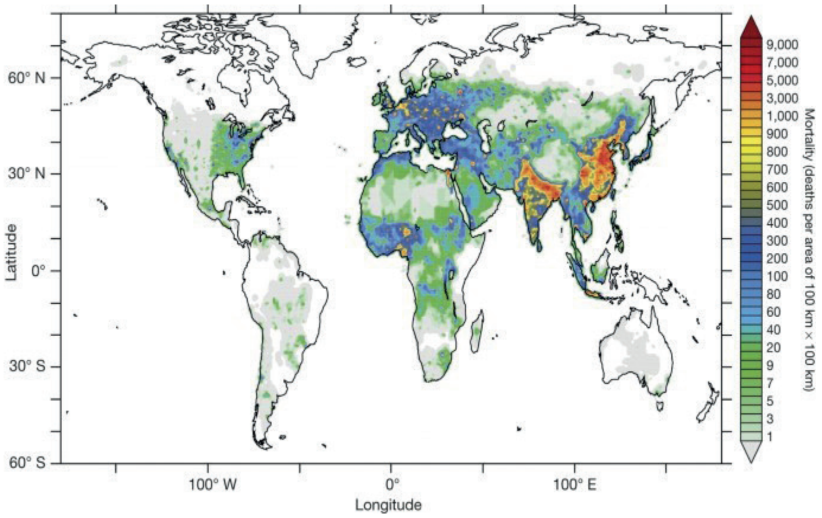

Figure 7
Mortality linked to outdoor air pollution in 2010.
Source: (Lelieveld et al., 2015)

A better understanding of the interplay between air pollution and poverty could be crucial to advance progress towards inclusive development in Africa. In the reviewed articles, only one investigates such link (Rentschler & Leonova, 2022). Air pollution tends to affect vulnerable communities, such as low-income neighbourhoods and marginalized groups, disproportionately. Poverty might increase individual susceptibility to air pollution due to poor health care; unaffordable nutrient-rich foods; and the increased likelihood of living in proximity to polluting industries, biomass burning, and unpaved roads, or depending on jobs that require outdoor physical labour (Katoto et al., 2019). Poor people also tend to have more limited access to adequate and affordable health care, thus increasing mortality rates. The estimates of Rentschler and Leonova (2022) shows that globally, approximately one in ten people exposed to unsafe levels of air pollution live in extreme poverty. In Sub-Saharan Africa, 405 million (or 57%) are directly exposed to unsafe PM2.5 concentrations (Figure 8). Considering the negative health consequences of poor air quality (as discussed above), these findings clearly shows the vulnerability of affected populations. Ensuring inclusive development in Africa requires addressing environmental (in)justice concerns by reducing disparities in exposure to air pollution and providing equitable access to clean air for all.

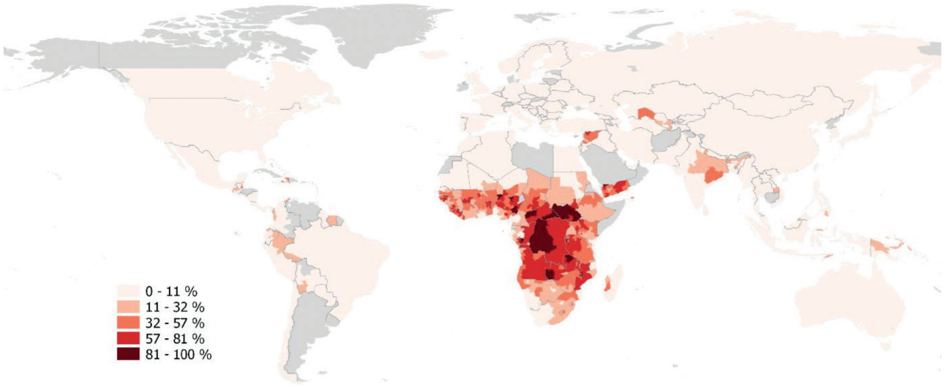

Figure 8
Share of population exposed to unsafe PM2.5 levels and living in poverty at $1.90/day
Source: (Rentschler & Leonova, 2022)

Within the reviewed articles, some links are also made between socioeconomic development and air pollution (Hickman et al., 2021); agriculture activities and air pollution (Shikwambana et al., 2022); identifying areas facing both high social vulnerability and air pollution levels (Clarke et al., 2022); assessing air quality trends with the climate factors, socio-economic indicators, and terrain characteristics (Ouma et al., 2024). Among the vulnerable population, children and the elderly in poor households are referred in this group of literature most frequently. Furthermore, urbanization not only increases the number of people exposed to outdoor air pollution but also subsequently raises the air pollution levels. Despite a clear link between the two concepts, the articles linking satellite air quality data to socio-economic dimensions of wellbeing and related policy dialogues/interventions are sparse.

Conclusions

This working paper reviewed the existing academic and grey literature on the use of satellite air quality data in Africa, as well as the inclusion of different socio-economic perspectives in this field of study. Based on the review of 88 papers, it can be concluded that the knowledge about air pollution on the African continent is growing, yet the evidence-base remain thin. While satellite measurements have the potential to provide a lot of information on air quality in Africa, there are few publications which utilize satellite-based air quality datasets. Despite some shortcomings of this type of data, satellite-derived estimates of exposure could also be leveraged in studies where ground-level measurements are not feasible. In addition, satellite measurement can be used to create so-called top-down emission estimates and inventories (i.e. NO_2).

It can be observed that the debate on air quality in Africa is often led by natural scientists. Complementary discussions bringing the social science perspective to light emphasizing spatial heterogeneity in the prevalence of air pollution, the resultant impacts on various population groups, and regional societal responses are underdeveloped. An increased number of publications led by African-based scholars have been noted in recent years, although the field remains dominated by non-African scholars.

In terms of links to inclusive development, the satellite-based air quality data, when used, is primarily to assess the impact of poor air quality on human health of a given population. Some studies link air quality to socio-economic status and exclusion (defined as low-income neighbourhoods or marginalized groups) but satellite-based data are not frequently used to establish such links. This observation points to the siloed approaches present in the mainstream of both natural and social sciences. These isolated silos lead to differences in how data is accessed to and used, which in turns hinders communication, co-creation, and cross-specialization learning around a common set of interdisciplinary data that could be utilized in both natural and social science domains.

This literature review concludes that the biggest issues for African countries in the debate about air quality relates to the lack of data on the emissions causing air pollution and climate change, lack of monitoring data for ground-level concentrations, Africa context-specific AQ assessment models, and siloed approach within the research community. There is also a general need for ground-level monitoring to validate satellite-derived concentration estimates and model output in the region.

Addressing air pollution, countries in Africa can reduce the burden of mortality and morbidity, thus healthcare expenses, as well as create healthier work environments and promote productivity, leading to more inclusive economic development. It is, therefore, important to prioritize creating awareness, invest in contextualizing the progress made and the unique challenges and solutions in monitoring air pollution in Africa and in assessing the impacts. Nevertheless, African governments need data to plan policies that can reduce air pollution and deliver national development priorities and climate goals. Air quality satellite data offers a promising source of such information. Collaborative efforts involving multiple science domains coming from both the Global North and South, can help create sustainable and inclusive research and practice communities. For this purpose, a methodology for contextual and reciprocal learning between natural and social sciences through joint data generation and use with a focus on air quality in Africa is needed.

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ANNEX 1

Most important types of air pollutant, their sources and average lifetime in the atmosphere

Pollutant	Classification	Source of emissions	Average lifetime in the atmosphere
Carbon dioxide (CO_2)	Key long-lived greenhouse gas	Combustion of fossil fuels Road traffic Industrial processes Coal-fired power generation Combustion of solid waste Combustion trees and wood products Changes in land use Deforestation and soil degradation	Carbon dioxide's lifetime cannot be represented with a single value because the gas is not destroyed over time, but instead moves among different parts of the ocean–atmosphere–land system. Some of the excess carbon dioxide is absorbed quickly (for example, by the ocean surface), but some will remain in the atmosphere for thousands of years, due in part to the very slow process by which carbon is transferred to ocean sediments. Account for about three-fourths of total emissions.
Nitrous oxide (N_2O) and Nitrogen dioxide (NO_2)	Key long-lived greenhouse gas	Agricultural activities Industrial activities Combustion of fossil fuels Combustion of solid waste Combustion of biomass	121 years
Sulfur dioxide (SO_2)		Sulfur dioxide can be created in high quantities from carbon and mineral oil combustion processes. Short-term exposure to SO_2 can damage the human respiratory system and cause difficulty when breathing. Children, elderly people, and those who suffer from asthma are particularly sensitive to the effects of this pollutant. Generally, sulfur dioxide emissions that lead to high concentrations of SO_2 in the air also contribute to forming other sulfur oxides. SOx can react with other compounds in the atmosphere to form small particles that can penetrate sensitive areas of the lungs and cause other health issues.	

Methane (CH_4)	Short-lived climate pollutant and greenhouse gas	Production and transport of oil, natural gas and coal Wetlands Livestock Agricultural practices The anaerobic decay of organic waste in municipal solid waste landfills	12.4 years
Tropospheric ozone (O_3)[11]	Short-lived climate pollutant and greenhouse gas	Ozone is not a pollutant that is emitted directly into the air, but rather it is generated due to chemical reactions between nitrogen oxides and volatile organic compounds (VOC) in the presence of sunlight. It is a powerful oxidizing agent generated from dioxygen by its exposure to ultraviolet light, and it reacts with other pollutants like nitrogen oxides and sulphur. Exposure to tropospheric ozone can cause several health issues, mainly in children, elderly people, and people with asthma and lung problems. In addition, it has damaging effects on vegetation and ecosystems. It is a major component of urban smog	Hours to weeks
Black carbon (BC)	Short-lived climate pollutant	A product of the incomplete combustion of fossil fuels, biofuels and biomass. A component of particulate matter, black carbon, also referred to as soot, is emitted into the atmosphere along with a complex mixture of air pollutants	Up to 2 weeks
Fluorinated gases	Short-lived climate pollutant*	A group of gases that contain fluorine. These gases are emitted from a variety of industrial processes and commercial and household uses and do not occur naturally. For instance, hydrofluorocarbons are man-made greenhouse gases used in air conditioning, refrigeration, solvents, fire extinguishing systems, and aerosols	A few weeks to thousands of years

[11] A reactive gas that exists in two layers of the atmosphere: the stratosphere (upper layer) and the troposphere (at ground level and up to 15km). In the stratosphere, ozone protects life on Earth from the sun's ultraviolet radiation. In contrast, at lower levels, it is an important greenhouse gas and air pollutant, which is harmful to human and ecosystem health (Climate & Clean Air Coalition, 2023b).

* Short-lived climate pollutants (black carbon, methane, tropospheric ozone, and hydrofluorocarbons) are the most important contributors to the man-made global greenhouse effect after carbon dioxide, responsible for up to 45% of current global warming.

Particulate Matter (PM)		Particulate matter is a mixture of extremely small particles and droplets in the air. They can be of different shapes and sizes and can include hundreds of different chemicals. The particles contain microscopic solids or liquid droplets that are so small that they can be inhaled and cause serious health problems. Particles of less than 10 micrometers in diameter are the ones that cause more problems, given that they can penetrate deeply into the lungs, and some can even enter the bloodstream. Fine particles or $PM_{2.5}$ are the primary causes of reduced visibility	

Source: (Climate & Clean Air Coalition, 2023a; US EPA, 2023; Vélez-Guerrero, Callejas-Cuervo, & Alarcón-Aldana, 2023)

ANNEX 2

Methodologies currently used for measuring atmospheric pollutants[12]

Among the methodologies currently used for measuring atmospheric pollutants, automatic methods are the most common, as shown below. These methods include a great variety of chemical processes to determine the concentration of pollutant gases and particulate matter. Some of these methods are beta attenuation, tapered element, oscillating microbalance, chemiluminescence, and UV absorption.

- Beta attenuation: This is a mass method for measuring particles usually used in detectors of particulate matter, total suspended particles, particulate matter less than 10 m (PM10), and particulate matter less than 2.5 m ($PM_{2.5}$) collected from ambient air with a ribbon. The rate at which the flow of beta radiation is attenuated or reduced by a solid matter depends on its mass.
- Tapered element oscillating microbalance: The measurement system has a filter at the end of a hollow glass conical tube. The latter vibrates at its natural frequency as the air sample passes through the filter, and the matter is deposited there. The vibration frequency decreases as the mass of particulate matter increases.
- UV fluorescence: This method applies to determine the concentration of sulphur oxides. SOx absorbs the UV light and becomes excited at one wavelength. Then they decay to a lower energy state, emitting UV light at different wavelengths. The intensity of fluorescence is proportional to the concentration of SOx.
- Chemiluminescence: This method applies to determine the concentration of a substance for the measurement of nitrogen oxides and consists of provoking a reaction between nitrogen monoxide and ozone to form nitrogen dioxide. Because of this chemical reaction, the molecules enter an excited state and emit detectable rays, such as ultraviolet, visible, or infrared radiation. The intensity of the light emitted is proportional to the concentration of NOx.
- UV absorption: This is a general method used to measure concentrations of ozone. The airflow divides into two equal flows, one of which goes through a section that contains molybdenum oxides as a catalyser that traps the ozone of the sample to direct later it to a measurement cell. The other flow goes directly to another measurement cell. The irradiation of the samples takes place in the cells. The absorbance signals of both cells are internally translated into electric signals by the analyser, and the difference between these signals is proportional and equivalent to the concentration of ozone present in the air sample entered.
- Gas filter correlation (GFC): The incidence of infrared radiation passes through a rotating gas-filled filter wheel before entering the sample chamber. The wavelengths absorbed by CO are removed from the radiation, creating a reference beam not affected by CO in the sample measured. When the IR energy passes through the middle of the wheel that contains nitrogen, the specific CO wavelengths are not removed from the radiation, and the measurement beam is attenuated by the CO in the sample. The rotation of the gas filter wheel generates a beam that alternates between the reference and measurement phases. A liquid state sensor detects the infrared energy that passes through the filter, and the sample chamber turns it into a concentration value. It is necessary to consider that polluting concentrations are usually measured in units of micrograms per cubic meter (μg/m3) or milligrams per cubic meter (mg/m3). The measurement methods shown above are currently used by gas sensors at air quality stations, which provide information on pollution at various times of the day (Vélez-Guerrero et al., 2023).

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[12] This section builds on (Vélez-Guerrero et al., 2023). This reference is recommended for more details about different air quality monitoring measurement techniques and Instruments.

ANNEX 3

Details behind satellite-based remote sensing of air quality

Satellite sensors measure interference in the light energy reflected or emitted from the Earth, which is used to calculate concentrations of air pollutants such as PM, nitrogen dioxide, carbon monoxide, and ozone. In the case of particles, the satellite sensors measure the Aerosol Optical Depth (AOD) – the degree to which light has been absorbed or scattered by particles in the atmosphere. Using geophysical models and statistical calibration, scientists continue to refine how they relate the satellite-based AOD observations to the surface concentration of $PM_{2.5}$. Targeted study of satellite observations of multiple atmospheric constituents over cities can facilitate the determination of spatial and temporal changes in air pollution. Satellite observations can be used to identify changes in urban pollution due to nearby agriculture and fertilizer use (using NH_3), industrialisation (using NO_2, CO, and HCHO as a surrogate for volatile organic compounds), ozone chemistry (with HCHO:NO_2 ratios), aerosol abundance (using AOD), and aerosol optical properties (using AI). Results from such observations can provide a useful context for the deployment of low-cost sensors, which all together will form a comprehensive integrated approach model for AQ monitoring (Avis & Bartington, 2020). Box 2 below presents key features of the selected remote sensing air quality monitoring instruments.

The following instruments play vital roles in studying Earth's atmosphere, climate, air quality, and land surface dynamics, providing scientists with valuable data for research, monitoring, and policymaking.

The Sentinel-5 Precursor Tropospheric Monitoring Instrument (TROPOMI) is an instrument onboard the European Space Agency's Sentinel-5 Precursor satellite. Its primary features include:

- High Spectral Resolution: TROPOMI provides high-resolution spectral measurements in the ultraviolet (UV), visible (VIS), near-infrared (NIR), and shortwave infrared (SWIR) regions. This allows for precise measurements of various atmospheric trace gases with a focus on air quality and climate-related parameters.
- Wide Swath Coverage: TROPOMI has a wide swath coverage of approximately 2,670 kilometres, enabling daily global monitoring and high spatial resolution measures of atmospheric column amounts (total, stratospheric, and/or tropospheric) of key gaseous air pollutants and some measures of clouds and the presence of aerosols (UV Aerosol index and aerosol layer height).
- Trace Gas Monitoring: TROPOMI measures a range of trace gases, including ozone, nitrogen dioxide, sulphur dioxide, carbon monoxide, formaldehyde, and methane. These measurements contribute to the understanding of air pollution, greenhouse gas emissions, and their impact on climate change and human health.

The Ozone Monitoring Instrument (OMI) is a spectrometer onboard NASA's Aura satellite. Its main features include:

- Ozone Monitoring: OMI is designed to measure ozone concentrations in the Earth's atmosphere with high accuracy and spatial resolution. It provides near-global coverage on a daily basis and monitors the distribution of ozone, allowing scientists to study ozone depletion and its impact on climate and air quality.
- UV Aerosol Index: OMI measures the Ultraviolet (UV) Aerosol Index, which indicates the presence and intensity of aerosols in the atmosphere. This data helps in understanding aerosol distribution, sources, and their effects on climate and human health.
- Trace Gas Measurements: OMI is capable of measuring various trace gases, including nitrogen dioxide (NO2), sulphur dioxide (SO2), formaldehyde (HCHO), and carbon monoxide (CO). These measurements aid in studying air pollution, identifying pollution sources, and assessing the impact on air quality and human health.

The Moderate Resolution Imaging Spectroradiometer (MODIS) is an instrument on NASA's Terra and Aqua satellites. Its key features include:

- High Spatial Resolution: MODIS provides high-resolution imagery of the Earth's surface, capturing details up to 250 meters (Terra) and 500 meters (Aqua). This enables the monitoring of land cover changes, vegetation dynamics, and the detection of natural and human-induced phenomena.
- Wide Spectral Coverage: MODIS measures radiation across a broad range of wavelengths, from the visible to the thermal infrared spectrum. This allows the characterization of atmospheric conditions, such as cloud properties, aerosols, and land surface temperature.
- Daily Global Coverage: With its wide scan swath, MODIS can acquire data covering the entire Earth every 1-2 days. This frequent revisit time is useful for monitoring rapidly changing events, such as wildfires, volcanic eruptions, and weather patterns.

The Multiangle Imaging Spectroradiometer (MISR) is an instrument on NASA's Terra satellite. Its notable features include:

- Multiple Viewing Angles: MISR captures images of the Earth's surface from nine different angles, ranging from forward to backward. This unique capability allows for the retrieval of important surface and atmospheric properties, including aerosol distribution, cloud heights, and surface topography.
- Stereo Imaging: By capturing images from multiple angles, MISR can generate stereoscopic views that enable the creation of 3D models of the Earth's surface. This aids in understanding terrain features, land cover changes, and assessing the impacts of natural disasters.
- Modern- Era Retrospective analysis for Research and Applications version 2 (MERRA-2) is a project focuses on historical climate analyses for a wide range of weather and climate time scales and places the NASA Earth Observation System of Systems (EOS) series of observations in a climate context.
- The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) is a joint US (NASA) and French (CNES) satellite mission that includes the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument, the millimeter-wavelength cloud radar aboard the NASA CloudSat, and the CNES Polarization & Anisotropy of 30 Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) that carried the Polarization and Directionality of the Earth's Reflectances (POLDER) instrument that was operational from 2004-2013.
- NASA Atmospheric Infrared Sounder (AIRS) gateways provide access to trace gases important to air quality. AIRS is a grating spectrometer on the Aqua satellite that collects infrared radiation from Earth's surface and atmosphere with a spatial resolution of 1° and provides measurements of temperature, water vapor, trace gases, and surface and cloud characteristics.

<u>Note on the ground level network to validate satellite retrievals</u>

- **The AERONET** is a network of Sun photometers on the ground that provides a long-term, continuous, and easily accessible public database of aerosol optical and radiative properties for aerosol characterization and validation of satellite retrievals. Version 3 algorithm processing includes three levels of quality: (1) data at level 1.0 has not been cloud-screened or calibrated; (2) data at level 1.5 has been cloud-screened but not calibrated or quality-assured; and (3) data at level 2.0 has been cloud-screened, calibrated, and quality-assured. As AERONET AOD data has low uncertainty (0.01–0.02) and high temporal resolution (every 15 min), it is used for the validation of satellite AOD products.

Box 2

Key features of the selected remote sensing air quality monitoring instruments

Sources: (Bouhachlaf, Mousli, & El Hajjaji, 2022; Elshora, 2023; eoPortal, 2012; Levelt et al., 2018; Limbacher, Kahn, & Lee, 2022; NASA, n.d.

ANNEX 4

Global air quality policy and guidance

Here are some notable global commitments related to clear air:

1. Paris Agreement: The Paris Agreement, adopted in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC),[13] aims to limit global warming to well below 2 degrees Celsius above pre-industrial levels. While primarily focused on mitigating climate change, reducing greenhouse gas emissions also contributes to improved air quality. All but four African countries have ratified the Paris Agreement.[14]
2. Sustainable Development Goals (SDGs): The SDGs, adopted by the United Nations in 2015,[15] include several goals related to environmental sustainability and health. Three SDGs, namely health and wellbeing (SDG 3), energy (SDG 7), and sustainable cities (SDG 11) have AQ as an explicit indicator.
3. In the UN system more broadly:
   a United Nations Environment Assembly (UNEA) adopted resolutions 1/7 "Strengthening the role of the United Nations Environment Programme in promoting air quality" (2014); 3/8 "Preventing and reducing air pollution to improve air quality globally (2017); 3/4 "Environment and health" (2017); and 4/21 "Implementation plan Towards a pollution-free planet" (2019);
   b World Health Assembly (WHA) resolutions (WHA) 68.8 "Health and the environment: addressing the health impact of air pollution" (2015) and 69.11 "Health in the 2030 Agenda for Sustainable Development" (2016);
4. World Health Organization (WHO) Guidelines: since in the mid-1980s, WHO has prepared guidelines with evidence-based recommendations for protecting populations worldwide from the adverse health effects of air pollutants. Fourth editions of WHO air quality guidelines have been produced so far, the latest in 2021 (Scotford et al., 2021; WHO, 2021).[16] These guidelines, however, are not intended to be taken as recommendations for air quality standard per se, but rather as "a rigorous scientific tool that can be used by regulatory authorities as a basis for setting standards, taking into account local socio-political and economic conditions and prevailing ambient concentrations of air pollutants" (Scotford et al. 2021: 28).
5. Regional Initiatives: Various regional initiatives have been established to address air pollution collectively. For example, the European Union has implemented comprehensive air quality policies and standards, resulting in notable improvements in air quality across many European countries. Similarly, initiatives like the Clean Air Asia program have focused on addressing air pollution issues in the Asian region.
6. National Air Quality Plans: Several countries have developed national air quality plans and policies to address air pollution. These plans may include measures to reduce emissions from industrial sources, transportation, and other sectors, as well as promote the use of cleaner technologies and renewable energy sources.
7. International Agreements on Emissions Reduction: Various international agreements focus on reducing specific air pollutants. For example, the Montreal Protocol aims to protect the ozone layer by phasing out the production and consumption of ozone-depleting substances, which are also potent greenhouse gases (it has been ratified by all United Nations member states). The Gothenburg Protocol under the United Nations Economic Commission for Europe (UNECE) focuses on reducing emissions of air pollutants in Europe.
8. Clean Air Initiatives and Campaigns: Several global initiatives and campaigns are dedicated to raising awareness about air pollution and promoting clean air. For instance, the BreatheLife campaign, led by WHO, the United Nations Environment Programme (UNEP), and the Climate and Clean Air Coalition, aims to mobilize cities and individuals to take action on air pollution. Clean Air for Africa (CCAC, SEI, UNEP, AUC), African Cities for Clean Air (C40).

The integration of statistics, geospatial information, Earth observations, and other sources of Big Data, combined with new emerging technologies, analytics and processes, are becoming a fundamental requirement for countries to measure and monitor local to global sustainable development policies and programs. For instance, the following indicators within SDGs utilize air quality satellite data:

- Ambient Air Pollution (Indicator 3.9.1): This indicator specifically focuses on measuring ambient air pollution, including particulate matter ($PM_{2.5}$ and PM_{10}) and nitrogen dioxide (NO_2). Monitoring air quality is crucial for assessing its impact on public health, particularly respiratory and cardiovascular health risks. Country population exposure to annual mean concentration of $PM_{2.}5$ are derived from methods using both ground measurements and satellite information, as regularly reported for SDG 11.6.2 for urban areas, but are also derived for urban and rural and can be used.
- Ambient Air Pollution in Cities (Indicator 11.6.2): This indicator specifically focuses on measuring ambient air pollution levels within cities. It typically considers parameters like

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[13] As well as preceding treaties: The United Nations Framework Convention on Climate Change (UNFCCC) (1992) and The Kyoto Protocol (1997). Additional global treaties targeting specific pollutants equally exists: The Vienna Convention for the Protection of the Ozone Layer (1985) and The Montreal Protocol on Substances that Deplete the Ozone Layer (1987); The Stockholm Convention on Persistent Organic Pollutants (2001) and The Minamata Convention on Mercury (2013) (Scotford et al., 2021).

[14] These countries are: Angola, Libya, Eritrea and South Sudan (UN, n.d.).

[15] All African member states adopted the agenda, with the exception of Western Sahara, which is not officially recognized as a sovereign state by the UN.

[16] The guidelines were published in 1987 (first edition), 2000, 2005 and the latest in 2021 (Scotford et al., 2021; WHO, 2021).

> $PM_{2.5}$, PM_{10}, and NO_2 to assess the air quality conditions in urban areas, particularly in relation to World Health Organization (WHO) air quality guidelines. The World Health Organization (WHO) is the custodian agency for SDG Indicator 11.6.2, using a variety of observations, including ground and satellite measurements, as inputs to models to estimate human exposure to harmful particulate matter of a diameter less than 2.5 micrometres, known as $PM_{2.5}$. The WHO maintains an air quality database to support reporting and has recently developed the Data Integration Model for Air Quality (DIMAQ) that incorporates data from a variety of sources in order to provide estimates of exposures to $PM_{2.5}$ at 0.1o × 0.1o globally (UN Statistics Wiki, 2023).

The United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) is advancing new approaches to data by implementing a global policy framework that will enable countries to better integrate geospatial and other key information into global development policies and into their own national plans. Established in 2011, UN-GGIM sets directions for the production and use of geospatial information within national and global policy frameworks, and for building and strengthening geospatial information capacity of nations, especially of developing countries. Through partnerships within the UN system and with organizations such as the World Bank, the Group on Earth Observations (GEO), the Committee on Earth Observations Satellites (CEOS), and other global actors, our combined ability to contribute towards an interconnected data ecosystem that will allow Member States to properly plan for and implement the SDGs, will be realized. Similarly, the Group on Earth Observations launched the Earth Observations for the Sustainable Development Goals (EO4SDG) initiative to contribute to the 2030 Agenda and realize the potential that Earth observations and geospatial information offer to the SDGs and the normative benefits they represent (Earth Observations for the Sustainable Development Goals, n.d.).

ANNEX 5

List of identified publications that assess AQ in Africa using satellite data and their reference to inclusive development lenses

#	Author / year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
1	(Edwards et al., 2006)	2006	Southern Hemisphere		Carbon monoxide (CO)	The Measurement of Pollution in the Troposphere (MOPITT) instrument (CO profiles), and MODIS (AOD)	In regions of significant convection, particularly in the equatorial Indian Ocean, the CO mixing ratio is greater at higher altitudes, indicating vertical transport of biomass burning emissions to the upper troposphere	None	Siloed	Natural science
2	(Brauer et al., 2012)	2012	Global		$PM_{2.5}$ and ozone; AOD	MODIS MISR	Assessments of global attributable disease burden. Combined with spatially resolved population distributions, these estimates expand the evaluation of the global health burden associat-ed with outdoor air pollution	None	Siloed	Natural science
3	(Fleischer et al., 2014)	2014	Global, including 5 countries from Africa (Algeria, DR Congo, Kenya, Niger, Nigeria		$PM_{2.5}$ between 2004 and 2008 AOD	AOD estimates from MODIS from (Van Donkelaar et al., 2010)	We examined whether outdoor $PM_{2.5}$ was associated with adverse birth outcomes among 22 countries in the World Health Organization Global Survey on Maternal and Perinatal Health. Outdoor $PM_{2.5}$ concentrations were associated with low birth weight but not pre-term birth. In rapidly developing countries, such as China, the highest levels of air pollution may be of concern for both outcomes	Indirect. AQ and adverse birth outcomes. Vulnerable population: new-borns.	Interdisciplinary (use of already existing processed AQ data; and databases)	Natural science Social science Health

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
4	Hersey et al., 2015)	2015	South Africa	Cape Town, Bloemfontein, Johannesburg and Tshwane, the Industrial Highveld Air Quality Priority Area (HVAPA), and Durban	Aerosol (2000-2009) & ground-level monitoring	MODIS & NASA's Giovanni Data and Information Services Center	Report poor agreement between satellite and ground aerosol.	None	Siloud	Natural Science
5	(Kumar et al., 2015)	2015	South Africa	Durban	AOD	MODIS, MISR, OMI, and AERONET	The results revealed that MISR-AERONET comparison indicated strong correlation compared to MODIS-AERONET comparison. Also, the comparison between MODIS and MISR AODs noticed significant positive correlation over DBN with the over- estimation of latter by former.	None	Siloud	Natural Science
6	Leveld et al., 2015)	2015	Global		AOD; $PM_{2.5}$	MODIS (AOD) and AERONET (ground-level)	The estimates of the numbers of premature deaths attributable to air pollution globally. They calculated that premature mortality could be reduced by 4.54 million each year by mitigating both ambient and household air pollution, mainly through changes in commercial and domestic energy use, especially in Africa where local energy mostly relies on solid fuels. Without concrete and appropriate mitigation plans and policies, the authors expect a doubling of mortality from air pollution by 2050 considering the projected rates of increase in population and air pollution levels.	Indirect, link between AQ and premature deaths	Interdisciplinary	Natural science Social science Health

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
7	(Jury, 2017)	2017	South Africa	Highveld	Sulphur dioxide (SO_2) and nitrogen dioxide (NO_2)	OMI, AIRS and MERRA-2	This new understanding will underpin better air-quality forecasts over the South African Highveld.	None	Siloed	Natural Source
8	(Owili et al., 2017)	2017	Africa		$PM_{2.5}$ AOD between 2000 to 2015	MODIS (AOD)	The types of ambient $PM_{2.5}$ are significantly associated with under-five and maternal mortality in Africa where the exposure level usually exceeds the World Health Organization's (WHO) standards. Appropriate policy actions on protective and control measures are therefore suggested and should be developed and implemented accordingly.	Indirect, AQ and under-five and maternal mortality. Vulnerable groups: young children and women	Interdisciplinary	Natural science Social science Health
9	(Lin, Guo, Di, et al., 2017)	2017	Six low- and middle-income countries: China, Ghana, India, Mexico, Russia, and South Africa		$PM_{2.5}$	Estimates from (Van Donkelaar et al., 2016)[6]	Few studies have explored potential effect modifiers for stroke in terms of demographic, behavioural, and dietary factors. Physical activity is beneficial to general health, but may increase air pollution exposures because breathing rates increase while exercising, resulting in more harmful health effects.	Indirect. Long-term $PM_{2.5}$ exposure was associated with stroke	Inter-disciplinary (use of already existing processed AQ data)	Natural science Social science Health

17(Van Donkelaar et al., 2016) derived the global $PM_{2.5}$ concentration fields by Geographically Weighted Regression (GWR) of satellite-derived Aerosol Optical Depth (AOD) retrievals from different satellite products (MODerate resolution Imaging Spec- troradiometer [MODIS], Multiangle Imaging SpectroRadiometer [MISR], Sea-viewing Wide Field-of-view Sensor [SeaWiFS], Cloud- Aerosol Lidar and Infrared Pathfinder Satellite Observation [CALI- PSO]), simulation from chemical transport model (GEOS-Chem) and ground-based observations from Aerosol Robotic Network (AERONET) and surface monitors for 1998 to 2014.

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
10	(Lin, Guo, Zheng, et al., 2017)	2017	Six low- and middle-income countries: China, Ghana, India, Mexico, Russia, and South Africa		$PM_{2.5}$ AOD	Estimates from (Van Donkelaar et al., 2016)	Exposure to ambient $PM_{2.5}$ might be one risk factor of disability in the low- and middle-income countries, women and older adults are the vulnerable population; and among the six domains (cognition, mobility, self-care, getting along, life activities, and participation in society), cognition, mobility and getting along are more relevant to this effect.	Yes. The direct relationship between air pollution and disability.	Interdisciplinary (use of already existing processed AQ data; sand other databases)	Natural science Social science Health
11	(Lin, Guo, Kowal, et al., 2017)	2017	Six low- and middle-income countries: China, Ghana, India, Mexico, Russia, and South Africa		$PM_{2.5}$	Estimates from (Van Donkelaar et al., 2016)	Investigating joint mental health effects of air pollution and tobacco smoking in low- and middle-income countries. The results suggest that exposure to ambient PM2.5 may increase the risk of depression, and smoking may enhance this effect.	Indirect. AQ and mental health	Interdisciplinary (use of already existing processed AQ data; surveys	Natural science Social science Health
12	(Boiyo, Kumar, & Zhao, 2018)	2018	East Africa		AOD between 2002-2016	MODIS	Classification of major aerosol types over major cities in EA revealed dominance of continental (74.47%) followed by the mixed (16.22%) and biomass-burning/ urban-industrial (8.02%) aerosols, with minor contributions from desert dust (1.03%) and clean maritime (0.32%) type of aerosols.	None	Siloed	Natural science
13	(Aklesso, Kumar, Bu, & Boiyo, 2018)	2018	Ghana, Togo, and Benin		AOD between 2005-2015	MODIS and OMI	In general, aerosols observed over the study domain were associated with long-range transport from the North Atlantic Ocean, Sahara Desert, and Nigeria.	None	Siloed	Natural science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
14	(Heft-Neal et al., 2018)	2018	Sub-Saharan Africa		$PM_{2.5}$ between 2001 and 2015	MODIS, the Multi-Angle Resolution Spectroradiometer (MISR) and the Sea-viewing Wide Field-of-View Sensor (SeaWiFS). These data are combined with aerosol profile measurements from the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP). Satellite, weather and seasonality data from the GEOS-Chem Chemical transport model to quantify the relationship between AOD and surface $PM_{2.5}$ measured at available ground-based stations.	Our estimates suggest that the actual number that attribute death of infants to poor air quality in 2015 in selected African countries is more than three times higher than existing estimates. Upward revision of disease-burden estimates in the studied countries in Africa alone would result in a doubling of current estimates of global deaths of infants that are associated with air pollution, and modest reductions in African $PM_{2.5}$ exposures are predicted to have health benefits to infants that are larger than most known health interventions.	Indirect A link between AQ and infant mortality	Interdisciplinary Average infant mortality rate (IMR) in study countries for 2001–2015, derived from Demographic and Health Surveys	Natural science Social science Health

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
15	(Tunde O. Etchie et al., 2018)	2018	Nigeria		$PM_{2.5}$ AOD 3-year moving average $PM_{2.5}$ concentrations for 2000 and 2015	Estimates from (Van Donkelaar et al., 2016)	We estimate the loss or gains in longevity using population-weighted average pollution level and baseline mortality data for cardiopulmonary disease and lung cancer in adults !25 years and for respiratory infection in children under 5. We conclude that mitigation interventions should target emission sources having the highest population exposures.	Indirect. AQ and life expectancy	Inter-disciplinary (use of already existing processed AQ data; and databases)	Natural science Social science Health
16	Ossohou et al., 2019)	2019	Africa		NO_2 and HNO_3 (Ground-based NO_2 between 1998-2015; from OMI between 2005-2015)	OMI	The decreasing NO_2 ground-based con- centration trends observed in wet savannas sites are correlated with OMI NO2 decreasing trends at these sites.	None	Siloed	Natural science
17	(Muthama, 2019)	2019	Kenya	Nairobi	SO_2, CO_2, dust dry deposition and AOD	MODIS	Monitoring and analysis of urban air quality in Kenya needs to be enhanced for improved understanding and quantification of health effects of pollutant.	None	Siloed	Natural Science
18	(Langley Dewitt et al., 2019)	2019	Rwanda		CO2, CO, CH_4, black carbon (BC), and O_3	MODIS	Our measurements indicate that air pollution is a current and growing problem in equatorial East Africa.	None	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
19	(Marais et al., 2019)	2019	Africa		AOD, Fine particles ($PM_{2.5}$), sulphur dioxide (SO_2) and nitrogen oxides (Nox)	OpenAQ (AOD)	Estimated air pollutant emissions in Africa from future (2030) electricity generation and transport. We calculate 48000 avoidable deaths in 2030 (95% confidence interval: 6000–88000), mostly in South Africa (10400),Nigeria (7500), and Malawi (2400), with 3-times higher mortality rates from power plants than transport. Sensitivity of the burden of disease to either population growth or air quality varies regionally and suggests that emission mitigation strategies should be most effective in Southern Africa, whereas population growth is the main driver everywhere else.	Indirectly. Air quality and health impact of future fossil fuel use for electricity generation and transport in Africa	Siloed	Natural Science
20	(Malings et al., 2020)	2020	USA, Rwanda, Malawi, the Democratic Republic of the Congo, Uganda, Ethiopia	Pittsburgh, Kigali, Kinshasa, Kampala, Addis Ababa	Low-cost monitors; the conversion of the satellite aerosol optical depth (AOD) to surface $PM_{2.5}$	MODIS	Combining ground-based low-cost sensor and satellite data, even without including additional meteorological or land use information, can improve and expand spatiotemporal air quality data coverage, especially in data-sparse regions.	None	Siloed	Natural Science
21	(deSouza et al., 2020)	2020	Kenya	Nairobi	Low-cost monitors; the conversion of the satellite aerosol optical depth (AOD) to surface $PM_{2.5}$	MODIS	Identifying factors that would reduce the uncertainty in the conversion of AOD into $PM_{2.5}$ in future experiments. Thus, the approach will have the potential to expand the range of cities that can afford to monitor long-term air quality trends and help inform public policy.	None	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
22	(Kwarteng et al., 2020)	2020	Ghana	The Agbogbloshie e-waste and scrap yard site in Accra	Ground level monitoring for PM and AOD for the presence of Harmattan dusts	MODIS	Exceptionally high concentrations of PM_{10} and $PM_{2.5}$ were sometimes encountered near combustion sources, considerably exceeding air quality standards.	Indirect. Assessing community and occupational exposures.	Siloed	Natural Science
23	(Shikwambana et al., 2020	2020	South Africa	The Mpumalanga, Gauteng and Limpopo provinces	The 39 year (1980–2019) trends of SO_2, NO_2 and SO_4	TROPOMI	Dispersion of SO_2 and NO_2 over South Africa were observed in the winter months, while confined SO_2 and NO_2 in the source region were observed in the summer months.	None	Siloed	Natural Science
24	(Bencherif et al., 2020)	2020	South Africa	Irene Station (one of the most ancient ozone-observing stations in the southern tropics)	Tropospheric ozone (ground-based and satellite observations)	Dispersion of SO_2 and NO_2 over South Africa were observed in the winter months, while confined SO_2 and NO_2 in the source region were observed in the summer months.	The results presented here indicated that the slowing down of the total ozone decline is somewhat due to the contribution of the tropospheric ozone concentration.	None	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
25	(Haddout & Priya, 2020)	2020	Morocco	Casablanca and Rabat	NO_2	OMI	The primary source for the contribution of troposphere NO_2 in Casablanca city was vehicular transport, and a complete lockdown resulted in a significant reduction in NO_2 concentration. As Rabat city was not that developed in terms of vehicular load than Casablanca city, the reduction in NO_2 concentration was marginal.	None	Siloed	Natural Science
26	(Stavrakou, Müller, Bauwens, Boersma, & van Geffen, 2020)	2020	Global		NO_2	OMI and TROPOMI	Sunday minima are also unambiguously common throughout Southern America and South Africa, and are even detected at cities in South Asia and Africa.	None	Siloed	Natural Science
27	(Nyasulu, Haque, Boiyo, Kumar, & Zhang, 2020)	2020	Malawi		AOD between 2008-2017	MODIS	The findings may be useful to better understand the sources and climatic effects of atmospheric aerosols in southeast Africa.	None	Siloed	Natural Science
28	(Garland et al., 2020)	2020	South Africa	The Highveld region	NO_2	TROPOMI and ground-based stations together with a 3D chemical transport model (CAMx)	Initial results show decreases in NO in April, with levels increasing from May.	None	Siloed	Natural Science
29	(Hammer et al., 2020)	2020	Glonal		$PM_{2.5}$ AOD from 1998–2018 & ground monitoring	MODIS, MISR, SeaWiFS	We develop global estimates of annual $PM_{2.5}$ concentrations and trends for 1998–2018 using advances in satellite observations, chemical transport modelling, and ground-based monitoring.	None	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
30	(Dasgupta et al., 2020)	2020	Tanzania	Dar es Salaam	PM_{10}; NO_2	TROPOMI	This paper uses satellite images to investigate the spatial dynamics of vehicle traffic, air pollution, and exposure of vulnerable residents in the Dar es Salaam metro region of Tanzania. The research identifies core areas where congestion reduction would yield the greatest exposure reduction for children and the elderly in poor households.	Yes. Research on AQ impact on the marginalised population. Vulnerable population: children and the elderly in poor households	Interdisciplinary	Natural science Social science
31	(Swartz et al., 2020)	2020	South Africa		SO_2, NO_2 and O_3 long-term trends based on 21-, 19- and 16-year passive sampling datasets available	MODIS	Statistical modelling of long-term trends of atmospheric inorganic gaseous species within proximity of the pollution hotspot in South Africa.	None	Siloed	Natural Science
32	(Adon et al., 2020)	2020	Côte d'Ivoire and Benin	Abidjan and Cotonou	$PM_{2.5}$	MODIS	This study constitutes an original database that characterizes specific African combustion sources.	None	Siloed	Natural Science
33	(Matandirotya & Burger, 2021)	2021	Southern Africa Region	Gaborone, Harare, Johannesburg and Maputo	NO_2	AURA OMI complemented by the HYSPLIT Model-NCEP/NCAR Reanalysis and GEOS-5 Model-MERRA 2	The study highlighted the phenomenon of transboundary air pollution over Southern Africa cities and brought to foe the need to adopt a uniform Southern Africa policy and guidelines on air quality management.	None	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
34	(Opio, Mugume, & Nakatumba-Nabende, 2021)	2021	The East African region		Nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and carbon monoxide (CO)	OMI (NO_2, SO_2) TROPOMI (NO_2, SO_2, CO)	Seasonal fires in the savanna woodlands were identified as the major source of NO2 and CO over the region, while cities such as Kampala, Nairobi, and Bujumbura and towns such as Dar es Salaam and Mombasa were identified as important NO2 hotspots. The active volcano at Mt. Nyiragongo near Goma was identified as the most important SO_2 hotspot.	None	Siloed	Natural Science
35	(Shikwambana, Ncipha, Sangeetha, Sivakumar, & Mhangara,	2021	South Africa	The Mpumalanga and KwaZulu Natal provinces	Number of pollutants, including BC, SO_2, and carbon dioxide (CO_2)	Various data sources and products, including satellite, reanalysis, and model data. That included the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)	Climatic conditions, such as warm temperature, high wind speed, dry conditions favour the intensity and spread of the fire, which is controlled. The emitted pollutants are transported to neighbouring countries and can travel over the Atlantic Ocean, as far as ~6600 km from the source site.			
36	(Tunde Ogbemi Etchie, Etchie, Jauro, Pinker, & Swaminathan (2021)	2021	Nigeria		AOD between 2001–2020	MODIS	Impact analysis using multiple linear regression revealed that favourable meteorological conditions due to seasonal change in temperature, relative humidity, planetary boundary layer height, wind speed and rainfall improved air quality during the lockdown.	None	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
37	(McFarlane et al., 2021)	2021	Democratic Republic of the Congo (DRC) and Republic of the Congo (ROC)	Kinshasa Brazzaville	$PM_{2.5}$ low-cost sensors & AOD	MODIS	The surface $PM_{2.5}$ level and the aerosol optical depth were about 40% lower during the COVID-19 lockdown in 2020 than the corresponding period in 2019, which cannot be attributed solely to changes in meteorology or wildfire emission. Hence, our results highlight the need to implement clean air solutions in the Congo.	None	Siloed	Natural Science
38	(Abulude, Damodharan, Acha, Adamu, & Arifalo, 2021)	2021	Nigeria	Lagos State	$PM_{2.5}$, PM_{10}, NO_2, CO, SO_2, and O_3 & low-cost sensors	Satellite data obtained from Air Matters and Air-quality.com (powered by Air Affairs) – a low-cost real-time, citizen-based PM sensor network	The pollutants were much higher than the World Health Organization (WHO) guidelines.	None	Siloed	Natural Science
39	(Wei et al., 2021)	2021	Africa		$PM_{2.5}$ between 2000-2018	The Atmospheric Composition Analysis Group (ACAG) provided the $PM_{2.5}$ concentrations from the African satellite	Given the differential impact of multi-dimensional urbanization on $PM_{2.5}$ concentrations inside and outside the region, this research provides support for the cross-regional joint control strategies of air pollution in Africa.	Indirect – urbanisation	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
40	(Kganyago & Shikwambana, 2021)	2021	Sub-Saharan Africa		Black Carbon (BC), smoke+polluted dust AOD, and Carbon monoxide (CO), as well as the burned area (BA) and fire density	MERRA-2 (BC), TROPOMI (CO), CALIPSO (smoke+-polluted dust AOD); MODIS (Burned Area, AED, Fire location), PROBA-V (land cover)	Generally, the results indicated an increase in emissions (CO, BC, smoke+-polluted dust AOD) due to COVID-19 lockdown. The increasing biomass burning emissions, as shown here, have important implications for air quality and public health.	None	Siloed	Natural Science
41	(Hickman, Andela, Tsigaridis, Galy-Lacaux, Ossohou, Dammers, et al., 2021)	2021	Africa		NO_2 between 2005-2017 and Ammonia (NH_3) between 2008-2017	OMI (NO_2) and the Infrared Atmospheric Sounding Interferometer (NH_3)	Regional variances were identified.	None	Siloed	Natural Science
42	(Hickman, Andela, Dammers, et al., 2021)	2021	African Regions		Atmospheric ammonia (NH_3) between 2008 through 2018	The Infrared Atmospheric Sounding Interferometer	Fertilizer use in Africa is currently low but growing; implementing practices that can limit NH_3 losses from fertilizer as agriculture is intensified may help mitigate impacts on health and ecosystems.	None	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
43	(Nyasulu et al., 2021)	2021	Malawi		Carbon dioxide (CO_2) and Methane (CH_4) between 2004–2016	Atmospheric Infrared Sounding (AIRS)	The major sinks of tropospheric CO_2 and CH_4 observed from the present study are precipitation and vegetation.	None	Siloed	Natural Science
44	(Buchholz et al., 2021)	2021	Global		CO and AOD	MOPITT (CO) and MODIS (AOD)	Local changes in biomass burning are sufficiently strong to counteract the global downward trend in atmospheric CO, particularly in late summer.	None	Siloed	Natural Sciene
45	(Bakayoko et al., 2021)	2021	East Africa	The Lake Victoria catchment	NH_3 and NO_2	The Atmospheric Infrared Sounding Interferometer (IASI) (for NH_3) and IMO (NO_2)	An extensive and regular monitoring of wet and dry nitrogen deposition is highly recommended both in-shore and off-shore to help improving the efficiency of nitrogen use in agricultural areas and reduce nitrogen losses around Lake Victoria.	None	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
46	(Angom, Angiro, & Omara, 2021)	2021	Kenya and Uganda	Nairobi and Kampala	Nitrogen dioxide (NO_2)	OMI	It is concluded that although there were substantial reductions in air pollution during 2020 (particularly the COVID-19 lockdown periods) in Kampala and Nairobi, these are not sustainable and deterioration of air quality after lifting of the re- strictions has started to occur. Therefore, legislative actions need to be upheld to maintain air quality within the recommended levels.	None	Siloed	Natural Science
47	(Hakkarainen et al., 2021)	2021	South Africa	Near the Matimba coal-fired power station	Nitrogen oxides (NOx) to carbon dioxide (CO_2)	TROPOMI and Orbiting Carbon Observatory-2 (OCO-2) observations.	The proposed method will also work ideally for new and upcoming satellite observations systems such as OCO-3, CO2M and GOSAT-GW.	None	Siloed	Natural Science
48	Van Der Velde et al., 2021)	2021	Global (incl. South Africa)		XNO_2 and XCO	TROPOMI	The findings indicate that deforestation fires to cause a 1.5 to 2 times larger increase in ΔXCO relative to ΔXNO_2 than the savanna fires, mainly because these fires reflect a larger fraction of surface smoldering combustion.	None	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
49	(Bachwenkizi et al., 2021)	2021	15 African countries		$PM_{2.5}$ for mass and a chemical transport model (GEOS-Chem) for its six constituents, including organic matter (OM), black carbon (BC), sulphate ($SO_{42}-$), nitrate (NO_3-), ammonium (NH_4+), and soil dust (DUST).	Estimates from (Van Donkelaar et al., 2016)	The carbonaceous fractions and sulfate play a major important role among $PM_{2.5}$ constituents on infant mortality. Our findings have certain policy implications for implementing effective measures for targeted reduction in specific sources (fossil fuel combustion and biomass burning) of $PM_{2.5}$ constituents against the risk of infant mortality.	Indirectly. AQ and infant mortality Vulnerable population: new-borns.	Inter-disciplinary A multi-country cross-sectional study based on the Demographic and Health Surveys in Africa.	Natural science Social science Health
50	(Hickman, Andela, Tsigaridis, Galy-Lacaux, Ossohou, & Bauer, 2021)	2021	North equatorial Africa		NO_2	OMI MODSIS	In contrast to the traditional notion that socioeconomic development increases air pollutant concentrations in low- and middle-income nations, our results suggest that countries in Africa's northern biomass-burning region are following a different pathway during the fire season, resulting in potential air quality benefits. How-ever, these benefits may be lost with increasing fossil fuel use and are absent during the rainy season.	Yes. Link between socioeconomic development and air pollution.	Inter-disciplinary	Natural science Social science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
51	(Fisher et al., 2021)	2021	Africa, with a particular focus on Ethiopia, Ghana, and Rwanda		Unspecified	Unspecified	Ambient air pollution is increasing across Africa. In the absence of deliberate intervention, it will increase morbidity and mortality, diminish economic productivity, impair human capital formation, and undercut development. Because most African countries are still early in development, they have opportunities to transition rapidly to wind and solar energy, avoiding a reliance on fossil fuel-based economies and minimising pollution.	Indirectly. AQ impacts on health, the economy, and human capital.	Interdisciplinary Data on household and ambient air pollution were from WHO Global Health Observatory, and data on morbidity and mortality were from the 2019 Global Burden of Disease Study.	Natural science Social science Health
52	(Hereher, Eissa, Alqasemi, & El Kenawy, 2022)	2022	Egypt	Greater Cairo	The seasonal variations of the nocturnal surface urban heat island intensity (SUHII) and the related seasonal distribution of NO_2, SO_2, and CO for the period from 2018 to 2021.	MODICS (SUHII) and TROPOMI (NO_2, SO_2, and CO)	The highest SUHII is observed during winter. Results of this study demonstrate the significance of geospatial technology tools in the subtle analysis and addressing regional air pollution. The outputs are also of a paramount implication on the management of urban environment and the adaptation of urban air quality.	None	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
53	(Shikwambana et al., 2022)	2022	South Africa		Methane (CH_4)	TROPOMI and the Atmospheric Infrared Sounder (AIRS)	Agricultural activities, i.e., involving livestock, are the greatest emitters of CH_4 in South Africa, followed by landfill sites. Efforts need to be made to drastically reduce emissions to fulfil its global commitments.	Indirect. Livestock	Interdisciplinary. Use of the livestock data.	Natural science
54	Kirago, Gatari, Gustafsson, & Andersson, 2022)	2022	Kenya	Nairobi	Black carbon	MODIS	Fossil fuel combustion emissions are a dominant source of black carbon throughout the year (85 ± 3%). Taken together, this indicates that black carbon emissions from traffic are a key stressor for air quality in Nairobi.	None	Siloed	Natural Science
55	(Musonda, Jing, Nyasulu, & Libanda, 2022)	2022	Zambia		AOD between 2000 and 2020	MODIS (2000–2020) and Aerosol Robotic Network (AERONET) data for 2001–2009	These findings may help enhance a better understanding of climatic effects and atmospheric aerosol sources in Zambia.	None	Siloed	Natural Science
56	Nyasulu, Haque, Musonda, & Fang, 2022)	2022	Southeast Africa		AOD between 2002 and 2020	MODIS	Regional open burning of biomass like bush fires and burning of crop residues during the dry months are the main sources of aerosol concentration.	None	Siloed	Natural Science
57	(Khamala, Makokha, Boiyo, & Kumar, 2022)	2022	East Africa		AOD	MERRA-2 and MODIS	The study domain exhibited decreasing trends in SSA, signifying strong absorption of direct solar radiation resulting in a warming effect.	None	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
58	(Makokha, Makokha, & Kelonye, 2022)	2022	Kenya	Nairobi, Malindi and Mbita	Cloud Physical Properties	MERRA-2 and MODIS	The study revealed patterns of trends in physical cloud properties and formed a basis for further research on clouds over Kenya.	None	Siloed	Natural Science
59	(Khamala, Makokha, & Boiyo, 2022)	2022	East Africa		AOD	MODIS, OMI and MERRA-2	ARIMA model ascertained can be applied to other fields of study such as climatology, and climate change among other areas to predict future values so that timely control measures can effectively be planned.	None	Siloed	Natural Science
60	(Jury & Buthelezi, 2022)	2022	South Africa	Durban	CO, NO_2, O_3, $PM_{2.5}$ and SO_2	MERRA-2, AIRS, MODIS and OMI	Statistical outcomes enable the short- and long-range prediction of atmospheric dispersion and risk of exposure to unhealthy trace gases and particulates.			

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
61	(Clarke et al., 2022)	2022	Uganda		$PM_{2.5}$	Atmospheric Composition Analysis Group's (ACAG, global $PM_{2.5}$ estimates. The ACAG used combined: AOD data from MODIS. Satellite observations were then calibrated to global ground-based observations of $PM_{2.5}$ using data from the World Health Organization (WHO) with geographically weighted regression.	Developed approach identified areas facing both high social vulnerability and air pollution levels. These areas can be prioritized for health interventions and policy to reduce the impact of ambient $PM_{2.5}$.	Yes, social vulnerability indices (SVIs) are calculated to determine where vulnerable populations are located. Vulnerable populations include children, the elderly, and those of lower socioeconomic status. The difference is made between social vulnerability and biophysical vulnerability.	Interdisciplinary. Use of census data about the population.	Natural science Social science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
62	(Mitra et al., 2022)	2022	The Red Sea		Carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and ozone (O_3)	TROPOMI and MODIS	This showed a relationship between meteorological data and CO and O_3. Although the satellite observations have some inherent limitations compared to in-situ measurements, this study provides an overall landscape of air pollution over the Red Sea, which will benefit policy-makers and researchers.	None	Siloed	Natural Science
63	Tahri, Benchrif, & Zahry, 2022)	2022	North Africa		$PM_{2.5}$ and PM_{10}	EDGAR	For $PM_{2.5}$, the major emitter sector in North Africa, during the same period, was also buildings with 38.2%, followed by transport (21.5%), other industrial combustion (17.3%), other sectors (12.4%), power industry (6%), agriculture (4.5%), and waste (0.2%).	None	Siloed	Natural Science
64	(Atuhaire, Gidudu, Bainomugisha, & Mazimwe, 2022)	2022	Uganda	Kampala	$PM_{2.5}$ and AOD	Satellite images (Sentinel-2 and Landsat-8)	Sentinel-2 data produced better predictions, signifying that increasing the spatial resolution can improve satellite-derived PM2.5 estimations. It is concluded that vehicle exhaust emissions could be the main sources of $PM_{2.5}$	None	Siloed	Natural Science
65	(Rey-Pommier et al., 2022)	2022	Egypt	Riyadh	NO_2	TROPOMI	We detect lower emissions on Fridays, which are inherent to the social norm of the country, and quantify the drop in emissions in 2020 due to the COVID-19 pandemic.	None	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
66	(Bouhachlaf et al., 2022)	2022	Morocco		Ozone and NO_2	OMI (ozon) and TROPOMI (NO2)	Traffic restrictions applied during the quarantine for COVID-19 pandemic in Morocco were remarkably convincing in reducing emissions of NOx. This reduction in ozone precursors reduces ozone.	None	Siloed	Natural Science
67	(Bachwenkizi et al., 2022)	2022	15 African countries		$PM_{2.5}$	Estimates from (Hammer et al., 2020)	We assessed the associations between maternal $PM_{2.5}$ exposure and low birth weight (LBW) and preterm birth (PTB) in Africa. This multicounty study in Africa demonstrated significant associations between maternal exposure to $PM_{2.5}$ and higher odds of LBW and PTB. Our findings may facilitate air quality control strategies that address adverse birth outcomes in LMICs.	Indirectly. AQ and low birth weight and preterm births. Vulnerable population: new-borns.	Interdisciplinary A multi-country cross-sectional study based on the Demographic and Health Surveys in Africa.	Natural science Social science Health
68	(Larson et al., 2022)	2022	Kenya		$PM_{2.5}$ AOD	MODIS MISR	This research uses georeferenced Demographic Health Survey (DHS) data from Kenya (2014) along with a remote sensing based raster of $PM_{2.5}$ concentrations to test associations between $PM_{2.5}$ exposure and acute respiratory infections (ARIs) symptoms in children for up to 12 monthly lags. Long-term exposure to high concentrations of $PM_{2.5}$ may increase risk for acute respiratory problems in small children. However, more work should be carried out to increase capacity to accurately measure air pollutants in emerging economies such as Kenya.	Indirectly. AQ and ARIs in small children. Vulnerable population: children for up to 12 monthly	Interdisciplinary A multi-country cross-sectional study based on the Demographic and Health Surveys in Africa.	Interdisciplinary A multi-country cross-sectional study based on the Demographic and Health Surveys in Africa.

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
69	(Awe et al., 2022)	2022	LMIC, including Ghana, Ethiopia, Senegal and Uganda	Accra, Addis Ababa, Dakar, Kampala	$PM_{2.5}$ (AOD)	MODIS	The goal of this report is to investigate if satellite observations could be used to improve $PM_{2.5}$ monitoring in LMICs and, if so, to identify pathways for LMICs to incorporate satellite data into their daily, city-scale $PM_{2.5}$ monitoring. This report shows that satellites are unreliable for estimating ambient concentrations of $PM_{2.5}$ in low- and middle-income countries (LMICs). Furthermore, satellite-derived measurements cannot replace properly operated and maintained ground-level monitoring networks for measuring the concentrations of $PM_{2.5}$ that human beings are typically exposed to daily.	None	Siloed	Natural Science
70	(Anenberg et al., 2022) Anenberg et al	2022	Global		NO_2	OMI (2005-2019)	We show that urban areas have higher NO_2 concentrations and disease burdens compared with rural areas. The proportion of paediatric asthma incidence that is attributable to NO2 declined in the high-income countries, Latin America and the Caribbean, and central Europe, eastern Europe, and central Asia from 2000 to 2019, and increased in the rest of the world, particularly in south Asia and sub-Saharan Africa. The study also shows the usefulness of satellite remote sensing for environmental and public health surveillance in urban areas worldwide.	Indirectly Via paediatric asthma incidence research. Vulnerable population: children	Interdisciplinary	Health

	Author/year	Year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
71	(Yombo Phaka et al., 2023)	2023	DR Congo	Kinshasa	Ground-based observations of NO_2 and H_2CO tropospheric vertical column densities	TROPOMI	The study further reveals the pronounced pollution levels of NO_2 , H_2CO and aerosols in both the city of Kinshasa and its adjacent regions, underscoring the imperative for consistent monitoring and effective regulatory measures by local authorities.	None	Siloed	Natural Science
72	(Opio, Mugume, Nakatumba-Nabende, & Mbogga, 2023)	2023	DC Congo	Mount Nyiragongo	SO_2	OMI	This study demonstrates the advantage that deep learning can provide in estimating volcanic SO_2 emissions.	None	Siloed	Natural Science
73	(Mokgoja, Mhangara, & Shikwambana, 2023)	2023	South Africa	Durban	CO, SO_2, and NO_2	TROPOMI, AIRS, OMI, and MERRA-2 Data	There was an inverse relationship between the trends of all investigated gases and the COVID-19 lockdown restrictions.	None	Siloed	Natural Science
74	(Mahmud et al., 2023)	2023	Nigeria	Aba, Benin, Ibadan, Kaduna, Kano, Lagos, Onitsha, Port Harcourt, and Umuahia	Nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), and Aerosol Index (AI) & night time light radiance	TROPOMI and NASA's Giovanni website (an online open-source tool for exploring, visualizing, and analysing NASA Earth Science data)	Associating the level of pollution with socioeconomic activities, especially during the absence of permanent air quality stations.	None	An attempt for interdisciplinarity via the use of night time light radiance to assess socioeconomic activities in the night time.	

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
75	(Ossohou et al., 2023)	2023	Africa		NH_3 between 1998-2018	The Infrared Atmospheric Sounding Interferometer	air temperature, leaf area index, and rainfall combined with biomass burning, agricultural, and residential activities are the key drivers of atmospheric NH_3 studies under review.	None	Siloed	Natural Science
76	(Merdji, Xu, Lu, Habtemicheal, & Li, 2023)	2023	North Africa		AOD	MODIS and Aerosol Robotic Network (AERONET)	The seasonal mean AOD was highest in summer, while the lowest was in winter due to very high easterly and north-easterly Harmattan surface wind.	None	Siloed	Natural Science
77	(Elshora, 2023)	2023	Egypy	Qena		MODIS and Aerosol Robotic Network (AERONET)	This study recommends necessary improvements regarding the aerosol model selection and the surface reflectance calculations.	None	Siloed	Natural Science
78	(Li et al., 2023)	2023	Sub-Saharan Africa		UVAI between 2010 to 2021	OMI	Air pollution in the region is closely related to climate change; moreover, the strengthening of composite studies in regard of air pollution and climate change will be the main work to be conducted in the future.	None	Siloed	Natural Science
79	(Khamala, Makokha, Boiyo, & Kumar, 2023)	2023	East Africa		AOD between 2001-2018	Aerosol Robotic Network (AERONET) and MERRA-2	The study contributed to understanding aerosol absorption and radiative characteristics over EA and can form the basis of other related studies over the domain and beyond.	None	Siloed	Social Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
80	(Kalisa et al., 2023)	2023	Africa		$PM_{2.5}$ and PM_{10} between 1990-2019 and Indoor and outdoor $PM_{2.5}$ from the literature review	Retrieved from the State of Global Air 2019 Report (Institute for Health Metrics and Evaluation, 2019)	The findings showed that schoolchildren in Africa are frequently exposed to $PM_{2.5}$ and PM_{10} levels exceeding the recommended World Health Organization air quality guidelines. More air quality measurements in schools and intervention studies are needed to protect schoolchildren's health and reduce exposure to air pollution in classrooms across Africa.	Yes, exposure to indoor and outdoor air pollution in schools in Africa. Vulnerable population: school children	Interdisciplinary: literature review and processed AQ data	Social Science
81	(Hakkarainen et al., 2023)	2023	South Africa	Highveld region	CO_2 and NO_2	Orbiting Carbon Observatory-3 (OCO-3) for carbon dioxide (CO_2), and TROPOMI for nitrogen dioxide (NO_2) observations	Overall, the satellite-based emission estimates are in good agreement (within the uncertainties) as compared to emission inventories, even for the cases where several plumes are mixed.	None	Siloed	Natural Science
82	(Cusworth et al., 2023)	2023	South Africa (and India)		Carbon dioxide (CO_2) & in situ stack emission observations	PRISMA and the Orbiting Carbon Observatory-3 (OCO-3)	Although an encouraging start, 2 years of observations from these satellites did not produce sufficient observations to estimate annual average emission rates within low (< 15%) uncertainties.	None	Siloed	Natural Science

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83	(Matandirotya & Burger, 2023)	2023	South Africa	Johannesburg, Durban and Cape Town	NO_2	OMI	The study also recorded that Cape Town and Durban were mainly influenced by long-range transport air masses originating from the South Atlantic Ocean, South America, Antarctica and the Indian Ocean particularly during the summer and autumn seasons possibly leading to the formation of marine nitrate aerosols.	None	Siloed	Natural Science
84	(Chen et al., 2023)	2023	Middle East and North Africa		Methane	TROPOMI	Decreasing methane intensities across the Middle East and North Africa to 0.2% would achieve a 90% decrease in oil–gas upstream emissions and a 26% decrease in total anthropogenic methane emissions in the region, making a significant contribution toward the Global Methane Pledge.	None	Siloed	Natural Science
85	(Nguyen, He, & Wooster, 2023)	2023	Africa		CO and AOD	TROPOMI	The methodology de- scribed in this work is forming the basis of a forthcoming near-real-time fire emissions product from Meteosat to be issued by the EUMETSAT LSA SAF.	None	Siloed	Natural Science
86	(Leguijt et al., 2023)	2023	Africa		CO	TROPOMI	Comparison of the TROPOMI-based emission estimates to the DACCIWA and EDGAR bottom-up inventories shows CO emission rates in northern Africa are underestimated in EDGAR, suggesting overestimated combustion efficiencies.	None	Siloed	Natural Science

	Author/year	year	Country/ Region	Detailed location	Pollutant measured	(Remote sensors) Data source	Key conclusion	Link to an ID lens	Approach	Science Domain
87	(United Nations Environment Programme, 2023b)	2023	South Africa		Carbon dioxide (CO_2), black carbon (BC), sulphur dioxide (SO_2), and carbon monoxide (CO) for the period from 1994 to 2019	The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2)	Emissions levels are generally correlated with economic growth. Therefore, a stringent regulatory system is needed to curtail the high emissions levels observed in this study, given the devastating impacts of global warming already ravaging the world.	Indirect Economic growth via the World Bank Indicators	Interdisciplinary	
88	(Ouma et al., 2024)	2024	Africa		$PM_{2.5}$ trends from 1980 to 2021 & compared with the climate factors, socio-economic indicators, and terrain characteristics	MERRA-2 reanalysis datasets comprising of sulphates (SO_4), organic carbon (OC), black carbon (BC), $Dust_{2.5}$ and Sea Salt ($SS_{2.5}$)	Socio-economically, highly populated, and bare/sparse vegetated areas showed higher $PM_{2.5}$ concentrations, while vegetated areas tended to have lower $PM_{2.5}$ concentrations. Northern and western Africa regions had the highest air quality index (AQI), while southern Africa had the lowest AQI. The approach and findings in this study can be used to complement the evaluation and management of air quality in Africa.	Indirect via socio-economic data	Interdisciplinary	

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