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Air Quality in Africa: Public Health Implications

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Keywords

Africa, air pollution, public health, urbanization

Abstract

This review highlights the importance of air quality in the African urban development process. We address connections between air pollution and (*a*) rapid urbanization, (*b*) social problems, (*c*) health impacts, (*d*) climate change, (*e*) policies, and (*f*) new innovations. We acknowledge that air pollution levels in Africa can be extremely high and a serious health threat. The toxic content of the pollution could relate to region-specific sources such as low standards for vehicles and fuels, cooking with solid fuels, and burning household waste. We implore the pursuit of interdisciplinary research to create new approaches with relevant stakeholders. Moreover, successful air pollution research must regard conflicts, tensions, and synergies inherent to development processes in African municipalities, regions, and countries. This includes global relationships regarding climate change, trade, urban planning, and transportation. Incorporating aspects of local political situations (e.g., democracy) can also enhance greater political accountability and awareness about air pollution.

Without good data, we're flying blind.
If you can't see it, you can't solve it.

—Kofi Annan (13)

1. INTRODUCTION

Air pollution is the most important global environmental factor of ill health (25, 76). Recent estimates ascribe 8.9 million deaths per year to airborne particulate matter smaller than 2.5 μm ($PM_{2.5}$) (22). From the first studies of London smog to sophisticated contemporary models and experimental studies, we have increasing insight into how air pollution influences health and the biological pathways from exposure to effect (25). The research has expanded from Europe and North America to Asia and South America. Africa, however, has been blindingly left behind in this quest for cleaner air and better health (26). In this review, we aim to highlight the importance of focusing on air quality in the process of sustainable urban development in Africa, a continent undergoing rapid urbanization with an extreme shortage of air pollution data (138).

The lack of attention this issue receives likely results from other pressing social, economic, and health-related problems, creating a negative feedback loop. The lack of data reduces public awareness and concern, which in turn leads to a lack of policy action; without policies to follow, few incentives exist to collect data. Better air pollution data enabled by capacity building could enhance public concern followed by a grassroots demand for, and development of, clean air strategies, as has been seen in Europe, North America, and more recently, China (54). Addressing air pollution could also drive other positive changes in relation to health, climate, and well-being.

This review addresses the connections between urban air pollution and (*a*) rapid urbanization, (*b*) social problems, (*c*) health impacts, (*d*) climate change, (*e*) policies, and (*f*) new innovations. We conclude with considerations for potential policy responses, new technologies and innovations, and further avenues for research. The interdisciplinary team compiling this review comprises researchers from epidemiology, medicine, engineering, natural sciences, and social sciences in close collaboration with African colleagues.

2. SETTING THE SCENE

2.1. Rapid Urbanization

Since 2007, there are more people in urban areas than in rural areas worldwide (72, 131). Although 60% of the African population lives in rural areas, urbanization is ongoing across the continent at a speed unprecedented in history (131). The continent's population is anticipated to be primarily urban by 2035 (109). The population is growing faster than the supporting infrastructure, leading to changes in urban environments that are hard to control. This burgeoning urban population can lead to an increase in deaths attributable to air pollution. A recent study suggests that for each percentage point increase in the urban African population the death rate of children under the age of 5 doubles (105).

With such rapid urban changes, serious coordination deficits (50) in urban planning and development strategies might occur. For instance, planned and unplanned buildings will likely reduce green areas in cities, resulting in biodiversity loss (46, 100) and an increase in urban heat island effects (87, 126). Both phenomena have negative impacts on human health and well-being (118), and studies from other parts of the world show that urban green areas are associated with mental health (77, 117). One study conducted in Nigeria showed that two-thirds of the socioeconomically disadvantaged population was dissatisfied with their access to green areas compared with less than one-tenth of people living in high-income areas (99). Moreover, the urban poor's already suboptimal health status might be worsened by the absence of waste and sanitation infrastructure (11). It is estimated that 189 million people, 20% of the total population in sub-Saharan Africa, live in slums (134) where population density is high, access to formal services such as waste collection or provision of clean water is low, and coordinated efforts for improving well-being are challenging at best and impossible at worst.

2.2. Pressing Social Problems

Social problems such as lack of jobs and poverty can diminish the concern that citizens and politicians show toward air quality. Although many cities in Africa have achieved improvements in air quality over the last few decades, many basic needs remain unmet (2). While the percentage of African people living in poverty decreased from 56% in 1990 to 43% in 2012, the total number increased (2). Additionally, the African continent has an informal employment rate of 86%, the highest rate globally (56). Most workers, particularly women and youth, lack social security and conditions to move out of poverty (2). Access to clean water and sanitation (Sustainable Development Goal 6, adopted by the United Nations) is lacking for many households (145). Access to improved sanitation was 36% in 2015, an extremely low number in comparison with, for example, Latin America at 83% or Asia at 62% (2). Malnutrition is common and mortality rates among children under the age of 5 and pregnant women are high (129).

The issues of political stability and respect for human rights are also of concern. Sub-Saharan Africa is still struggling with urgent challenges related to disregard for the rule of law, weak freedom of expression, and widespread corruption (1). Moreover, colonial and postcolonial systems often coexist with traditional and customary laws in a pluralistic environment (43). Although important improvements in terms of elected governments have occurred (48), elections still suffer from sporadic violence and fraud (48, 123). Moreover, many countries in Africa are still afflicted with armed conflicts (108). Thus, in the face of multiple challenges, such as high poverty, weak governments, widespread corruption, and violent conflicts, some governments in Africa may have difficulty prioritizing the monitoring, regulation, and control of air pollution (**Figure 1**).

3. THE AIR POLLUTION PROBLEM

3.1. Anthropogenic Air Pollution

Growing populations, increasing urbanization, and resource-intensive activities have made African cities a significant source of pollution. African urban growth rates are and will likely continue to

Figure 1

Common sources of air pollution. (*a*) Roadside waste burning (Addis Ababa, Ethiopia). (*b*) Vehicle exhaust (Adama, Ethiopia). (*c*) Indoor cooking with solid fuel (Adama, Ethiopia).

be the highest in the world at 3.1–3.8% annually (147). The World Health Organization (WHO) estimates that the annual median concentration of $PM_{2.5}$ surpassed 26 $\mu g/m^3$ in more than half of the African continent (142), greatly exceeding the limit of 10 $\mu g/m^3$, established by WHO as the annual average for healthy outdoor air (140). Air pollution monitoring is vastly lacking; among the 47 countries comprising sub-Saharan Africa, only 6 can provide long-term data on airborne particulate matter (PM), spanning a total of 16 cities (141). The few available emission inventories are seldom precise and are typically based on surveys of, for example, fuel consumption (91).

3.1.1. Outdoor air pollution. African PM emissions originate from sources different from those in developed countries (91). The predominant contributors to outdoor air pollution are the extensive number of old diesel-powered vehicles, poor household waste management, and households burning biomass (91), sources that include carcinogenic polyaromatic hydrocarbons (PAHs) and their nitro-derivatives (64).

The vehicle fleet is the greatest contributor to outdoor urban air pollution (51). The highway and road networks carry 80–90% of all passenger and merchandise traffic (47). There is a significant increase in the number of two-wheel vehicles used for public transportation (e.g., motorcycle taxis) (30). These two-stroke motorcycles use a mixture of gasoline and oil, a cheap and highly polluting fuel (15). Although the number of vehicles per 1,000 inhabitants is much lower in Africa than anywhere else (28), it is rising considerably (101). The increasing number of vehicles (91) and the lack of urban planning cause severe traffic congestion, which contributes not only to increased air pollution (113) but also to significant economic losses in terms of time and fuel. PM from road traffic is much higher in sub-Saharan Africa than in developed countries (91). In a review of eight studies of outdoor air pollution in African cities (covering seven countries), $PM_{2.5}$ levels varied between 40 and 260 $\mu g/m^3$ (90), compared with an annual average of 13 $\mu g/m^3$ in urban Europe (33) and 9 $\mu g/m^3$ in urban United States (58) in 2019. Road traffic was the main source of black carbon and $PM_{2.5}$ (88%) in four West African cities (32), with diesel exhaust being the largest contributor (7, 19, 55). Several elements associated with adverse health effects, such as chromium, cadmium, zinc, and lead, were found in PM at roadsides in Addis Ababa, Ethiopia (35). Diesel exhaust from road transport is of great concern, especially if the vehicle fleet is old and poorly maintained (106). Most vehicles in Africa meet this description. In fact, vehicles no longer upholding the environmental standards of their origin countries, such as Japan and European nations, are regularly shipped to Africa after the catalytic converters and air filters are removed (91). Africa is arguably becoming a dumping ground for the world's old cars, so-called superemitters (21). Moreover, exhaust emissions are not regulated in most African countries (91).

Overall, solid waste generation in sub-Saharan Africa is low, less than 0.6 kg per capita per day, compared with >1.5 kg per capita per day in developed countries (52). Despite this low quantity, solid waste still affects air quality. Due to lack of waste transport services and funding for waste collection, household burning is a common method of elimination (124) and a large contributor to air pollution (91). The total quantity of waste burned in Africa, by households and at dump sites, was 161.31 million tons in 2010 (146). Waste burning emits toxic pollutants such as PAHs (53), heavy metals (136), and dioxins (79).

3.1.2. Indoor air pollution. Biomass used for domestic cooking is high and increasing in most African countries (91). Wood, charcoal, and crop residues are used for 50% of the cooking and 30% of the residential heating in Africa (84). In many African countries, however, these numbers are much higher. Surveys conducted in 18 African countries indicate that at least 95% of the households use biomass for cooking (143). Burning biomass in traditional cooking stoves emits high levels of PM and a multitude of other pollutants, including sulfur oxides, nitrogen oxides, hydrocarbons, and carbon monoxide (91). For instance, in Addis Ababa the average PM levels during coffee making were 905 $\mu g/m^3$ in the personal breathing zone and 845 $\mu g/m^3$ in the room's background air (67). Another study from Addis Ababa measured indoor $PM_{2.5}$ in 59 homes in slum neighborhoods and demonstrated a 24-h average of 818 $\mu g/m^3$ (116), 30 times higher than the residential average of 27 $\mu g/m^3$ in developed countries (88). A quadruple increase in $PM_{2.5}$ was shown when animal dung rather than other biomass fuels was used (119). Indoor cooking exposes African women and their young children rather than men to much higher levels and longer intervals of air pollution (86). A study from Uganda and Ethiopia found that women were exposed to $PM_{2.5}$ levels that were 7 times higher than the levels to which men were exposed (102). This extensive exposure is causing long-term respiratory health complications and other diseases (37, 73, 85, 122).

3.2. Biogenic Saharan Dust

Half of the global atmospheric mineral dust originates from the Saharan Desert (71). Although the Sahara contributes to extremely high levels of total PM mass in some parts of Africa, the health impact thereof compared with that of anthropogenic sources has been questioned (42). Additionally, there has been no study of the combined exposure of biogenic dust and anthropogenic air pollution in any part of Africa (29, 44). Studies from Southern Europe show inconsistent results of health impacts from Saharan dust (65, 112). The dust lacks several of the toxic compounds that are generated by anthropogenic sources (65), but does have some components, such as calcium oxide (CaO), which can also originate from construction and road dust, and iron oxide (Fe_2O_3), which can emanate from vehicle brake disks (112). Simply excluding Saharan dust when modeling air pollution may inadvertently eliminate other sources of PM and thus mask true health effects (135).

4. HEALTH IMPACTS

Urban Africa is undergoing a rise in chronic diseases stemming from lifestyle changes, such as consuming a more Western diet and performing more sedentary work (98). Compounding this, the region continues to fight a battle against infectious diseases (83). In addition, Africa is subject to morbidity and mortality from air pollution: Adverse health effects attributable to air pollution have been extensively studied around the world, and studies conducted specifically in Africa are outlined below. Outdoor PM is increasing throughout the continent while indoor air pollution from cooking remains high. Thus, Africa faces a triple burden of disease due to changed lifestyles, infectious diseases, and air pollution. The region is also undergoing a demographic shift exemplified by a quickly growing young population and rapid urbanization, as often younger people from rural areas flock to urban centers searching for a better life. These developments further strain the already economically challenged population.

4.1. Outdoor Air Pollution and Health

The health impact of air pollution in African cities has only been sparsely studied, as highlighted by a previous review (26). Health impact studies of sub-Saharan outdoor air pollution are especially scarce; a systematic review identified 12 such studies of the sub-Saharan region. Of these 12 studies, 9 were focused on South Africa (26). When occupational exposure and coverage of the whole continent were added to the search parameters, still very few studies were found (62). Most of these studies focus on respiratory outcomes, and some focus on cardiovascular, prenatal, and mortality effects (62). Only 36 of all the identified studies focused on urban air pollution (62). Another review of studies of outdoor air pollution in sub-Saharan countries identified

23 studies, in which only 7 of the sub-Saharan countries were represented; moreover, 14 of the 23 studies were from South Africa (66). A majority of the studies were cross-sectional and used crude exposure assessments such as proximity to road or industry (66).

Despite this lack of research, recent health impact assessments indicate that sub-Saharan Africa suffers the highest burden of disease and premature deaths attributable to environmental pollution in the world (26). These studies, however, rely on effect estimates from other parts of the world, because data from the African continent is largely deficient (66) due to, for example, low access to quality healthcare, the coprevalence of infectious diseases, and differing sources of air pollutants (26). As a result, the health effects in Africa are likely underestimated. For example, the number of infant deaths in Africa that could have been prevented with better air quality are more than three times higher than previously estimated, causing 22%, or 449,000 [95% confidence interval (CI) (194,000, 709,000)], of all infant deaths per year (49). Even though it is already known that children and pregnant women are vulnerable to the effects of air pollution, studies from Africa suggest that HIV-infected individuals might also be at higher risks (16).

The discussion above indicates that the effects of air pollution have been identified despite the methodological challenges. Nevertheless, more studies are clearly needed to derive more precise exposure-response functions for the region. Also, poverty might increase individual susceptibility to air pollution due to poor health care; unaffordable nutrient-rich foods; and the increased likelihood of living in proximity to polluting industries, biomass burning, and unpaved roads (66). Urbanization not only increases the number of people exposed to outdoor air pollution but also subsequently raises the air pollution levels. The number of deaths attributable to air pollution globally is projected to double by 2050 (78), with many of these deaths occurring in Africa. Thus, there is a great need for studies of the health effects in this region that focus on outdoor air pollution.

4.2. Indoor Air Pollution and Health

Similar to health impact assessments of outdoor air pollution, studies of indoor PM exposure in Africa are lacking. Most studies of cooking emissions are cross-sectional and assess exposure by questionnaires (62). These data are seldom supported by measurements (127) or emission factors. Some studies of indoor exposure focus on dust deposited on household surfaces and have identified the hazardous chemicals DDT (dichlorodiphenyltrichloroethane) and DDE (dichlorodiphenyldichloroethylene) in the dust (62). In countries where many households rely on biomass for cooking, indoor air pollution is the largest environmental health risk factor (122). According to health impact assessments, biomass burning for cooking causes nearly 600,000 premature deaths in Africa annually (141). Epidemiological studies indicate that exposure to biomass combustion can cause pneumonia, acute respiratory infections, tuberculosis, chronic obstructive pulmonary disease, lung cancer, and asthma (70, 103). Most studies of indoor air pollution in Africa have focused on cardiovascular or respiratory outcomes (62). Increases in respiratory symptoms in households using biomass fuel have been demonstrated in South Africa (6, 85, 95) and Malawi (94). Indoor air pollution from cooking has been associated with premature mortality in adults (96) and children (5, 105, 114) and has been linked to poor neonatal health and fetal thrombotic vasculopathy in Tanzanian women's pregnancies (148) and to low birth weight in Ghana (10).

5. CLIMATE CHANGE AND AIR POLLUTION

Biomass burning contributes not only to severely polluted indoor air and poor health outcomes but also to climate change by emitted soot particles (57). Furthermore, deforestation, forest degradation, and loss of habitat and biodiversity can result from unsustainable harvesting of wood for fuel (12).

Temperatures in Africa are already high and will most likely continue to rise throughout this century. Depending on various climate feedback models, the best estimates indicate a warming of 1.3–3.2°C (125). The broad range of potential scenarios also adds uncertainties regarding how much climate change will impact air pollution, and how (104). For instance, climate change is expected to impact both formation and removal rates of air pollutants and their temporal and geographical distributions (40). African precipitation patterns are projected to change (20), which will impact the wet scavenging (i.e., deposition by precipitation) of PM and of water-soluble, particle-forming trace gases such as sulfur dioxide (SO_2). Such shifts would likely result in dry regions becoming more polluted (39, 41). Large uncertainties remain surrounding the sensitivity of air quality to climate change (75), and studies have mainly focused on the United States, Europe, and Asia.

Rising temperatures can promote ozone (O_3) and PM formation (38). Fang et al. (38) estimate that global O_3 and $PM_{2.5}$ levels will rise by 5% and 2%, respectively, increases that have already been reported in North America (59, 111). $PM_{2.5}$ is projected to rise throughout most of the African continent due to increased temperatures, whereas O_3 levels are expected to increase only over the Central and Southeast regions (38). Anthropogenic pollutants, including greenhouse gases, will probably increase over West Africa and are anticipated to become dramatically higher by 2030, primarily due to rapid urbanization (69).

PM from sources upwind of cities contributes to urban air pollution. These sources are affected by shifts in precipitation patterns, which can be catalyzed by climate change. Such alterations may increase the windblown soil and desert dust carried into cities (110). Climate change may also affect the frequency and intensity of wildfires (80, 81). The health impact of worsening air quality caused by climate change is relatively small compared with that of air pollution exposure in general and with other climate change effects, such as heat and extreme weather (78, 120, 137). Even still, a comparison of global mortality rates from past models of human-induced climate change illustrated large variation, with model means of 1,500 and 2,200 deaths due to O_3 and $PM_{2.5}$ exposure, respectively (121). A later study indicated that climate change will induce a substantially greater health impact, with up to 55,600 deaths in 2030 compared to the 21,500 deaths estimated to have occurred in 2010 (120). The Intergovernmental Panel on Climate Change (IPCC) (57) has stated that short-lived climate forcers like soot, nitric oxide, and methane emissions must be reduced to limit climate warming to 1.5°C. Such reductions would have the cobenefit of better air quality.

6. POLICY RESPONSE

Governance and regulation of air pollution present a tremendous challenge for many African cities. Although important global and regional initiatives for better regulation and monitoring systems exist, they are seldom regarded with urgency in the political agenda. Regulatory frameworks are generally weak or nonexistent, and most countries experience a poor knowledge transfer surrounding the health risks of air pollution (9). In this section, we explore the regulation of air pollution in African cities, the challenges of controlling outdoor and indoor pollution, and the role of attitudes and beliefs.

Globally, WHO's air quality guidelines (140) are the most comprehensive norms on air pollution. These guidelines were adopted in 1987, updated in 1997, and will be revised in 2020 (140, 144). Nonbinding in a strict legal sense, these norms are translated to national law as each country sees fit. A study conducted in 2015–2016 to determine whether the WHO's guidelines have been incorporated into national legislation found that there was no incorporation in many African countries, and that 45% of African countries lacked any air pollution regulation whatsoever (61). Cameroon, which adopted WHO guidelines for nitrogen dioxide (NO_2), O_3, PM_{10}, and $PM_{2.5}$, had the best regulatory framework (61). South Africa and Senegal have adopted WHO's standards for NO_2, while Malawi has incorporated the PM_{10} and $PM_{2.5}$ guidelines (61). No African country had adopted the guidelines for SO_2 (61).

Even with air pollution laws in place, monitoring and enforcing them are often beyond the capacity of many governments. Moreover, air pollution legislation in Africa typically focuses on industries, even though the most pressing pollution sources are road traffic and domestic biomass burning (17, 92).

6.1. Road Traffic

The levels of outdoor air pollution are a result of international trade policies allowing for second-hand vehicles and dirty fuels to be imported from Europe, North America, and Japan (9). This inequitable export of polluting vehicles and fuels deemed too dirty by their place of origin is not regulated on a global level. Instead, countries must set their own policies and standards. A small but important step toward rectifying this trade situation can be seen in the decisions of Kenya, Uganda, Tanzania, Burundi, and Rwanda to limit the sulfur content in fuels as of January 2015 (132).

Addressing traffic-related air pollution, however, requires more than strict rules on vehicles and fuels. Public transportation and infrastructure for walking and bicycling must be improved to provide safe alternatives to the personal vehicle (113). Such initiatives necessitate coordination at various governmental levels as well as collaboration with the private sector and civil society. Some cities are initiating more strict regulation, demonstrating that local governments can play a key role in mitigating air pollution. An important example is South Africa's Air Quality Act (Act 39 of 2004), which allows local governments to create their own standards (115). Furthermore, local governments often face a shortage of incentives and lack the capacity to monitor air pollution (11), which is why transdisciplinary, multisectoral collaboration is needed. On a larger scale, several regions are taking the lead in controlling air pollution. Gossas in Senegal and Plateau in Benin, for example, are members of BreatheLife (**https://breathelife2030.org/**), a campaign initiated by WHO, the United Nations Environment Programme, and the Climate and Clean Air Coalition, which can be considered a sign of political commitment to improve air quality. Indeed, BreatheLife's objectives outline the importance of governmental commitment, private sector innovation, and population-wide involvement for air pollution mitigation (**https://breathelife2030.org/about/**).

Transboundary air pollution is a significant problem in many African cities (149). The only binding norm concerning air pollution on a global level is the Convention on Long-Range Transboundary Air Pollution, which aims to reduce acidification of the environment as well as levels of ozone, organic pollutants, heavy metals, and PM (130). This Convention, however, has not been signed by any African country.

6.2. Indoor Air Pollution

Reducing indoor air pollution caused by biomass burning requires governmental action (17, 92). Laws (e.g., prohibiting particularly polluting fuels or banning outdated stoves) must be accompanied by development policies targeting households living in poverty and by initiatives enabling these households to improve their cooking conditions. Moreover, homeowners need to be better informed of the health consequences of air pollution, as many continue to use old stoves in parallel with modern ones because of cultural traditions (11). A review of interventions shows that encouraging behavioral changes can reduce child exposure to indoor air pollution (18). The study authors cautioned that the number of studies is limited and not robust enough to draw firm conclusions (18) and that the need exists for more research connecting air quality control, technological improvements, and behavioral change.

Policies related to reducing societal inequality can indirectly reduce exposure, as high exposure levels are experienced mainly by low-income and minority communities, and is thus an issue of environmental justice (4, 82). These communities often bear the economic and health-related costs of polluting industries and vehicles from which they reap minimal rewards. Additionally, women and children living in poverty are more exposed to indoor pollution (14) because they often lack resources to purchase, utilize, and maintain cleaner cooking solutions; are more exposed to dust from poorly maintained roads; and burn their household waste due to a shortage of waste collection services (74). Although some practices can be linked to cultural traditions, such as cooking with charcoal for better taste (67), most practices are performed because no better options exist. Thus, this already vulnerable group has little to no voice, choice, or agency to obtain cleaner air.

7. PROGRESSING TOWARD BETTER AIR QUALITY AND PUBLIC HEALTH PROTECTION

Regarding overall development strategies, there is ample evidence that urban air quality will become an increasingly important political, economic, and social issue for African countries. In this section, we discuss potential policy responses, explore technological innovations, and propose avenues for future research.

7.1. Potential Policy Responses

Policy responses to air pollution can occur at all levels—global, international, national, local, and individual.

7.1.1. Global and international commitment. Promising signs indicate that governance and regulation of air pollution will become more strict. First, the World Health Assembly unanimously adopted Resolution WHA68.8 in 2015 to address the health impact of air pollution on a global scale (139). Although this resolution is not yet binding, it has more strength than guidelines and provides an important sign of political commitment. Second, the United Nations adopted the Sustainable Development Goals, which include a variety of targets specific to air pollution, for example, the goals for good health and well-being (Target 3.9), clean and affordable energy for all (Target 7.1), and sustainable cities and communities (Targets 11.2 and 11.6). Because most countries have signed the resolution adopting these goals, it is expected that they will take measures toward regulating air pollution. Finally, air pollution is regulated indirectly through climate norms, such as the Paris Climate Agreement. As carbon dioxide (CO_2) emissions often coexist with other important polluters, improving air quality will be a gain of the commitment to combat global warming (68).

Policy commitment can also be embraced through international cooperation by African regions. For instance, all 15 countries that compose the Economic Community of West African States recently gathered to develop and adopt comprehensive regulations for cleaner vehicles and fuels (133). The initiatives included regulating the sulfur content of fuel, requiring imported vehicles to meet a EURO 4/IV emission standard (minimum), improving fuel efficiency, promoting electric vehicles, and improving consumer awareness (133). Once adopted, the regulations will be legally binding (133) and are anticipated to significantly improve air quality in West Africa.

7.1.2. National and local commitment. While global and international campaigns are influential, initiatives at national and local levels are necessary. National and regional regulation should be firmly established, with the adoption of the WHO guidelines signaling commitment to better air quality. In addition to regulation, air pollution monitoring and capacity building are cornerstones of air quality control. Furthermore, the dissemination of scientific knowledge regarding adverse health effects of air pollution is crucial to raise awareness, to stimulate behavioral change throughout the general public, and to motivate political commitment. Considering the social needs in African cities, air quality policies should be articulated in connection to policies that address citizens' basic needs and broader societal challenges. For instance, in discussing how air pollution is intertwined with health, poverty, sanitation, transportation, and climate change, more governmental departments, private investors, and regular citizens may understand the urgency and be inclined to act. In this way, African cities could develop policy responses that are context specific and tailored to their own needs as well as generate intersectoral action.

7.1.3. Individual commitment: raising awareness. Attitudes and awareness about air pollution are critical to encourage behavioral changes (89, 97). Studies of attitudes and awareness about air pollution in African cities showed that knowledge about health effects is limited (34, 89, 97). Among people with limited awareness are those working in close proximity to the streets (97). Exposure to high concentrations of air pollution is an everyday occupational hazard for street vendors, rickshaw and bus drivers, and shop clerks (11, 92, 97). A Nairobian study of air pollution awareness reported that many people felt powerless to demand air quality controls (89). As awareness is essential to inspire agency and to generate change, we agree with researchers who emphasize the importance of participatory research methodologies (93). Thus, residents' understanding of air pollution and their capacity to act can be improved.

7.2. Technological Innovations

Examples of technological innovations that could mitigate the problems stemming from air pollution include measuring air pollution, cleaner cooking, cleaner transportation, and satellite monitoring.

7.2.1. Measuring air pollution. As highlighted above, the lack of data from the African continent is a serious hindrance for mitigation actions. Future approaches therefore need to include technological innovations to monitor air pollution where the availability of stable electricity and Wi-Fi is scarce. Such devices, including cell phones, satellite remote sensing, and low-cost sensors, could also create awareness and design policies. It should be stressed, however, that investment in new technologies alone will not solve the problem of air pollution. The technological innovations must be compatible with this unique context and accommodate the multiple challenge areas where qualified staff, resources, and multisectoral, cohesive planning are lacking. With this in mind, low-cost sensors, as opposed to more expensive technologies that require trained personnel and high investment costs, could be a suitable option to address the scarcity of air pollution measurements in Africa. This shortcut, however promising, needs careful data calibration to ensure reliability (8).

7.2.2. Cleaner cooking. Many factors, including socioeconomic factors such as income, age, gender, and education, and product-specific factors such as safety, indoor smoke generation, cost, and stove price, affect a person's ability to use more-energy-efficient, less-polluting stoves and cleaner fuels (128). Field studies (3, 24, 27) in Africa have reported that saving firewood, reducing smoke, and shortening food preparation time were the main factors motivating the switch to cleaner stoves. Participants also named various health-related motivations for changing stove type such as fewer eye and respiratory symptoms, as well as improved health, particularly for women and children. Participants who chose not to switch to cleaner stoves cited a lack of understanding of how to use and maintain the new stove, the additional cost, and the new stove often being damaged upon arrival (36, 63, 116). Given some of the adherence problems identified, longer-term increased generation and distribution of electricity from renewable sources could spur adoption of appliances that greatly reduce indoor emissions.

7.2.3. Cleaner transportation. Improved public transportation can generate fewer traffic jams, less air pollution-related morbidity and mortality, increased physical activity, and increased mobility. Yet most African cities still rely on minibuses, motorcycle taxis, and other informal means of transport (23). As mentioned above, many of these cities receive outdated vehicles and fuels from countries and companies in other parts of the world. Such disadvantages slow the ability to make technological advances, and limit air pollution mitigation. Therefore, continued and expanded regulation of such imports is necessary. The growing production of modern and low-cost vehicles in Africa by African manufacturing companies in Uganda, Nigeria, and Ghana, among others (45), may help reduce the demand for imported vehicles. Local entrepreneurs, designers, and engineers have produced a range of vehicles adapted for both regular transportation and off-road terrain (45). Further support and resources could be provided to encourage sustainable manufacturing initiatives and eco-friendly products, such as the electric hybrid car produced by Kiira Motors Corporation in Uganda (45). Additionally, increasing investments in nonvehicular commuting, including bicycle lanes, and public transportation, such as the electric rail network in Addis Ababa (the first metro system in sub-Saharan Africa), are needed to reduce high-polluting, time-consuming traffic congestions.

7.2.4. Satellite monitoring. Satellite remote-sensing retrievals and ground-level estimates of pollutant concentrations offer new opportunities to understand the spatial and temporal distribution of air pollutants without having to establish expensive government monitoring regimes or rely on low-cost sensors (31). Increasingly, remote-sensing retrievals of aerosol optical depth are being combined with atmospheric chemistry models to produce accurate and fairly resolved estimates of ground-level concentrations of $PM_{2.5}$ (25). Such estimates are being used to approximate the global burden of disease, but some studies suggest that reliance solely on remote sensing tends to underestimate health effects (60). Despite this, the benefit of having nearly global coverage without having to rely on ground data offers advantages for Africa, where ground monitoring will likely remain sparse for some time to come.

8. CONCLUDING REMARKS AND OUTLOOK

African cities are amassing more inhabitants in a fast-paced and oftentimes unprecedented and unplanned expansion. This differs greatly from the urbanization that occurred in Europe during the mid-nineteenth century, when migrants were integrated into new labor-demanding industries, filling urgent needs for a workforce. European municipalities and states were also better equipped to keep pace with changing demographics. In many African cities today, urbanization occurs under poverty, whereby authorities lack the finances, human resources, mandates, and planning tools to support urban populations and their infrastructural needs (46, 50, 107).

Our review calls for a greater understanding of the complexities of air pollution and health in African cities. We implore the pursuit of interdisciplinary and transdisciplinary research that combines expertise from different disciplines and more involvement to create new instruments, models, and innovative holistic approaches. This is crucial for facilitating dialogue between key actors and stakeholders, including scientists, policy makers, nongovernmental organizations, and the public. The efforts of researchers can not only establish new air-monitoring projects in areas where data are lacking but also inspire local officials to continue monitoring after the campaign has ended, which the Eastern Africa GEOHealth Hub (138) has successfully done. Moreover, to be successful, research must incorporate conflicts, synergies, and tensions inherent to development processes in African municipalities, regions, and countries. This includes global relationships regarding climate change, trade, urban planning, and transportation. Incorporating aspects of local democracy can also enhance greater political accountability and awareness about the lack of political commitment to solving problems caused by air pollution.

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The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

All have contributed equally to this review from their respective fields, and authors are thus listed alphabetically in the byline. The contribution from each author is as follows: A.A., local context and air pollution levels in Africa; A.M.V., air pollution in a policy context; M.J., new technology for air pollution assessment; E.M. and T.T., air pollution and health; J.F., air pollution in a climate change context; C.I., air pollution sources, levels, and content; and C.S., air pollution from a social justice perspective. All authors have edited the text, reviewed previous drafts, acquired funding, and contextualized the focus of this article.

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