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Advancement in the Monitoring Techniques of Particulate Matter and Nitrogen Oxides in African States: A Systematic Review with Meta-Analysis

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ABSTRACT

Air quality monitoring is fundamental to mitigating the impacts of air pollution on human health and the environment. This ensures that air quality management is effective and that the potential negative effects on the environment and human health associated with poor air quality are understood and mitigated. Despite this, Africa continues to struggle with a lack of sufficient air pollution exposure data that can influence the understanding of air pollution status. The purpose of this research is to look at the progress made by African countries in developing monitoring techniques for pollutants such as particulate matter and nitrogen oxides in urban settings. The study conducted meta-analyses of studies that looked at technological advancements in monitoring PM and NOx exposure levels on the African continent. Every country in the African continent that has monitored both PM and NOx ambient pollutants was included in the review. Furthermore, in an attempt to include the most recent studies that monitored PM and NOx only ambient air quality studies published between 2010 to 2022 were eligible for inclusion in the current study. From eligible studies, authors, publication year, exposure characterization method, study setting, pollutants and technique used were extracted. Microsoft Excel 2019 was used for data analysis. To this end, the data was presented using graphs and numerical techniques. The results of this study show that 67% of African countries use fixed monitoring systems, which has a serious limitation. Whilst, on the other hand only 10% of the countries, geographically located within North Africa (Tunisia, and Algeria), and Southern Africa (South Africa) regions used the mixed monitoring techniques, such as active sampling and remote sensing. In conclusion, most African regions rarely conduct air quality exposure assessments that incorporate air quality modelling techniques.

1. INTRODUCTION

Air pollution is a scourge that is a distinguished pollutant in Africa by surpassing all other forms of environmental pollution [1, 2]. As a result, in most African cities air quality has deteriorated due to rapid population growth, urbanization, increased vehicle ownership, industrial development, as well as the massive use of solid fuels and poor waste management practices [3, 4]. Somvanshi et al. [5] corroborate that most cities are prone to excessive air pollution levels due to industrialization, uncontrolled growth of population and increased dependence on motor vehicles. Due to the excessive air pollution concentrations discharged into the atmosphere, ambient air pollution is accountable for 176,000 deaths and 626,000 Disability Adjusted Life Years in the African regions. It is for this reason that recently air pollution has been declared the greatest environmental risk to human health [6]. Engendering a wide range of adverse health effects affecting both the respiratory and the cardio-vascular systems [7]. So much so that the detrimental impacts on human physiological function have been said to outweigh the effects of water pollution and child malnutrition in Africa [8]. Consequently, to mitigate the impacts of air pollution on human health and the environment governments across the globe have agreed on the importance of air quality monitoring [9].

However, despite the public health risks associated with air pollution exposure, many African countries lack air pollution exposure data. Even though most developing countries have been reported to be at risk of high exposure levels of air quality exceeding WHO guidelines, but still the lack of sufficient air pollution exposure data that can influence the understanding of air pollution status is a continuous struggle [10-12]. Moreover, appropriate monitoring and maintaining ambient air quality at levels as prescribed by WHO is one of the many greatest challenges that confront the African continent [13]. The lack of air pollution exposure data as corroborated by multiple scholars due to the absence of sufficient monitoring can negatively influence the comprehensive understanding of air pollution status and the estimation of subsequent impacts [3, 10, 11]. The lack of data limits understanding of pollution exposure levels and the health risks associated thereof. Especially within densely populated cities where high emissions of air pollutants are linked with anthropogenic activities.

It is for this reason that developed countries across the globe, have unequivocally engaged in techniques that promote exposure monitoring of air pollutants. For example, in well-developed countries network of air quality monitors is usually used to collect continuous data on the most important air pollutants in urban areas [14]. This practice presents developed nations with air quality data that contribute to the understanding of air pollution exposure and the possible potential health risks. Given that monitoring of air pollution is fundamental in the process of ensuring compliance with prescribed air quality standards that seek to mitigate the risks of exposure. Therefore, exposure monitoring efforts allow for the protection of human health and the environment as suggested by Yi et al. [9]. Furthermore, it ensures that the management of air quality is effective and the potential negative impacts on the environment and human health linked to poor air quality are understood and mitigated [15]. Central to the practice of air quality monitoring is the World Health Organization which encourages countries to monitor exposure to risks of air pollutants with the prospects of compromising human health.

To this end, various measurement methods for assessing exposure to air pollution have been developed [16]. However, the most traditional approach to measuring exposure to air quality has always been characterized by the employment of overpriced complex stationary equipment. This approach makes use of fixed monitoring stations capable of collecting regulatory pollutants, such as nitrogen oxides (NO_x, NO, NO_2) and particulate matter (PM_{10}, $PM_{2.5}$) amongst others have been internationally recognized as environmental priority air pollutants since they can constitute threat to human health and the environment [17, 18]. These methods are deemed to be expensive as they range between €5,000 and €30,000 [18]. This has subsequently influenced the ability to conduct exposure assessments of air pollution. Thus, favouring the developed countries in contrast to developing nations which are mostly located in Sub-Saharan Africa. It is for this reason that developed countries such as the United States, Canada and China have been able to investigate and characterize air pollution exposure levels with ease [19, 20].

However, for Africa, the lack of financial muscle is at the centre of the lack of air pollution exposure data as stated by Forbes [21]. The exorbitant tag prices associated with the installation and maintenance of fixed monitoring stations could be a deterrent for developing countries to effectively conduct air quality exposure [18]. More recently there has been technological development and the advent of the 4th industrial revolution. Thus, there have been multiple ways of monitoring exposure to air pollution. Kumar et al. [22] attribute the evolution of monitoring air quality to technological development that has positively impacted the air quality management space. Since the conventional fixed monitoring technique is characterized by inherent limitations such as the inability to capture the spatial variability of pollutants. Jiao et al. [23] corroborate that technological advancements in air pollution equipment fitted with a sensor have simplified the monitoring of ambient air pollution. Therefore, 'the deployment of a large number of sensors across a small geographic area would have potential benefits to supplement traditional monitoring networks with additional geographic and temporal measurement resolution'. Thus, improving the measurement of the spatial distribution of air quality. Forbes [15] corroborates that indeed exposure scientists are constantly investigating novel alternatives to existing analytical methods, which may offer advantages in terms of parameters such as cost, speed, selectivity, sensitivity, portability and accuracy towards pollutants monitoring. To this effect, it is evident that most countries have moved ahead with the times thus maximizing technology to monitor air pollution exposure whilst most African states still battle with air pollution monitoring [24]. This study aims to examine the advancement made by African countries in the development of monitoring techniques for pollutants such as particulate matter and nitrogen oxides in urban settings.

2. MATERIALS AND METHODS

2.1 Search strategy

This paper used secondary data from the existing literature across the African continent, which strictly included peer-reviewed and published journal articles to developing a metanalysis approach for African monitoring techniques. During the literature search, English peer-reviewed articles and relevant reports were examined. Information for the evaluation and appraisal was collected from extensive project reports, published papers and websites. Therefore, Scientific databases such as Google Scholar, Sematic scholar, Sage and Research Gate are search engines that were primarily used to conduct electronic searches. Thematic search terms such as (a) Ambient air pollution, (b) PM and NOx air quality monitoring techniques, (c) air quality concentrations and (d) PM and NO_x air pollution are variables that were used to narrow down the search of literature within the relevant scope of air quality within the African continent. These thematic searches were performed in five regions that make up the African continent (North Africa, Southern Africa, Western Africa, East Africa and Central Africa). Every country in the African continent that has monitored both PM and NOx ambient pollutants was included in the review. Furthermore, in an attempt to include the most recent studies that monitored PM and NO_x only ambient air quality studies published between 2010 and 2022 were eligible for the current study. Mkwanazi et al. [25] suggest that in cases where articles are inaccessible from scientific databases, other sources, such as the general Google search engine should be used. To this end, the current study followed this suggestion. To cover a wide range of articles from different regions across the continent, additional searches were sourced through the reference lists of key articles as standard practice illustrated by Mkwanazi et al. [25]. This assisted to access several relevant articles and reports related to the topic a second search was conducted. This second search incorporated the use of snowball methodology from the appropriate list of references generated in the first search. Limitations of the literature search methods included the search for related academic papers written in English.

2.2 Data extraction

From eligible studies, authors, publication year, exposure characterization method, study setting, pollutants and technique used were extracted. Two authors extracted data independently for each study, and a third author resolved conflicts between them. Attempts were made to obtain raw data by contacting original authors in the case of studies with insufficient data for pooling [26]. Study quality was evaluated based on design, exposure characterization and covariate adjustment, and sensitivity analyses were performed where possible based on these factors. The two investigators checked and verified all the data extraction and eligibility assessments. In the event of disagreement, a third reviewer was asked to weigh in.

2.3 Data analysis

Microsoft Excel 2019 was used for data analysis. To this end, the data was presented using graphs and numerical techniques. For analysis intents, all the data of the monitoring techniques that formed part of the study were categorized according to five regions (Southern African, North Africa, East, West and Central Africa). Subsequently, the studied monitoring techniques applied within the African continent that measure exposure to PM and NOx were each assigned to their geographical regions. This facilitated the generation of graphs and numerical values.

3. RATIONALE BEHIND THE SELECTION OF PM AND NOX POLLUTANTS IN MONITORING AIR QUALITY

3.1 Nitrogen oxide

The family of (NO_x) is made up of Nitric oxide (NO) and Nitrogen dioxide (NO_2) composite gases. Nitrogen oxides form part of the highly reactive gases of the nitrogen oxides (NO_x) family. Thus, they are renowned as strong oxidizing agents. Nitrogen gas is described as reddish brown and very reactive in the atmosphere coupled with a pungent suffocating smell. While nitric oxide is described as a colourless and odourless gas [27]. Multiple scholars concur that (NO_x) is a by-product of high-temperature fuel combustion that in the process converts rapidly into Nitrogen dioxide (NO_2) [28, 29]. Primary NO_x gases are associated with combusting fuel at high temperatures, emissions from the metallurgical furnace, blast furnace and vehicle emissions [30]. Characterizing nitrogen oxides, Aamster et al. [31] and Erickson et al. [32] states that nitrogen oxides are highly reactive gases capable of irritating the respiratory system of human beings. To this end, a correlation between the number of hospital admissions and high concentrations of nitrogen oxides in the atmosphere has been observed. The epidemiological studies present that during high traffic-related emissions asthma morbidity cases are usually reported [33, 34]. Because in urban neighbourhoods' high atmospheric concentrations of nitrogen oxides emanate from vehicle traffic [35].

Furthermore, nitrogen oxide pollutants are precursors for other pollutants such as Ozone (O_3) in the atmosphere. It is for this reason that in most cases nitric oxide and nitrogen dioxide are classified within the same spectrum of (NO_x) gases. In the atmosphere, NO emissions substantially interconvert into NO_2 [36, 37]. That is, nitrogen oxide is oxidized into nitrogen dioxide [38]. Sources of NO_X are thought to be both primary and secondary pollutants in nature. Primary pollutant emanates directly from emission sources, while secondary pollutants are formed during chemical reactions in the atmosphere [27].

3.2 Particulate matter

Particulate Matter (PM_{10}, $PM_{2.5}$) is the most abundant air pollutant comprising a mixture of particles from natural and anthropogenic sources [39]. Its abundance in the atmosphere in contrast to gases has to do with its sources of exposure. Because even in the absence of anthropogenic sources PM pollution can occur naturally [13]. Ukaogo et al. [40] avow that a vast amount of PM pollutants are released into the atmosphere each year from a variety of natural sources. These vast numbers of particulates contain both liquid and solid constituents. Even the NO_x pollutants do contribute to the formation of PM. PM can be synthesized when gaseous pollutants such as NOx are transformed in the atmosphere to form the fine size particulates [41].

To this end, the size of the particulates is important in determining the impact of the particulate matter on human health. Thus, particulate matter is categorized into two types: coarse particulates (2.5-10) and fine particles (<2.5). Coarse particles are PM_{10} particles with an aerodynamic diameter of 10 µm or less whilst fine particles are $PM_{2.5}$ particles with an aerodynamic diameter of 2.5 µm or less. Fine particles ($PM_{2.5}$) are considered to have a greater risk of causing human health effects in contrast to coarse particles (PM_{10}) due to their size [42]. Particulates are emitted by either natural or anthropogenic sources and could be emitted directly into the atmosphere as primary particles or could be formed by secondary processes. The most common natural sources of particulate matter are sea salt aerosols, bushfires, crustal dust, vegetation made up of pollen and fungal spores, volatile organic compounds (VOCs) and animal remains. Whilst the anthropogenic sources include the combustion of engines, power stations, mining, other industrial processes, agriculture and domestic heating appliances [43].

Furthermore, the distinction of sources between coarse particles and fine particles indicates that PM10 is emitted from biological particles, particles generated mechanically from agriculture, mining construction, road traffic and other related sources. While in contrast $PM_{2.5}$ include particles from motor vehicle combustion, burning coal, wood, fuel and dust from the road and soil [44]. The WHO Air Quality Guideline recommends a maximum annual mean concentration of 10 and 20 µg/m^3 for $PM_{2.5}$ and PM_{10} respectively and a maxi-mum daily 24-hour mean concentration for $PM_{2.5}$ and PM_{10} at 25 and 50 µg/m^3 respectively [45]

4. MONITORING TECHNIQUES TO DETECT PARTICULATE MATTER AND NITROGEN OXIDES POLLUTANTS IN AFRICA

The advancements in air quality monitoring technology have presented innovative possibilities for the management of air quality. As a result, the air pollution monitoring paradigm is rapidly changing due to recent developments for instance the creation of portable, less expensive air pollution sensors reporting data in near-real time at a high temporal resolution, improved computational and visualization capabilities and wireless communication/ infrastructure that embodies the advancement in technology [46]. In addition to the advanced technologies that have improved air pollution exposure monitoring are integrated approaches that focus on using satellite data, ground-based data and models combined with data assimilation [47]. These monitoring techniques have been a game changer in the field of air quality monitoring techniques as they provide air quality forecasts and improved characterization of surface-level air pollution in contrast to traditional monitoring techniques [48]. However, even though the application of these technological advancements simplifies monitoring, to date in the African continents there has not been much constant air quality monitoring of particulate matter and nitrogen oxides. Central to this according to Forbes et al. [21] is the lack of resources such as financial muscle, and skilled human capital, as well as the lack of political will.

These challenges holistically characterize the factors that impede constant air quality monitoring in many developing countries. Thus, the lack of resources influences the monitoring techniques that can be applied to measure exposure to air pollutants. For example, in the African context, the few African states (South Africa, Morocco, Egypt, Algeria and Tunisia) that constantly monitor exposure to PM and NOx make use of fixed monitoring stations [49-51]. However, because the fixed monitoring stations are expensive to install, maintain and operate most African states resort to passive and active sampling techniques [52]. In this respect, Cameroon and Ethiopia are good examples of countries with no government monitoring programs. Dust sentry and Air-test Model-CW-HAT2005 are portable instruments designed for continuous real-time monitoring of PM and NO_x, as well as a passive sampling of PM and NO_x [53, 54].

These measurement methods are employed as the main monitoring techniques due to their affordability and convenience. But the challenge with these monitoring techniques across the continent is that it characterizes monitoring which is employed in ad hoc air quality monitoring projects designed to last for a short term. While in well-developed continents such as Europe the application of passive and active sampling coupled with modelling techniques is used to supplement the continuous monitoring of PM and NO_x air pollutants [46] The context of monitoring PM and NO_x pollutants using modelling techniques is founded on the evolution of monitoring air quality that integrates the components of technology [22]. Most developed countries take advantage of these technological advancements to integrate for instance GIS models in air quality monitoring which conveniently facilitates obtaining air quality information directly from remotely sensed data [5]. This is useful and fundamental not only in the monitoring of PM and NO_x concentrations but in the characterization of these pollutants [55]. Even within the African continent, some of the modelling monitoring techniques that incorporate technological advancements have been applied, even though to a lesser degree. For example, in addition to their continuous monitoring systems (fixed monitoring stations), countries such as Algeria and South Africa are amongst the African countries that so far have mainly monitored and characterized PM and NOx using the modelling techniques [56, 57]. In Algeria, Belhout et al. [56] made use of The Air Pollution Model to alternate conventional methods that predict meteorology and air pollution concentrations of particulate matter and nitrogen oxides in the urban areas of Algiers city (Algeria).

Similarly, Tularam et al. [57] in South Africa (Durban) employed air pollution dispersion modelling and land-use regression modelling methods to describe the local scale variations of PM and NOx air pollution levels. These methods are advantageous because they provide spatially varying relationships between ground measurements and other factors that are helpful in the estimation of air quality [5]. In light of this, it is evident that within the African continent, the application of modelling is often predominantly witnessed and abundant within countries that are perceived and branded as upper-middle income economies. Because in most cases these countries have covered a lot of ground on infrastructure and technological advancement. Hence, the premise is that the socio-economic status of a state can influence the methods of monitoring air pollutants. It is for this reason that in the African continent in some regions exposure data for PM and NOx exists whilst in some other regions it is very scarce to almost non-existence [58].

5. REGULATORY FRAMEWORK OF PARTICULATE MATTER AND NITROGEN OXIDES

The air quality standards are significant for effective air quality management. These air quality standards are used to determine the maximum concentration levels of air pollution in the atmosphere. The air quality standards provide a guideline which assists to determine and indicate the difference between polluted and non-polluted atmospheres. Furthermore, these standards indicate what is a safe exposure level for public health and general welfare purposes. Higher concentrations measured against air quality standards are likely to affect public health and cause environmental pollution. These air quality standards and their resultant effects are based on scientific findings [59]. The World Health Organisation (WHO) is responsible for providing countries with scientific findings that serve as reference and guidance for developing air quality standards cognitive of health effects.

However, the challenge with WHO scientific guidelines is that they are generic in approach, and they do not consider individual economic status per country (Table 1). The primary aim of the air quality standards that constitute the legal framework for exposure threshold and limit is to provide a uniform basis for the protection of public health and the environment at large from the adverse effects of air pollution. According to WHO (2021) 'By reducing air pollution levels, countries can reduce the burden of disease from stroke, heart disease, lung cancer, and both chronic and acute respiratory diseases, including asthma'. To achieve this objective, the World Health Organization have developed the limits and threshold for pollutants of concern such as particulate matter and nitrogen oxide as presented in Table 1 below. However, recent studies have proven that adverse health effects due to exposure to air pollution can persist even below the safe recommended threshold and limits [60, 61].

Table 1. World Health Organisation air quality guidelines

Air quality standards			
Pollutant	**Averaging time**		**Reference**
$PM_{2.5}$ ($\mu g/m^3$)	Annual	5	[62]
	24-hour	15	
PM_{10} ($\mu g/m^3$)	Annual	15	[62]
	24-hour	45	
NO_2 ($\mu g/m^3$)	Annual	10	[62]
	24-hour	25	
	1-hour	200	

6. FINDINGS AND DISCUSSIONS

6.1 African monitored sources of PM and NO_x identified as major polluters of the atmosphere

Monitoring air quality helps the national and local governments to better understand the emissions sources of air pollutants. The lack of knowledge and understanding of the primary sources of pollution makes the compilation of emissions inventories which is a key input for predicting air pollutants through modelling very difficult. Figure 1 below presents the sources of PM and NO_x pollutants exposure across the five African regions as classified in this study. Figure 1 above presents the sources of air pollution across the five African regions. To be able to develop an effective air quality monitoring program, it is necessary to understand the sources of air pollution. This helps to discover and comprehend the most significant polluters in the neighbourhood. The composition of the major contributing sources of air pollution in the five African region's neighbourhoods mainly consists of vehicular traffic (16.43%), industrial areas sources (8.22%) and dust from unpaved roads (5.14%). Vehicular traffic emissions contribute to the significant anthropogenic discharge of air quality pollutants in the urban areas of developing countries [63, 64]. This is exacerbated by the need for economic development activities that rely on transportation and personal excessive use of private transport for the sake of convenience. Due to constrained transportation infrastructure in developing countries, Kim Oanh et al. [65] cautions against the risks of vehicle emissions pollution because of the increase in the number of vehicles fleet owned by individuals.

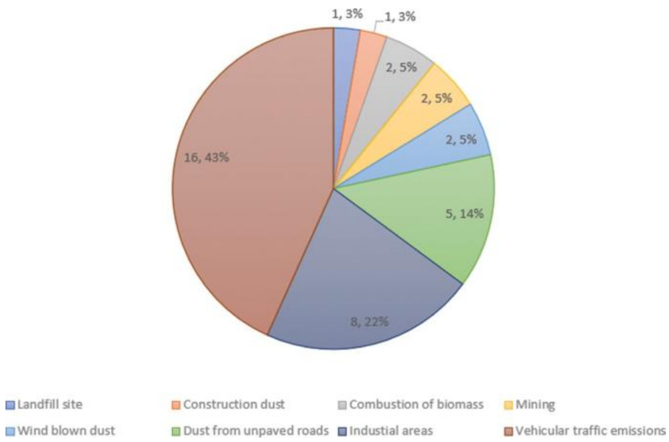

Figure 1. Sources of air pollution derived from African literature

Eventually, this coupled with the high traffic density increases the exposure concentration along the roadside. Following traffic emissions is the industrial emission that is regarded as the second largest pollutant of the atmosphere [66]. Industrial areas are associated with emissions of particulate matter and gases such as Nitrogen oxides [67]. Industrial emission is one of the global challenges responsible for the majority of pollution. Walton [68] expounds that the melting industry is responsible for the release of 99% of the total emissions of particles and gases. Thus, pollution generated by the industry is influenced by what product is manufactured in the process. For example, industries that manufacture glass and metals generate emissions such as CO, NO_x, SO_2 and PM. Furthermore, the combustion of various fuels used for production contributes to the level of VOCs produced and the release of heavy metals into the environment [69]. The majority of the industrial emissions are reported to emanate from metallurgical plants and smelters, chemical plants and petroleum refineries, cement production, fertilizers and synthetic rubber manufacturing, pulp and paper milling. Likewise, Fugitive dust from the unpaved particles released by traffic-generated turbulence contributes significantly to particulate matter pollution in the urban settings of developing countries.

These emissions present a risk to public health and air quality [70, 71]. These sources are greatly associated or linked with public health risks.

According to Gupta et al. [72], there appears to be a well-established link between transportation-related pollution exposure and public health concerns. This is because vehicles produce pollutants which can compromise human health and cause ecological damage [73]. Extensive epidemiological studies associate vehicular traffic emissions with adverse health effects such as cardiac symptoms, lung cancer and premature mortality [74-76]. While similarly to vehicular traffic emissions, studies focusing on the air pollution burden of disease indicate that exposure to industrial pollution is associated with cancer, respiratory disease and cardiopulmonary complications [77, 78]. Exposure to unpaved road dust road has adverse health effects on the respiratory system. According to numerous reports, these effects included asthma and respiratory carcinoma such as mesothelioma [79, 80].

Furthermore, continental comparisons suggest that these sources to some extent are like the sources of air pollution observed in Europe which are characterized by road transport exposure (37%) and stationary combustion which is non-residential (29%), except for the dust emanating from unpaved road given that Europe generally has advanced infrastructure in the form of sophisticated roads in contrast to the African continent [81]. However, incongruent with the air pollution sources from South America which suggest that the large part responsible for air pollution emanating from forest fires (37%), and vehicular traffic (21%) and the industry is accountable for 12% contribution [82]. Nevertheless, these sources are corroborated by the World Health Organisation [83]. According to WHO globally, the sources of air pollution comprise industries, households and transportation as the main contributing sources of ambient air pollution.

6.2 Techniques used in monitoring exposure levels of PM and NOx pollutants across the five African regions

The various monitoring techniques of air quality are influenced by several factors which are linked to financial capability, educational level and technological advancement just to name a few. Figure 2 below shows the different types of air pollution monitoring techniques used across the African regions to monitor exposure to PM and NOx pollutants.

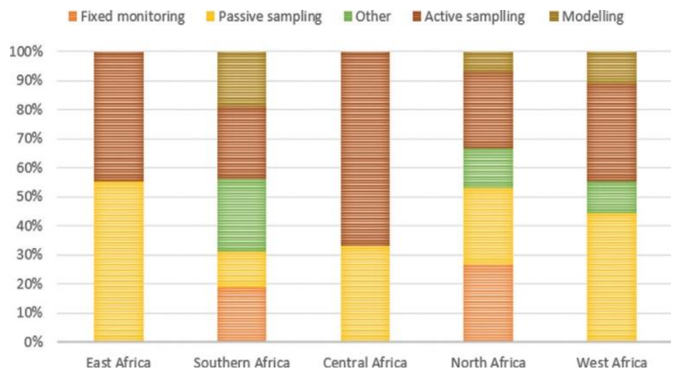

Figure 2. Air pollution exposure monitoring techniques of African regions

Figure 2 presents the air quality exposure monitoring techniques across five African regions. According to the above results, exposure monitoring of PM and NO_x pollutants in African regions is mainly characterized by fixed monitoring stations, passive sampling, active sampling, and, to a lesser extent, modelling. In addition to soiling index monitoring, mobile air quality monitoring and remote sensing, monitoring techniques that are rarely used are grouped and categorized as 'other'. Air pollution in Africa is commonly monitored with passive and active sampling, as indicated in Figure 2 above. As a result, passive monitoring is the most common method of monitoring exposure in the East African region, followed by active sampling (44%). Central African regions, in contrast to East Africa, frequently monitor PM and NO_x using active sampling (67%) techniques. In other regions such as West Africa, North Africa and Southern Africa, monitoring techniques like modelling and 'other' were observed in addition to passive and active sampling.

In light of this observation, monitoring in the West African region is largely done via passive sampling techniques (45%) and active sampling techniques (33%). A similar monitoring practice can be found in the North and Southern African regions to a certain extent. Although modelling (10%) and 'other' monitoring techniques are equally (10%) infrequent in this region, they are similarly applied in the North and Southern African regions. There are many monitoring techniques in both regions that include fixed monitoring stations as well as passive and active sampling, modelling and 'Other'. Nevertheless, the individual results in Figure 2 indicate that PM and NOx exposure is constantly monitored using fixed monitoring stations (19%) and modelling techniques (19%) in Southern Africa. A similar trend was observed for active sampling (25%) and a combination of 'other' techniques (25%). Passive sampling (12%) is rarely used. To measure particulate matter and nitrogen oxide exposure risks in North African regions, passive sampling (27%), active sampling (27%) and fixed monitoring stations (27%). Among these monitoring techniques, 'other' (13%) and modelling (6%) are included.

From the above results, it is evident that passive and active sampling methods embody the bulk monitoring techniques of the African regions. This is not surprising as these traditional sampling methods are one of the viable alternative techniques that have ever emerged to measure air pollutants from a practical and economic perspective [84]. Generally, the application of these monitoring techniques assists individuals or any interested parties to measure the air pollution concentrations that can compromise and impact human health with ease. Given that these techniques are relatively cheap since there are no costs associated with installation and in some instances, no electrical energy is required for operation [85, 86]. Furthermore, they can be installed in numerous sites to provide high spatial resolution air quality data [87]. As a result, most African regions are in favour of these monitoring techniques. Especially within the regions of East Africa, West Africa and Central Africa where continuous monitoring of air quality exposure data is scarce.

Therefore, in cases where monitoring is limited, these sampling techniques enable interested parties to take it upon themselves and monitor exposure to poor air quality. This subsequently 'provide[s] citizens and communities with opportunities to monitor the local air quality that can directly impact their daily lives' as Snyder suggests [46]. Hence, their prevalence in the agenda of African monitoring techniques. Against this background, it is worth mentioning that the use of passive and active monitoring techniques enables the detection of human exposure to air pollutants as well as the estimation of the health effects of air pollution exposure. The latter is very fundamental for epidemiological studies that seek to link exposure with health effects. But in order to achieve this, it's crucial to make sure that monitoring systems are set up as dense monitoring networks that can monitor air pollution in a long term.

The lack of monitoring exposure on a long-term basis is one of the inherent drawbacks associated with this monitoring technique. Especially since most of the African regions do not have exposure data on air pollution. Because most of them do not monitor air pollution exposure on a frequent basis [88]. As a result, the discoveries of short-term exposure monitoring projects that employ passive and active sampling techniques are extrapolated and integrated into air quality management to influence ambient air pollution regulatory policies. But to develop effective air quality policies, long-term studies are needed to characterize air pollution levels across all seasons and to continually assess the related public health risks and their impacts; as well as to explore the pragmatic mitigation approaches informed by science. Thus, in addition to the deployment of dense passive and active monitoring networks, African regions should strive to avoid applying these techniques in ad hoc, short-term air quality monitoring programs.

Furthermore, the fixed monitoring techniques observed in some of the African regions as shown in Figure 2 is indicative of continuous monitoring and some government in that region is committed to issues of air quality management [58]. Thus, across the African regions, the fixed monitoring stations belong to the government authorities. It is for this reason that in Africa the presence of fixed monitoring stations predominantly coexists with the laws that regulate exposure to prescribed ambient air pollution standards in that region. For example, this has been observed in Southern Africa where only South Africa has set up continuous air quality monitoring systems; while similarly to Southern Africa in North Africa, some cities in Morocco, Tunisia, Egypt and Algeria have air quality monitoring stations that complement the prescribed air quality standards of these countries [50]. In Africa, the link between fixed air quality monitoring stations and prescribed air pollution standards is influenced by the guarantees of long-term exposure measurement brought about by this monitoring technique. Because the fixed monitoring technique can provide precise and accurate long-term data which can be used as a baseline for risk assessment exposure to poor air quality [89].

However, in as much as this monitoring technique ensures long-term exposure assessment of air quality data it is not devoid of limitations. Amongst the other limitations faced by African government agencies that use fixed monitoring stations is the inability to capture the spatial variability of pollutants. The lack or inability to capture the spatial variability of air pollutants increases the risks of exposure misclassification. Exposure misclassification is thus a significant issue and, as a result, air quality concentrations associated with exposure misclassification have little to no impact on air pollution policies and regulations [90]. Because the exposure concentrations of pollutants vary greatly over a large area. Therefore, the measured concentrations of pollutants devoid of spatial variability are imprecise to correctly estimate the risks of exposure. Hence the data collected using this technique in some instances is considered limited and its reliability is questioned due to exposure misclassification.

For instance, Jenner [91] resolved not to incorporate exposure data from a fixed monitoring station in an epidemiologic study of the health effects of exposure to ambient air pollution. Asserting that the exposure misclassification rendered monitoring station exposure data inapplicable for an ambient air quality investigation study related to epidemiological health effects outcome of air pollution. Similarly, Xie et al. [92] corroborate that the low spatial resolution of the fixed monitoring station data may lead to inaccurate assessment, especially over the whole study area. To remedy the low spatial resolution there is a need to deploy multiple numbers of fixed monitoring stations. However, this is almost impossible for most African regions as the installation and operation of this monitoring technique are associated with exuberant costs.

Therefore, to enhance the monitoring techniques that are essential to epidemiological studies that can inform air quality policies, the African continent must adopt multiple technological advancement techniques, similar to what developed countries do, which incorporate central-site monitors, GIS models and remote sensing satellites [93]. In recent times Amegah [90] has raised a similar issue stating that incorporating technology in Africa to monitor exposure to poor air quality will result in a better understanding of chronic exposure and chronic outcome of epidemiological studies. At this point and time, the characterization of African monitoring techniques indicates that most of the African regions greatly prefer the traditional monitoring techniques to measure air pollution in contrast to their well-developed counterparts that generally maximize technological advancement to monitor exposure to air quality. Consequently, the risks of exposure misclassification are too high given how these monitoring techniques are applied.

7. CONCLUSION

The current study sought to look at the progress made by African countries in the advancement of monitoring techniques of particulate matter and nitrogen oxides within urban settings of the African states associated with the criteria pollutants of concern, such as particulate matter and nitrogen oxides, which are responsible for millions of preventable deaths worldwide. Although air pollution exposure assessment has evolved over the last several decades, the current study discovered that traditional monitoring techniques such as passive sampling, active sampling and fixed monitoring continue to dominate air quality monitoring across the African continent. Despite the ability of air quality modelling techniques to detect human exposure to air pollutants and estimate the health consequences of air pollution exposure, the majority of African regions rarely conduct air quality exposure assessments that incorporate air quality modelling techniques. This observation contrasts with well-developed counterpart continents, such as Europe, which prioritizes air pollution modelling that incorporates recent advanced technological applications. According to the findings of this study, African regions should consider and incorporate modelling techniques in their exposure assessments of particulate matter and nitrogen oxide air pollutants. Furthermore, the study advocates for a paradigm shift away from the current exposure assessment of air pollution compliance which focuses on air quality standards and move toward comprehensive assessments that prioritize and integrate air pollution epidemiology. This will educate both the government and the general public about the actual health risks of exposure to poor air quality. However, this will necessitate a change in air quality monitoring techniques.

DATA AVAILABILITY STATEMENT

The data presented in this study is available on request from the corresponding author.

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