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Urban diagnostics and a systems approach to air quality management: Pathways towards sustainable economic development and a healthy nairobi, Kenya

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Taking holistic actions to improve urban air quality is central to reducing the health risks associated with urbanisation, yet local evidence-based and institutional frameworks to achieve this are still challenging especially in many low-and middle-income countries (LMICs). This paper develops and applies an integrated systemic approach to explore the state of air quality management in Nairobi, Kenya; as an LMIC exemplar city. The urban diagnostics approach developed assesses current particulate matter air pollution in Nairobi; quantifies anthropogenic emissions for the years 2015 and 2020 and projects scenarios of impacts of actions and inactions to 2030. This was combined with a review of grey literature on air quality policies, urban development and interviews with key stakeholders. The analysis suggests that commendable progress has been made to improve air quality in Nairobi but continuing hazardous levels of air pollution still require concerted policy efforts. Data available for numerical simulations have low spatial resolution and are generated from global emission inventories that can miss or misrepresent local emission sources. The current air quality data gap that needs to be addressed are highlighted. Strong political support is required to ensure that current air quality improvement approaches are evidence based to achieve long-term sustainability goals.

KEYWORDS

air pollution, PM emission, anthropogenic emission, public policy, urbanization, east africa

1 Introduction

Poor air quality has a significant negative impact upon human life (WHO, 2018a). The World Health Organization (WHO) assesses that more than 90% of people living in urban areas are exposed to air pollution levels that exceed the 2005 recommended health-based air quality guidelines threatening lives, productivity, and economies (HEI, 2019). More recently, the standard was updated to even stricter limit values (WHO, 2021). Urban air pollution is a major and increasing concern as around 55% of the global population now live in cities with this percentage expected to increase to 68% by 2050 (UN, 2018). Over the last few years, rapidly developing low-and middle-income countries (LMICs), mainly in Asia (i.e., India, Thailand, Bhutan, Bangladesh, Nepal and Malaysia etc.) and Africa (i.e., Botswana, Ethiopia, Ghana, Morocco, Nigeria, Rwanda and Uganda etc.), are increasingly experiencing ambient air quality problems associated with industrialisation, urbanisation and economic development (Mannucci and Franchini, 2017; WHO, 2018b) and Kenya is no exception. This paper sets out to develop and apply an urban diagnostics approach to develop a system approach to air quality that would contribute to enhancing the development of air quality management initiatives in Sub-Saharan East Africa.

The average population of Sub-Saharan East African countries (Burundi, Dijbouti, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Somalia and Uganda) more than tripled from 146 million in 1980 to 445 million in 2020 and according to population projections, could grow to 1.4 billion by 2,100 (WPR, 2022). The United Nations World Population Prospects identified that the population of Nairobi city is growing rapidly at a rate of 4% annually (WPR, 2022). The city's population has increased from 3.1 million (2009) to 4.2 million (2021) over the past decade and is projected to increase to 7 million by 2030 (WPR, 2022). This rapid growth has been accompanied by rapid industrialisation and increasing vehicular transportation, along with ongoing domestic reliance on biomass fuels contributing to worsening air quality and increasing citizen exposure to air pollution (Pope et al., 2018; Rajé et al., 2018; Kalisa et al., 2019; Singh et al., 2020). Nairobi faces urbanisation challenges including inadequate formal housing resulting to expanding informal settlements, unplanned housing estates, and lack of coordinated planning and poor enforcement of zoning rules and regulation (Mwaniki, et al., 2015; UN, 2018). The city's inadequate public transportation system led to an increase in private transport to meet the economic and travel needs of the growing urban population. The Government of Kenya has invested significantly in socio-economic and environmental infrastructures, yet the challenges associated with urbanisation persist in Nairobi and in urban areas across Africa (Güneralp et al., 2017; Mansour et al., 2017). Though these urbanisation challenges are common to most developing countries, significant progress is being made in most parts of Asia to address these problems but less so across Africa (Turok and McGranahan, 2013).

Airborne particulate matter (PM), i.e., $PM_{2.5}$ and PM_{10} (PM with aerodynamic diameters less than 2.5 and 10 μm respectively - WHO, 2006), from both indoor and outdoor sources, is of major concern in urban areas, and consistent epidemiological evidence associate short and long-term PM exposure with a wide range of adverse health impacts (Kim et al., 2015). The health impacts of PM air pollution, including increased risk of chronic respiratory, cardiovascular diseases and a range of cancers, all-cause mortality and have now largely surpassed unsafe water and sanitation and child malnutrition as the leading cause of premature death in urban areas (Forouzanfar et al., 2016; Wong et al., 2016). The WHO sets Global Air Quality Guidelines (limits) based upon concentrations of PM necessary to protect human health. The 2005 WHO guidelines for daily $PM_{2.5}$ and PM_{10} were 25 μgm^{-3} and 50 μgm^{-3}, respectively (WHO, 2006) and have been recently updated to 15 μgm^{-3} and 45 μgm^{-3} respectively (WHO, 2021). However, epidemiological evidence suggests there is no safe limit for exposure to PM in terms of health impacts. These challenges have made air quality improvement a priority focus for national and international development policy initiatives with the need to improve air quality being reflected in the Sustainable Development Goals (SDGs) (UN, 2021). Notably, SDG 7 aims to ensure access to affordable, reliable, sustainable and modern energy (Landrigan et al., 2018). In addition, SDGs 3, and 11 are targeted at taking holistic, evidence-based policy actions with improving urban air quality being integral to sustainable development (UN, 2015; Amegah and Agyei-Mensah, 2017).

In recent years, there is increasing research interest in understanding air pollution trends and their associated health and environmental impacts in Sub-Saharan East Africa, typically through short-term measurement campaigns (Vliet and Kinney, 2007; Kume et al., 2010; Kinney et al., 2011; Gaita et al., 2014; Schwander et al., 2014; Ngo et al., 2015; Egondi et al., 2016; Amegah and Agyei-Mensah, 2017; deSouza et al., 2017; Pope et al., 2018; Gatari et al., 2019; Coker et al., 2021; deSouza et al., 2021; Mutahi et al., 2021). Researchers have made efforts toward filling the air quality data gap in the region through ambient air quality monitoring (specifically, particulate pollutants), however, the absence of long-term air quality data and a related monitoring network make it difficult to develop a complete assessment of the magnitude of the air pollution problem (Pope et al., 2018; Singh et al., 2020).

This paper explores air quality management by developing and applying an urban diagnostics approach to Nairobi (Kenya); as an exemplar LMIC city, to highlight the complex nature of the policy challenge and the importance of enhancing air quality measurement to underpin air quality policy-development and implementation. This approach draws upon complexity science, acknowledging that factors influencing urban air quality include multiple heterogeneous interactive elements, with effects arising which are different from the influences of individual components, and which persist over time and adapt to changing circumstances (Luke and Stamatakis, 2012). In the context of urban Nairobi, we use these methods to recognise the complexity and interconnectedness and responsiveness of the numerous elements that lead to air pollution and the associated harms, and the need for institutional arrangements and regulations (including implementation) to minimise the impacts upon air quality (Mabry et al., 2008; Allender et al., 2015). This paper argues that current actions to improve air quality in the city are not holistic or sustainable in the long-term without up-to-date air quality data to inform local control measures to manage impacts at source. It reiterates the critical role of air quality data in taking a systems approach to address complex problems like urban air pollution. Such a systems approach requires an appreciation of possible actor-orientated adaptations and mitigations framed within the context of existing structural constraints.

The paper is presented in four sections. The next section 2 discusses materials and methods employed in the study. It also explores the social and spatial characteristics of Nairobi and the justification for its choice as the case study city. This is followed by the presentation of the findings of the study in section 3, the discussion and implications of the findings and the conclusions are developed in section 4.

2. Methodology

2.1 Study approach: Urban diagnostics and systems approach to sustainable air quality management in nairobi

Urban policymaking is both responsive and proactive with the latter approach defined politically or in response to some type of debate or policy concern. An alternative approach is based on urban diagnostics (Leach et al., 2019) which is a methodological approach to understanding the challenges faced by a city and ideally diagnostics should precede policy development and should also include an on-going policy evaluation process. The urban diagnostics approach is a formalised data evaluation process to identify, assess, and test challenges facing a city as part of a process that has been described as being similar to "reading a city" (Bryson et al., 2018; Leach et al., 2019). This approach is informed by the emphasis placed in medical diagnostics on combining abductive and deductive approaches to assess complex systems (Leach et al., 2019). This paper develops an urban diagnostics approach to exploring air quality by exploring three linked diagnostic stages: pollutant monitoring, numerical modelling and urban planning and environmental policy making (Figure 1). The European Directive 2008/50/EC on ambient air and cleaner air for Europe (EC, 2008) highlights the necessity of developing integrated plans for air quality management and encouraging the use of numerical modelling in combination with monitoring network for the preparation of air quality plans oriented to primary emissions abatements (Miranda et al., 2015). Moreover, existing studies have shown the need to address development issues associated with urban air pollution in the context of city-specific sub-systems the city depends (Clarke, Annez and Lin, 2010; Amin and Thrift, 2017; Gani et al., 2022). Such a system recognises the need for adequate and appropriate local evidence base for policy makers and the public to facilitate responsible environmental behaviour in the long term. In the above context, the urban diagnostic approach as applied in this paper is elaborated in the next subsection.

2.2 Data collection and analysis methods

The first stage—of the diagnostics process involves exploring the current state of air quality in Nairobi with air quality data sourced from recent literature. To understand spatial and temporal trends in urban air quality, a sustained and long-term calibrated dataset is required. Efforts to assess air quality information in Nairobi are hindered by the limited air quality monitoring network and lack of historical data (Pope et al., 2018). The key challenge of measuring and monitoring air quality in cities like Nairobi is the costs related to monitoring including equipment, maintenance, calibration, certification and staff time associated with data acquisition and modelling. Data must be credible to support effective policy development and monitoring and conflicts of interest avoided. In addition, we need understanding of how this data will be used by relevant stakeholders, both for policy development and evaluation processes.

In the light of the above challenges, an overview of current air quality trends in Nairobi is presented based on the most recent research undertaken to measure the city's air quality. In addition to the above, secondary data was used to analyse the most up-to-date emission inventory for East Africa focusing on Nairobi to explore the future implications of the impacts of population growth on air quality (Brauer et al., 2016).

Anthropogenic emissions are the main contributors to urban air pollution and represent the first area of intervention for local and national authorities for the development of air quality policies. Moreover, the manipulation of anthropogenic emissions for air quality modelling permits the creation of air

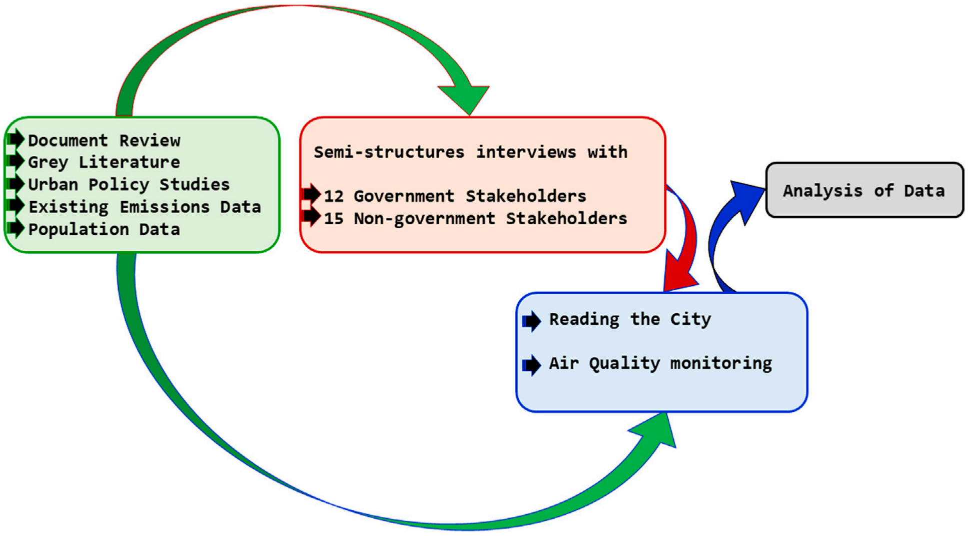

FIGURE 1
Urban diagnostics approach for the assessment of air quality management in Nairobi.

quality scenarios to show the effects of emission reductions on air pollution levels. In addition, development of air quality scenarios can support policy makers in understanding the impacts of changes in the level of exposure on citizens, and the associated health costs and benefits of emission reduction measures (Markandya et al., 2018).

In the above context, the focus is on the analysis of primary $PM_{2.5}$ emissions available from global emission inventories. The choice of this pollutant was firstly motivated by the key role that $PM_{2.5}$ play in the deterioration of urban air quality in East Africa (Singh et al., 2021). Secondly, there is evidence to suggest the efficacy of mitigation policies in reducing $PM_{2.5}$ emission in urban areas in other parts of the world (Sofia et al., 2020). Thirdly, $PM_{2.5}$ is consistently recognised to be harmful to human health, livestock and the ecosystem.

Anthropogenic emissions projections for East Africa and Kenya were provided by the European Union's Seventh Framework Programme project ECLIPSE (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants) (Stohl et al., 2015). The ECLIPSE database, version V5a (the most up-to-date version at the time of the analysis) provides realistic and effective mitigation scenarios for short-lived climate pollutants (SLCPs); black carbon, methane, tropospheric ozone and hydrofluorocarbons and quantifying their climate and air quality impacts. The emissions were evaluated using advanced Earth system models (ESMs) and six chemistry transport models (CTMs). ECLIPSE V5a database provides emissions for year 2015 and includes environmental laws and regulations applied in that period and represents. For year 2020 and 2030, the database provide projections according to three developed scenarios: (i) Current legislation (CLE) including current and planned environmental laws, considering known delays and failures up to now but assuming full enforcement in the future, (ii) No further control (NFC) using the same assumptions as CLE until 2015 but without any further legislation introduced subsequently and, (iii) A mitigation (MIT) scenario including all measures with beneficial air quality and climate impact applied to the methodology described by Stohl et al. (2015). In this work we use CLE emissions for the years 2015 and CLE projections for 2020 because of the lack of mitigation policies applied at regional and national level in East Africa and Kenya and NFC and MIT projections for 2030 (hereafter 2030nc and 2030ms, respectively). They will be used to quantify the increase or decrease of emissions of $PM_{2.5}$ by sector according to the different scenarios for the geographical domains at a resolution of 18 km × 18 km and 2 km × 2 km obtained by the Weather Research and Forecasts Model (WRF, version 3.9.1) and centred on East Africa and Kenya (Skamarock et al., 2008) (Figure 2).

The second stage—of the urban diagnostics process involved identifying and exploring the key policy documents that had been produced that cover air quality related issues across the Nairobi including air quality regulations and urban infrastructure. This stage also includes an assessment of existing academic research on Nairobi and how this relates to air quality. This stage provides an overview of the evolution of policy to enhance air quality based on identifying and reviewing institutional arrangements and infrastructure interventions (Leach et al., 2019).

The third stage—involved 27 face-to-face semi-structured interviews with representatives of national, regional and local governments, non-governmental institutions (NGIs), researchers, non-profit organisations (NGOs) and community-based organisations (CBOs) undertaken between August 2018 and May 2019 (Figure 1) out of 30 participants

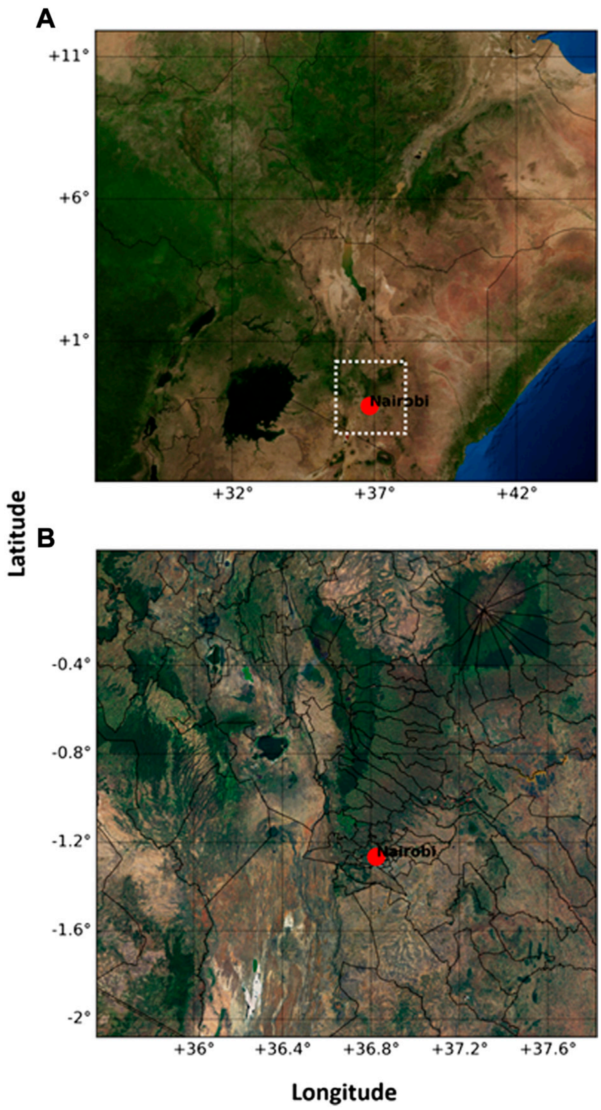

FIGURE 2
Geographical domain of **(A)** East Africa and **(B)** Kenya, with spatial resolution of 18 km × 18 km and 2 km × 2 km, respectively used for the quantitative analysis of the ECLIPSE emissions. Topography relief generated from ArcGIS 2021 (http://server.arcgisonline.com/ArcGIS).

approached as informants in the study. The interviews focused on key policy challenges facing Nairobi, the effect of the challenges on urban air quality and key policy lessons learned to improve air quality regulations.

Participants were purposely selected considering their roles and responsibilities and their abilities to contribute to the issue of air quality improvement in Nairobi (Robinson, 2014). We adopted a convenient sampling strategy which involves identifying and selecting convenient subjects who fit the study criteria on a first-come, first-served basis (Robinson, 2014). The choice of this sampling approach is based both its simplicity and importance in context based studies (Saunders et al., 2012). Moreover, some of the stakeholders cannot be substituted neither are they easily accessible nor available. The participants represent both government and non-government stakeholders directly and indirectly connected to urban air pollution in Nairobi as service users, regulators, citizens and civil societies.

Participants were approached through emails to introduce the research and request for their participation. This was followed by fixing date, time, and venue of the interview with respondents who showed interest in the study. The study had ethical approval from the University of Birmingham Ethical Committee. In line with the ethical consideration, each participant was informed of their role in the study and consent was sought in written or recorded form before participation. During the interview, open-ended questions

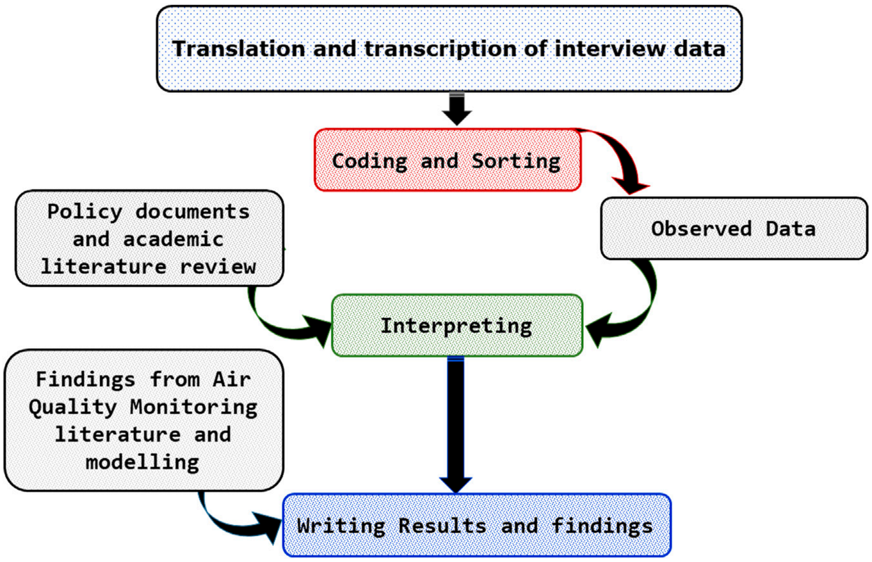

FIGURE 3
Analytical framework for the understanding of the state of air quality management in Nairobi.

were used to allow the respondent to express themselves and share their experience on the issues relating to urban air quality management in Nairobi. The interview sessions varied between 30 min and 60 min. The interview data were transcribed, coded and sorted in NVivo software using codes generated from both the interview data and theoretical and empirical literature review. Findings from the analysis were interpreted along with findings from the policy and academic literature review before integrating the findings with the air quality monitoring literature and modelling data to understand the state of air quality management in Nairobi. The analysis involved two levels of government—national and Nairobi City County and considered how urban population growth and infrastructure improvements are integrated into air quality control measures in theory and practice in Nairobi. Figure 3 presents the analytical framework applied to integrate findings from data collection processes discussed in stages 1–3 above to understand the state of air quality management in Nairobi.

3 Results and discussion

3.1 Current state of air quality in nairobi

Within the first stage of urban diagnostics to support the development of a systems approach to air quality management in Nairobi, we assessed the current state of air quality from monitoring literature and modelling translations.

3.1.1 Measurements (monitoring) translation

Over the last 10 years a number of short-term and geographically restricted air pollution studies have been undertaken in Nairobi to understand temporal trends in PM pollution (Kinney et al., 2011; Ngo et al., 2015; Egondi et al., 2016; Gaita et al., 2016; deSouza et al., 2017; deSouza et al., 2021; Pope et al., 2018; Gatari et al., 2019; Singh et al., 2021). Most of these studies determined PM pollution within the city, by measuring $PM_{2.5}$ and PM_{10} mass concentrations using gravimetric methods and low-cost sensor technologies. For all studies PM concentrations were considerably higher than the WHO limits and were found to vary considerably temporarily and spatially. Here we highlight the most recent studies that considered current PM air quality in Nairobi.

There are very limited studies that have explored Nairobi's long-term air quality. For example, a recent study (Singh et al., 2020), provided an estimation for long-term urban air quality in East African cities (including Nairobi) using visibility measurements as a proxy for PM air pollution. The study found that the PM concentrations are increasing by approximately 4.1% per year in Nairobi. The study linked the increase in long-term PM pollution to increased rates of citywide fuel use and vehicular traffic along with other socio-economic developments. The longest continuous measurement study of PM air pollution for Nairobi is provided by Gaita et al. (2014), which measured $PM_{2.5}$ concentration at two locations (urban background and at a suburban site) within the city for two years (May 2008—April 2010) using gravimetric sampling. The study found that the daily mean $PM_{2.5}$ concentration at the urban background and suburban sites exceeded the 2005 WHO limits on 29% and 7% of days, respectively. The overall mean $PM_{2.5}$ concentrations for the urban background and suburban sites (21 μg m^{-3} ± 9.5 μg m^{-3} and 13 μg m^{-3} ± 7.3 μg m^{-3} respectively) were relatively lower than 2005 WHO limits (25 μg m^{-3}) but higher than revised 2021 guidelines (15 μg m^{-3}) for the study period. However, the reported monitoring was carried out at heights of above 17 m above ground level (agl) and the values can translate to higher concentrations at human breathing level. Kinney et al. (2011) undertook a height dispersion experiment which showed that at about 1.5 m agl on the curbside the mean concentration of $PM_{2.5}$ was 110 μg m^{-3} ± 19 μg m^{-3} and at 17 m agl it was 43 μg m^{-3} ± 8 μg m^{-3} at the same site while at the urban background measurement site (Gaita et al., 2014) it was 35 μg m^{-3} ± 12 μg m^{-3}.

Findings from recent monitoring studies (Pope et al., 2018; Singh et al., 2021) clearly indicate that current air quality in Nairobi, especially at roadside locations is at an unhealthy level as defined by the EPA daily US Environmental Protection Agency (EPA) air quality index (AQI) (AirNow, 2022). Pope et al. (2018) measured PM mass concentrations using low-cost sensors at three locations (roadside and urban background in Nairobi and in rural Kenya) during February—March 2017. It was observed that mean $PM_{2.5}$ and PM_{10} concentrations regularly exceeded the WHO thresholds. Overall mean concentrations of $PM_{2.5}$ at the roadside, in the urban background and at rural sites were 36.6 μg m^{-3}, 24.8 μg m^{-3} and 13.0 μg m^{-3} respectively, while mean PM_{10} concentrations at the same locations were 97.7 μg m^{-3}, 53 μg m^{-3}, 19.5 μg m^{-3} respectively. This analysis identified that vehicle emissions were a key source of air pollution in Nairobi, accounting for an estimated 47.5% and 48.1% of the total PM loading in the $PM_{2.5}$ and PM_{10} size fractions respectively at roadsides (Pope et al., 2018). The study by Gatari et al. (2019) reported gravimetrically evaluated high black carbon (BC) concentrations in 11 h sampled $PM_{2.5}$ from a Nairobi roadside site (on River Road) close to the measurement site used by Pope et al. (2018). The study used co-location and Kinney et al. (2011) samples to evaluate BC. It was estimated that BC near the curbside of roadways was in the range of 34–56% of $PM_{2.5}$, implying traffic was a dominant source of $PM_{2.5}$ emissions in Nairobi. Due to the observed high concentrations of BC the authors raised concerns regarding potential health threats to workers, residents, and visitors, and highlighted the need for policies to address traffic-related air pollution in Nairobi. A study published by Singh et al. (2021) explored short-term air quality trends at various locations in East African cities (including Nairobi), using low-cost sensor technology. This study generated data for two months (February—March 2019) $PM_{2.5}$ and PM_{10} monitoring at urban, roadside and rural locations in Nairobi, where measurements were taken at the same locations as in Pope et al. (2018). They reported higher (approx. 30%) mean $PM_{2.5}$ mass concentration in 2019 compared to Pope et al. (2018) measurement performed in 2017 at both urban and roadside sites. They noted that overall mean PM concentrations at both urban and roadside sites were at unhealthy levels for sensitive groups in reference to the EPA AQI and mostly exceeded the WHO limits (WHO, 2006 and, 2021). Within their study, overall mean $PM_{2.5}$ concentrations at roadside, urban background and rural sites were 48.5 μgm^{-3} ± 14.9 μgm^{-3}, 31.6 μgm^{-3} ± 15.4 μgm^{-3} and 4.5 μgm^{-3} ± 1.4 μg m^{-3} respectively, with mean PM_{10} concentrations at the same locations of 103.6 μgm^{-3} ± 45.2 μgm^{-3}, 47.1 μgm^{-3} ± 37.2 μgm^{-3} and 12.3 μgm^{-3} ± 3.0 μg m^{-3} respectively (Singh et al., 2021). A study by deSouza et al. (2021) estimated spatial $PM_{2.5}$ concentrations in Nairobi using low-cost mobile monitoring and a random-forest model to explore the impact of COVID-19 lockdown measures in 2020. This highlighted that the highest $PM_{2.5}$ concentrations were in poor neighbourhoods of the city centre of Nairobi (Mathare, Kariobangi, Umoja, and Dandora) before and during the lockdown. Their model estimations showed $PM_{2.5}$ levels were reduced in the Viwanda industrial area of Nairobi after the lockdown was imposed, but the model showed inconsistent information on overall changes in $PM_{2.5}$ in Nairobi (d'Souza et al., 2021). From the study no conclusions could be drawn on the overall changes in $PM_{2.5}$

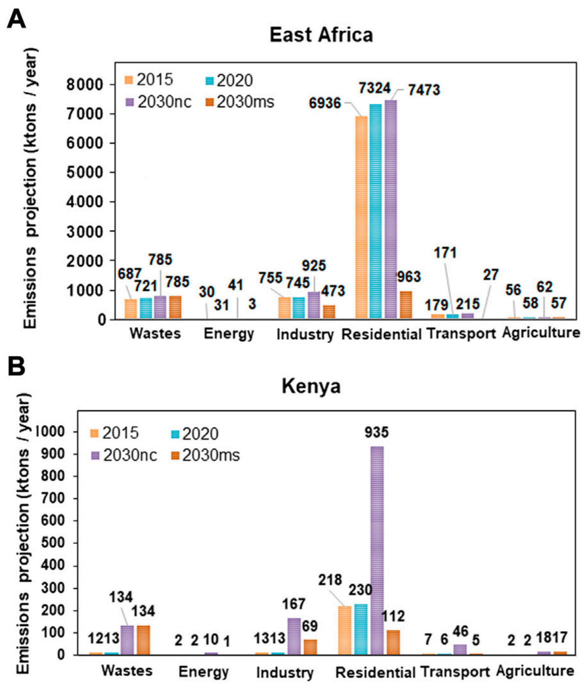

FIGURE 4
Annual ECLIPSE projected emissions of $PM_{2.5}$ for **(A)** East Africa and **(B)** Kenya, according to the geographical extent shown in Figure 2. The emissions are relative to the CLE cases of 2015 and 2020, while emissions for 2030 are from the NCF scenario (2030nc) and MIT scenario (2030ms).

levels in Nairobi due to sampling limitations and measurement uncertainties. However, the study clearly highlights the importance and need for high spatial resolution data to understand the structural disparities reflected in the Nairobi's disproportionate air pollution burden. An indoor and outdoor air quality study by Mutahi et al. (2021) observed unhealthy indoor pollution experienced by poor urban and rural neighbourhoods. The observed situations of high pollutants' concentrations, especially $PM_{2.5}$ and BC, were blamed on the communities relying on low grade and inefficient fuel as households could not afford cleaner fuels. The authors doubted the effectiveness of implementing existing regulations and how well they are understood by stakeholders. They also reported that the reluctance to implement existing regulations could be due to the lack of baseline air quality measurements, budgetary constraints, and absence of political goodwill.

3.1.2 Modelling translation

The existing studies can be supplemented by the analysis of ECLIPSE projected emissions of $PM_{2.5}$ for the years 2015, 2020 and 2030 in East Africa, focusing on Kenya. In the CLE scenario (including present and planned environmental laws) from 2015 to 2020 emissions of $PM_{2.5}$ grew between 3.7% and 4.8% in all emission sectors, with the exception for the industrial sector that showed a decrease of 1.7% going from approximately 755,000 tons in 2015 to 745,000 tons in 2020. The highest increase over this period was in the residential sector where emissions grew from approximately 6 million tons to 7 million tons, an increase of 5.3% (Figure 4A). Scenarios for 2030 following NFC regime (2030nc) for East Africa estimated an increase between 7% and 27% in all the sectors from 2015, with the highest increase in the energy (27.7%), industrial (18.4%) and transport (16.9%) sectors according to the projection of industrial growth and urbanization. In contrast, the MIT scenarios (2030ms in Figure 4A), including all possible mitigation policies beneficial for air quality and climate impact, from 2015 to 2030 estimated all sectors could see a decrease of anthropogenic emission of between 37% and 89% with the exceptions of the waste and agriculture sectors for which the emissions are projected to remain stable. Emissions from the energy, residential and transport sectors showed the highest relative percentage decreases of 89.6%, 86.1%, and 84.7%, respectively (Figure 4A) for mitigation policies based on policies oriented to the use of cleaner fuels and engines, eliminating high emitting vehicles, and the replacement of wood burning with cleaner biomass cooking stoves (Stohl et al., 2015).

Emissions from the ECLIPSE database for the domain of Kenya (Figure 4B) show that between 2015 and 2020, PM emissions were estimated to increase by between 1% and 5% in all sectors with the transport sector being the exception. The residential sector is most affected with the highest increase in emissions (5%) while the industry sector showed the lowest increase (1%). The projected NFC scenario of 2030 (2030nc in Figure 4B) estimated a drastic increase in emissions from all sectors of between 77% and 91%. The highest rates were visible for industrial activities (92%), waste treatment (91%) and transport (86%), but also for the agricultural sector (91%). In contrast, estimates with MIT regime for 2030 (2030ms in Figure 4B), suggested a similar increase to NFC in the waste and agricultural sectors, of 91 and 90%, respectively, but decreases in the other sectors. Industrial activities and transport projections decreased by 19%, residential by 49% and energy production by approximately 56%.

TABLE 1 Key environmental policies related to air quality in Kenya (UNEP, 2015).

Key environmental policies	Year
Air quality regulations	2014
Environmental policy	2013
Occupational health and safety act	2007
Public health act, cap 242	2012
National transport and safety act	2012
Energy act	2006

3.2 State of air quality management regulation in nairobi

The second stage of the urban diagnostics process involves exploring the evolution of policy intended to enhance air quality in Nairobi combined with a review of the academic literature. Historically, efforts to address air pollution in Nairobi date back to the 1990s with the financial and technical support of international institutions including the WHO and the United Nations Environment Programme (UNEP) (UNEP, 2022). This led to the introduction of National Air Quality Regulations (2014) in response to pressure for systemic actions to address urban air pollution in Nairobi from non-governmental institutions. These institutions included independent researchers, the Kenya Air Quality Network, and the African Population and Health Research Centre (West et al., 2020). This is in addition to time bound financial and technical support provided by international organisations and foreign governments. The National Environmental Management Authority (NEMA) serves as the national body for the implementation and enforcement of air quality regulations. The Kenyan government approved regulations on air quality management in 2014 highlighting the national government's commitment to address urban air pollution (NEMA, 2014). Prior to this period, other policies related to air quality and environment were disjointed and did not reflect local realities (see Table 1). Although, the standard used in the regulation was developed based on comparison of countries with similar characteristics like Kenya because there was no baseline data (Non-Government Institution/NGO, Kenya 17, 26 October 2018).

Despite these multiple policies, there were enforcement challenges, alongside ongoing population and economic growth resulting in continued high ambient and household air pollution levels (Muindi, 2017). Moreover, the interviews identified that this problem was related to the lack of air quality data to forecast scenarios and inform evidence-based air quality control measures. Lessons from the Global North also indicate that environmental public policies often fail at implementation stages despite strong commitments at different scales of government (Brunt et al., 2016; Barnes et al., 2018). Such failure may reflect policy development and implementation that was not informed by an urban diagnostics process. One key problem is that the sources of pollutants may require adjustments to other policy areas, for example, transportation, rather than the implementation of a standalone air quality policy, and such problems may lead to unanticipated or unintended consequences as air quality policy interventions fail to target key pollutant sources. This suggests that concerted efforts must be holistic and inclusive to improve air quality, people's health and wellbeing by addressing root causes of environmental pollution (Bakare et al., 2018) and this requires a coordinated cross-cutting approach spanning diverse policy domains.

4 Discussion

Evidence-informed air quality policy needs to be supported by an urban diagnostics process to identify emission sources and this can then be supported by modelling to identify the most appropriate policy responses. In resource constrained environments like Nairobi policy must balance tensions between measures that would enhance air quality, but at the same time might limit economic growth. Ideally, policy must focus on identifying more sustainable development pathways that include an appreciation of the SDGs.

The air quality policy context in Nairobi reflects efforts to take an integrated, approach to air quality management at the city level. There is a recognition that data and institutional challenges need to be addressed to avoid past mistakes. The interviews highlighted that policymakers appreciated that better local air quality data was required to support the development of a coherent institutional approach to urban air quality improvement, but a more practicable holistic approach to reducing air pollution remains elusive. Findings from the interviews, monitoring of air quality based on short-term data and quantitative analysis of anthropogenic emissions corroborate the findings of the policy review. Long-term high-resolution air pollution data is currently unavailable, and policymakers and academics must rely on shorter term air quality data to understand temporal trends in particulate matter pollution and exposures, and to evaluate the effectiveness of intervention measures. The existing data clearly shows that currently Nairobi's air quality is poor; although understanding of existing health impacts remains limited, particularly with regards to the burden of household air pollution exposure. Our analysis shows that the application of modelling approaches can help predict future air quality and classify emission sources in Nairobi.

The quantitative analysis of anthropogenic emissions from ECLIPSE projections for East Africa and Kenya, highlight how through the implementation of legislation and/or mitigation policies it is possible to greatly reduce emissions. The analyses only show the impacts that these measures could have on primary emissions of pollutants, and they should also be used for numerical simulations of chemistry-transport processes to understand the real-world consequences of primary reductions in the final concentrations of both primary and secondary $PM_{2.5}$ both for East Africa and Kenya (Mazzeo et al., 2022).

The emissions adopted in this analysis have a spatial resolution of 50 km × 50 km that is insufficient to give detailed results applicable to Nairobi's urban scale. This is unfortunate as exposure to poor urban air quality reflects the characterisation of local contexts including street layout and the underlying topography. A key policy challenge is that additional effort is required to produce up-to-date emission estimates of anthropogenic emissions for the East Africa region, to create high resolution inventories that are able to simulate urban air quality concentrations with greater accuracy. All this is required to support policy formulation, implementation and monitoring.

The academic and policy evidence exists based on detailed studies of cities in many different national contexts regarding the links between urban air quality and mortality, morbidity and wider socio-economic impacts. Nevertheless, local politicians and policymakers still require local evidence to convince them that additional interventions are required. A key issue is the relative importance of addressing air quality compared to what might be perceived locally as more immediate policy priorities. One respondent noted, with reference to the success of the implementation of the plastic ban policy in the country, that:

"We can't say a particular air is polluted until a certain gadget portrays that. So, the government need to strengthen the policies, like they did on plastic ban. (Non-Government Institution/ Residents' representative, Kenya 21, 17 May 2019)".

Similarly, another respondents highlights why the efforts to address air pollution in Nairobi may not be effective with reference to recent policies to relocate motor parks away from Nairobi central area:

"I think the timing and their approach is the problem. Because for us to be able to say that we don't want to allow Matatus (commercial buses) into the city. It means that we have been able to put in place adequate infrastructure to make sure that people are able to connect to the last mile... Because even in some of the areas people are expected to walk through to their CBD are quite insecure. So, before we even talk about blocking Matatus from getting to the CBD we must make sure that there is adequate security on the roads which we want people to walk. (Non-Government Institution/Residents' representative, Kenya 20, 22 February 2019)".

This paper has highlighted that with current available data, it is possible to capture the main level or $PM_{2.5}$ contamination in urban and rural areas but further efforts are required to identify additional local sources that are still misrepresented in existing inventories and to have a more accurate spatial distribution of the emissions by the creation of local higher resolution emission inventories (Mazzeo et al., 2022).

For air quality interventions, measurement and monitoring are critical. The development of a wide air quality sampling network in Nairobi would increase the quantity and the detail of the information relative to air pollution concentrations. This information could be used to refine and update databases for air quality numerical simulations, increasing the reliability and precision of any analysis and widening the possible application of modelling for urban policy improvement. Nevertheless, the cost of developing a sensor network reflects an investment that could be spent on other policy areas. Innovations in low-cost sensors will eventually make air quality measurement affordable for resource constrained cities.

Air quality regulations are only effective if they are informed by local evidence generated through monitoring and modelling of local air quality data. This raises questions about the actions, intentions and interactions of different stakeholders concerned with policymaking and practice. Policy implementation and enforcement challenges are highly context dependent. Countries in East Africa have well-developed urban development plans and policies, but the key problem is with implementation and enforcement, which produces disconnections between policy and practice giving rise to alternative substitute approaches based on individual or community action (Ndah, 2010; Andres et al., 2019). Such policies also risk unintended or unanticipated negative consequences, including fuel substitution of more heavily polluting solid fuels in the context of progressive fuel sales or taxation policies.

One of the challenges for a city like Nairobi is related to capacity and the number of policymakers available to support the policy development, monitoring and implementation process. For many urban residents, survival is based on their own actions, and this is especially the case in informal settlements. Formal planning needs to be supplemented by alternative substitute approaches based on citizen actions and interventions supported by community groups and social enterprises. These reflect informal processes developed and applied by citizens in situations where formal provisions is either not available or unreliable (Bakare et al., 2020a). Alternative substitute approaches place citizens as agents of change and challenges the boundaries between lay and expert knowledge (Andres et al., 2019; Bakare et al., 2020). For planners, politicians and those involved in measuring air quality in a city like Nairobi the implication is that urban residents should be included in both the policy development and implementation process. Residents should be encouraged to engage in local activities designed to enhance the quality of their local environment by reducing environmental pollution. The everyday routines of urban residents contribute to environmental pollution and for a resource constrained environment the policy process must draw upon the benefits that would come from small scale alterations in resident behaviour. Moreover, citizen understanding of air quality health impacts, coupled with the availability of sustainable and healthier alternatives, is critical for making change happen.

Air quality management policies are expected to protect public health and to remove many of the adverse socio-economic impacts that are associated with air pollution. To be able to do this, there is need for continuous monitoring of air quality and the use of real time demographic and air pollution data to model and forecast sustainable scenarios and control measures that will address pollution in the long term and to enable quantification of public health costs and benefits. A key challenge rests on ensuring that politicians and policymakers appreciate the importance of reducing air pollution. This requires research to highlight the multiple negative feedback loops between poor health quality and socio-economic outcomes. Major challenges identified during the interview stage of the urban diagnostics process include the lack of political interest in air pollution leading to a disconnect with local realities. A key government official admitted that:

"There is not much emphasis on air quality regulation, national policy is not elaborate on air pollution. Capacity is one of the challenges, a bit of equipment, technical and human (Government Representative/National, Kenya 02, 29 August 2018)".

Another respondent highlighted that without financial support and political leadership to integrate air quality improvement plans into development policies at the national level then this challenge may not easily be resolved:

"But unless you have people from the Ministry of Planning, people from the Ministry of Finance, to really begin to engage with some of these processes, I really don't think we can get the kind of reforms that we are looking (Non-Government Institution/NGO, Kenya 10, 26 October 2018)".

Moreover, there is a need to localise policymaking to establish local action plans informed by monitoring and design control measures based on the local context (Schumacher and Shandas, 2019). This highlights the salient role that city governments play in air quality improvement. Barnes et al. (2014), suggest that reconceptualising air quality action planning needs to address the issue of not only devolution but also flawed subsidiarity that may hinder intra-governmental cooperation and inter-government coordination. In 2013, the Nairobi City County government became a devolved government empowered to bring governance closer to the people and involve them in issues of interest (Ngigi and Busolo, 2019). The newly created City County Government in partnership with UN Environment Programme and other stakeholders developed the City's first Air Quality Action Plan in 2019 (ECI, 2022). This is in line with the Kenyan National Environment Policy (2013, p. 9), which states that "the management of the environment and natural resources will be through decentralisation and devolution of authority and responsibilities to the lowest level possible". This action plan identifies four broad overlapping actions, beginning with developing the scientific evidence base to support policy interventions for air quality management: raising public awareness on the health and environmental impacts of air pollution; developing effective approaches for air quality management and building an effective implementation and enforcement programme for air quality legislation (ECI, 2019).

The development of an action plan highlights the importance of bringing governance closer to the people including the development of a systems approach to air quality management (Bakare et al., 2018). One challenge in the case of Nairobi is that national government is responsible for the provision of urban infrastructure across the country. The ability to build scientific evidence for policy interventions and the development of an effective systems approach to implementation might not be successful in the long term without intra-governmental cooperation and inter-governmental coordination. The draft air quality plan recognises the importance of existing collaborations between academia and civil society. The scientific community's role in monitoring and analysing evidence on air pollution in the city of Nairobi must now include investment in air quality monitoring and modelling substantially to proffer long-term solutions to air pollution in Nairobi. The draft plan also highlights the need for training of policymakers to improve technical capacity in air quality monitoring (ECI, 2019). However, in terms of public health the plan only aims to raise public awareness about air pollution with this responsibility domiciled in the environment department. The ability to use air quality data to forecast and model practicable control measures must also be enhanced. Following the approval of the Air Quality policy in 2020 and the development of the Air Quality Bill for the city that recently completed its first reading, air quality sensitization and awareness workshops were organised for parliamentarians (NCCA, 2021; Osano et al., 2021). The idea was to encourage policymakers to take ownership of the problem by ensuring that air quality improvement across the city was based on local evidence and was inclusive and effective.

The inconsistencies associated with the siloed approach that exists at the national level may hinder the success of Nairobi City Council in improving air quality. Air quality regulations were formulated over a number of years before they were approved. Yet after their approval, these regulations became a political document that was referenced rather than implemented and this set a bad precedent as the underlying societal issues were not addressed including altering attitudes towards particular approaches to cooking and heating. Developing a systems approach to air quality management requires cooperation between the national government and the role it plays in infrastructure provision and local government with an emphasis on developing cleaner and affordable urban infrastructure. For instance, traffic emissions are the most prominent and challenging source of air pollution in Nairobi (Rajé et al., 2018). Yet, investments in infrastructure at the national and city level have not yielded the desired results because of poor institutional arrangements (Kawira, 2014). However, infrastructure development is capital intensive and requires international loans, and devolvement to the city scale might result in unsurmountable problems. In addition, policy interventions intended to reform transport services in recent years have been unsuccessful as policy has been driven by political interests rather than by a concern with formulating a holistic people-centred approach. Thus, a representative of an NGO noted that:

"The problem is that [air quality policy] was being done in an ad hoc way without proper thinking through and without proper planning, which will end up causing more problems than solutions. So, it isn't that it is not a good idea but if it is done without thinking through very careful planning, it can end up bringing more problems than we have even expected (Non-Government Institution/NGO, Kenya 20, 22 February 2019)".

In addition, any air quality intervention needs to recognise that the transport sector is one of the largest employers in Nairobi; feasible and inclusive interventions must be identified reduce air pollution rather than ambitious political projects based around major infrastructure capital investments (NCC, 2018).

In cities, political debate, and related policy outcomes, is informed by a complex nexus of policy-related actors including opposition parties, residents, community groups, lobbying groups including NGOs, academics, and other interested parties. Effective lobbying by a group interested in a single-issue may distort urban outcomes undermining the ability of a city to deliver better outcomes for all. Thus, what is required is the application of a more holistic urban diagnostics approach to support the identification of cross-cutting policy interventions that would enhance urban living and livelihoods. For air quality, more urban diagnostics is needed to support the development of city-based discussions focused on identifying pathways towards more sustainable economic growth. A key issue remains the need for reliable and integrated urban diagnostics to support policy development and implementation intended to enhance air quality and to encourage sustainable development. This type of approach to policy development needs to be implemented as soon as possible given population growth projections and their implications for air quality and this requires strong political leadership at all levels of government.

5 Conclusions: Towards a systems approach to air quality management in nairobi

This study developed an urban diagnostics approach to assessing the state of air quality and air quality management in Nairobi. The assessment focused on the likely impacts of Nairobi's increasing population and urban housing, transport and energy infrastructure provision. Based on the analysis, we conclude that Nairobi faces challenges related to policy integration, overlapping mandates, and institutional coordination within and between government institutions at both national and city levels. This poses a major threat to air quality and the links to health and wellbeing and productivity in Nairobi. Effective implementation of local air quality management action plans requires the support of an urban diagnostic process combined with a systems approach to defining the problem and developing solutions.

There is evidence of high levels of $PM_{2.5}$ in the city arising mainly from inadequate transport causing traffic congestion and energy infrastructure linked to cooking and heating. It is important that solutions to enhancing air quality are implemented sooner rather than later in Nairobi. Population growth trends indicate there will be increased pressure on existing infrastructure and an increase in energy demands and this will exacerbate air pollution. Appropriate regulations are required to improve urban air quality, alongside effective implementation, monitoring and evaluation mechanisms. Such regulations must be evidence based taking into consideration the social, economic and environmental factors that are the causes of air pollution in Nairobi to promote responsible and healthy behaviours (Andres et al., 2020)

Current air quality data in Nairobi are generally adequate for information and public awareness purposes but cannot support the development and testing of possible mitigation interventions (including relevant tools) intended to bring anthropogenic atmospheric emissions into line with WHO guidelines. The problem is the lack of well-established air monitoring networks operating in urban areas that are able to provide long-term observations of pollutants. Raising awareness of the air pollution problem will sensitize the public to the wider impacts and the need for behavioural change, but what is required is a systems approach based on balancing local, city-wide and national interventions combined with alterations in household behaviour. The City County must be encouraged to develop a systems approach including significant investment in the technical and human resources needed to generate reliable air quality data that is required to couple the monitoring of air quality levels with numerical modelling to create scenarios for regulatory purposes. This should be in addition to the formulation of people-centric and liveable infrastructure and socioeconomic development policies that focus on altering norms, expectations and behaviours regarding mobility, cooking, heating and cooling (Andres et al., 2019). Recognising that transport is a means to an end and has an impact on the livelihoods of the majority but related emissions impact on health of the people is an important starting point for enhancing air quality. One outcome would be investment in transport infrastructure intended to create more environmentally friendly jobs.

Interventions intended to increase air quality informed by an urban diagnostics approach would include transformations to address air pollution from source and this requires systemic change in liveability and livelihoods. Taking such policy actions now will not only address short-term economic needs but would also prevent the worst case environmental and public health scenarios from emerging based on currently unsustainable behaviours. The United Nations call to "leave no one behind" highlights the need to encourage and support individual behavioural change to achieve the SDGs but this also requires alterations to urban infrastructure, planning and societal norms that are required to underpin behavioural change (UN, 2017; Rajé, 2018).

The key implication of this paper's contribution relates to the need for policy formulation and implementation that is based on an appreciation of the structure–agency relationships that sit behind sources of air pollution. This includes the need for alterations in urban planning and related infrastructure, combined with societal norms including local cultures that shape local lifestyles including cooking conventions. This type of policy intervention must provide a framework to support individual and group action. These frameworks must balance liveability with livelihoods to enable all urban residents to create sustainable and healthy lives whilst minimizing environmental pollution.

Conceptually and methodologically, this paper has contributed to the need for city-region transformations based on the development of a systems approach informed by urban diagnostics to underpin policy development and implementation. In addition, this approach offers the opportunity to triangulate quantitative and qualitative data on a single socio-environmental issue thereby promoting interdisciplinary approaches to addressing sustainable development challenges. This application of urban diagnostics to Nairobi can be applied to other cities by combining quantitative and qualitative approaches to understanding major societal challenges. Further research is required that explores the integration of national regulations with local air quality actions to promote effective local urban air quality improvement. Key policy and research challenges are to deepen understanding of the links between infrastructure, societal norms, culture and local traditions and behaviours, structures and policies that contribute to urban air pollution.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the data collection had ethical approval from the University of Birmingham Ethical Committee (ERN_17-0994B). The patients/participants provided their written informed consent to participate in this study.

Author contributions

AS: Investigation, Writing—original draft, Methodology, Formal analysis, Data Visualisation, Writing—review and editing; HB: Writing—Original draft, Formal Analysis, Writing—review and editing; AM: Writing—Original draft, Methodology, Formal Analysis, Writing—review and editing; WA: Writing—review and editing; D N: Validation, Writing—review and editing; MG: Writing—review and editing; SB: Writing—review and editing; GT: Funding Acquisition, Writing—review and editing; JB: Funding Acquisition, Methodology, Validation, Writing—review and editing; LA: Funding Acquisition, Writing—review and editing; AQ: Funding Acquisition, Writing—review and editing; MB: Funding Acquisition, Writing—review and editing; EN Writing—review and editing, Validation; GM: Writing—review and editing, Validation; TR: Writing—review and editing, Validation, FP: Funding Acquisition, Supervision, Writing—review and editing, Validation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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