A citizen science approach for air quality monitoring in a Kenyan informal development

Manshur, Talib; Luiu, Carlo; Avis, William R.; Bukachi, Vera; Gatari, Michael; Mulligan, Joe; Ng'an'ga, David; Radcliffe, Jonathan; Singh, Ajit; Waiguru, Ezequiel; Wandera, Amos; Pope, Francis D.

DOI:
10.1016/j.cacint.2023.100105

City and Environment Interactions 19 (2023) 100105

Contents lists available at ScienceDirect

City and Environment Interactions

journal homepage: www.sciencedirect.com/journal/city-and-environment-interactions

Research Articles

A citizen science approach for air quality monitoring in a Kenyan informal development

Talib Manshur [a], Carlo Luiu [b,i], William R. Avis [c], Vera Bukachi [a,d,e], Michael Gatari [f], Joe Mulligan [g,k], David Ng'an'ga [f], Jonathan Radcliffe [h], Ajit Singh [i,j], Ezequiel Waiguru [f], Amos Wandera [a], Francis D. Pope [i,*]

[a] Kounkuey Design Initiative, Nairobi, Kenya
[b] Institute for Global Innovation, University of Birmingham, Birmingham, United Kingdom
[c] International Development Department, School of Government, University of Birmingham, Birmingham, United Kingdom
[d] Bartlett School of Sustainable Construction, Faculty of the Built Environment, University College London, United Kingdom
[e] Arup East Africa Limited, Nairobi, Kenya
[f] Institute of Nuclear Science and Technology, University of Nairobi, Nairobi, Kenya
[g] Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology, Stockholm, Sweden
[h] School of Chemical Engineering, University of Birmingham, Birmingham, United Kingdom
[i] School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, United Kingdom
[j] Institute of Applied Health Research, University of Birmingham, Birmingham, United Kingdom
[k] Kounkuey Design Initiative, Stockholm, Sweden

ARTICLE INFO

Keywords:
Citizen science
Air quality
Sensors
Informal settlements
Nairobi
Kenya

ABSTRACT

This paper investigates the use of a citizen science approach for air quality monitoring to explore the likely pollution impacts of the new Missing Link #12 road passing through the informal settlement of Kibera, within Nairobi. Citizen science approaches are gaining relevance in air quality monitoring thanks to the advancement in environmental monitoring technology and the opportunities created for community-based organizations to collect data on air pollution through low-cost sensors. Fourteen households located in proximity to the Missing Link#12 were equipped with optical particle sensors. Data collected indicated that people living along the road are exposed to levels of $PM_{2.5}$ and PM_{10} above WHO recommendations, mainly due to the particulate generated by the construction site and fuels used for indoor cooking. A community engagement workshop revealed that participatory approaches are useful for improving awareness of air pollution and associated health implications. It also allowed the community to enhance their capability to gain and use scientific tools to address local issues, and potentially lobby decision-makers to solve them. In the context of transport infrastructure development in African cities, such an approach can be a means of collecting data and monitoring the impacts of air pollution during and after road building.

1. Introduction

1.1. The association between exposure to air pollution and health impacts in LMICs cities

In 2015, the Lancet Commission on pollution and health estimated that air pollution was leading to the premature deaths of over 9 million people globally [29]. These values remain consistent nowadays, contributing to one in six deaths worldwide [18]. Air pollution can be broadly split into ambient (outdoor) and household air pollution [67]. Household air pollution (HAP) originates from cooking, heating, and lighting; ambient air pollution (AAP) is external to buildings and can result from man-made sources including electricity generation, vehicular emissions, agricultural fires, and natural processes like natural forest fires and wind-blown dust. According to WHO, HAP from biomass fuel smoke is a leading cause of global disability and mortality with an estimated 3.2 million deaths [74]. Similarly, the WHO estimates that AAP caused 4.2 million premature deaths [73]. The effects of air pollution on human health are well documented in a range of epidemiological studies and the economic cost of this health loss is significant;

* Corresponding author.
E-mail address: f.pope@bham.ac.uk (F.D. Pope).

https://doi.org/10.1016/j.cacint.2023.100105
Received 20 January 2023; Received in revised form 5 April 2023; Accepted 13 April 2023
Available online 3 May 2023

the World Bank estimates that globally in 2013 air pollution led to an estimated $5.11 trillion in welfare losses, and $225 billion in lost labour income [77].

Airborne particulate matter (PM) is a major environmental risk factor with well-documented short and long-term effects on human mortality and morbidity [64]. Several studies have linked non-communicable diseases including stroke, chronic obstructive pulmonary disease (COPD) and lung cancer respectively to exposure to HAP [13;28;30]. Gordon et al., [21] argue that half of the deaths due to pneumonia among children under 5 years old are brought about by HAP exposure.

Overall, it is estimated that air pollution is higher in LMIC cities, with over 92% of global pollution-related deaths occurring in these countries compared to higher-income countries [17]; Pope, Gatari, Ng'ang'a, Poynter, & Blake, 2018; [52], and 97% of cities with more than 100,000 inhabitants do not meet WHO air quality guidelines [2]. Within LMICs, health inequalities in urban areas contribute to increased exposure to air pollution that exposes those that live, work, socialize and commute in highly urbanized areas, which typically have a substantially higher concentration of air pollutants [47].

Despite the extensive links between air pollutants and human health, environmental degradation and the economy, the long-term monitoring of air quality is still under-resourced in many LMICs resulting in a poor understanding of levels of concentration and sources of air pollution [67,72]. A critical issue is the lack of longitudinal data, especially the apportionment of different pollution sources, such as vehicular emissions, industrial sources and resuspension of soil and dust, to the overall pollution [46]. An additional gap is the geographical and temporal understanding of how these contributions to pollution vary between urban, *peri*-urban and rural environments, as well as within them [2]. To date, a variety of air quality monitoring has been used to assess pollution levels in LMICs cities. These include predominantly ground-level quality monitoring [4], low-cost sensor-based technology [10,47;58], satellite remote sensing [4,70], air pollution modelling [34] and visibility as a proxy [56].

1.2. Engaging communities for air quality monitoring practices

Community engagement is gaining particular attention and relevance in air quality monitoring practices [71]. The Center for Disease Control and Prevention [9] defines community engagement as "the process of working collaboratively with and through groups of people affiliated by geographic proximity, special interest, or similar situations to address issues affecting the well-being of those people". Such an approach employs both research and actions, and it has the potential for addressing and tackling problems concerning air pollution at the community level and reducing inequalities in air pollution exposures [36]. Indeed, previous research indicates that communities and key stakeholder organisations working with professionals and policymakers can lead to significant outcomes in terms of solutions and policy development, especially contextually designed to meet local communities' needs. For these reasons, community engagement is also becoming an essential component of policy design, implementation, project governance, delivery, monitoring and evaluation [20,71]. Avis et al. [3] identify four levels of community engagement: 1) informing (i.e. providing information through different channels); 2) consulting (i.e. obtaining inputs from community members to identify needs, assets, setting priorities, making decisions); 3) collaborating (i.e. partnering with community members in processes of planning and decision-making) and 4) empowering (i.e. providing support to enable community members to define issues and create solutions).

Citizen science is considered one of the most frequent approaches to engage communities and, more in general, different stakeholders in air quality monitoring processes [71]. This approach is particularly employed to increase awareness of air pollution and understand its cumulative implications [33]. Indeed, citizen science is often motivated by the need and concerns of communities to investigate and understand health-related issues linked to exposure to air pollution. Typical examples are the concerns linked with the development or more in general the proximity of high-pollutant infrastructures like industries or High Volume Transport (HVT) corridors [6,27,75]. The advancement in environmental monitoring technology and specifically the availability of low-cost sensors that are becoming relatively cheap and easy to use is resulting in rapidly evolving approaches to air pollution monitoring [14,15,24], creating new opportunities for communities to collect data on air pollution.

In their review, both Ward et al. [71] and Commodore et al. [11] identify several outcomes linked to engaging communities in air quality monitoring processes. First, such practices are strongly associated with an increase in awareness about the issues of air pollution. This is especially valid in terms of understanding the wider impacts of air pollution and the health and social implications of vulnerability and exposure. By accessing such information, communities can organize and develop coping and mitigation strategies [5,16,23,27,50,54,60,69,75]. Another significant outcome can be identified in the enhanced capability of members of the community to gain increased understanding and scientific content knowledge and the ability to employ such assets to address local problems [25,31,50,53,60]. Moreover, involvement in the research process has been found to boost the community's sense of empowerment and contribution to science [22]. Finally, lasting partnerships are a common achievement of engaging communities in air quality monitoring campaigns, with positive results for the development of environmental, health and planning interventions and policies addressing the issue of environmental justice, especially at local and regional levels [7,8;35].

1.3. Case study - The Nairobi Missing Link#12 bypass

Nairobi, the capital of Kenya, is currently undergoing a significant urban growth period, with the population projected to nearly double by 2030 [49,66]. Home to around 4.3 million people (over 30% of Kenya's urban population), Nairobi has one of the highest population growth rates in Africa at 4% per year [26]. Nairobi's urbanization has led to a significant increase in infrastructure projects including the building of numerous new roads in and around the city, whilst air quality has decreased markedly over the last decade [12,49,56]. Da Silva and Charles [12] identify air pollution as one of the 15 hazards linked to HVT road infrastructure development in Nairobi. This situation has led the Nairobi City County, with the support of partners such as UNEP and the Stockholm Environment Institute, to set up a responsive regulatory framework to tackle air pollution [40–42,61].

In 2016, the Government of Kenya and the Kenya Urban Roads Authority (KURA) announced the development of a new high-volume-transport (HVT) road infrastructure connecting the Southern "Langata" Bypass with the Ngong Road and the Kilimani Ring Road. The project, named "Missing Link #12" (ML#12), aims to connect two of Nairobi's busiest roads with an infrastructure 60 m wide and 4.2 km in length, of which over 2.5 km goes through Kibera (Fig. 1).

Kibera is an informal settlement located southwest of the Nairobi Central District Business, hosting a population of more than 300,000 people subdivided into 13 villages across 250 ha. Such numbers make Kibera the most populated and densely packed informal settlement in Kenya [37,39,62]. Kibera is characterised by a high level of economic poverty, poor housing conditions, inadequate access to water, sanitation and hygiene (WASH) infrastructure, unreliable electric supply, waste management challenges, and poor levels of healthcare services. Moreover, people living in Kibera are significantly exposed to environmental hazards, fire outbreaks and flooding above all [32,38,43].

Although ML#12 has the potential to contribute to reducing traffic congestion and connectivity on Nairobi's roads, this development has caused a variety of issues for the community of Kibera. These include evictions and displacements at the clearance stage of construction,

Fig. 1. Missing Link#12 in relation to Kibera.

community severance impacts due to the physical separation caused by the road (see Figs. 1 and 2), and concerns over the deterioration of air quality. Indeed, the resuspension of soil and road dust by wind or moving vehicles, as well as construction work and industrial emissions, results in the pollution of coarse particles (PM_{10}) [48].

Fine particles are derived primarily from direct emissions from combustion processes such as gasoline and diesel fuel, wood burning, coal burning for power generation, and industrial processes [55] and travel long distances (over 100 km) with potential for high background concentration over a wide area [68]. Therefore, it is expected that the residents of Kibera will have greater exposure to polluted air, both during the construction phase and upon completion of the new road.

1.4. Aim of the study

Whilst ML#12 is likely to bring both benefits and disadvantages to residents of Kibera, the proximity to a major road often leads to greater exposure to air pollution [59]. To inform the development and implementation of effective pollution reduction and mitigation strategies, good quality data is required [57]. This study takes a citizen science approach to provide Kibera residents with calibrated low-cost sensors that allow them to collect their own air quality measurements. The study aims to identify the current state and awareness of air quality within the Kibera community and create a baseline index against which the effect of the new road development can be monitored. This will allow for informed decision-making on how to reduce locally generated air pollution, and adapt and mitigate against the air pollution that is outside the control of the community. Finally, the study assesses the impact of road-building development and community-based air quality monitoring on the Sustainable Development Goals (SDGs).

2. Methodology

The study employs a three-stage mixed-method approach using qualitative and quantitative data to investigate community-based air quality monitoring concerning HVT road infrastructure development affecting Kenyan informal settlements. Data collection methods employed for this study comprise: 1) air quality monitoring sensors deployment; 2) community engagement workshop and 3) phone-based questionnaire survey.

Fig. 2. Initial tarmacking of ML#12 - January 2020 (left) and road completed in November 2022 (right) (Kinyanjui, 2022).

2.1. Air quality monitoring

2.1.1. Study participants and recruitment process

Fig. 3 provides an overview of the strategy employed to carry out air quality monitoring. The initial stage involved engaging the community leaders of Kibera, providing them with an overview of the project aims and objectives to create awareness within the community through community cascading. A follow-on workshop was carried out with 20 Kibera residents to inform them of the project aims and objectives, explore the willingness of the community to participate and collaborate in the study and recruit potential participants for the installation of the air quality monitor sensors. In the workshop, the community members were engaged to express their views and experiences about air pollution in association with the development of ML#12. The discussion mainly revolved around the risks and opportunities that the new road could have on the community. The discussion also involved a demonstration of how the air quality sensors worked, with a specific emphasis on explaining and demonstrating the sensors, given the low literacy levels among participants and their eagerness to see the equipment in operation.

The workshop also provided the opportunity to recruit participants for the installation of the air quality monitoring sensors. A purposive sampling technique [65] was used to select the participants for this part of the study, building on the relationship between the Kibera community and the research team. Such an approach was used to was to facilitate a smooth entry point to the community and promote ease of participation in the study [19,39;45]. The study aimed to monitor how air quality in houses near the road building was affected by the excavation and transportation of materials. Households within 100 m from either side of the road were therefore selected to monitor the accrued effect of outdoor and indoor air pollution. Out of 27 potential participants, 15 were selected using the following selection criteria: 1) location and proximity to the road; 2) having diverse household characteristics and demographics. Following the recruitment, the research team visited the shortlisted households to assess their locations and demographics and identify where to mount the sensors. To avoid issues that could arise in the households concerning diverse cultures and values, participants were involved only with the permission of the head of the household. The number was then reduced to 14 households due to technical issues experienced during the data collection (see Section 3.1.2).

2.1.2. Deployment of optical particle sensors

Air quality monitoring was carried out between October and December 2020 (rainy season) with six small low-cost optical particle sensors AlphaSense OPC-N2 sensors (firmware version 18), following the design used by Pope et al. [47]. The OPC-N2 is a miniaturized OPC, which has dimensions of 75 mm × 60 mm × 65 mm and weighs under 105 g. The unit cost of an OPC-N2 is approximately GBP 250 or KES25,000; hence it is significantly cheaper than reference OPC instruments which cost approximately 30–50 times as much. To adapt the OPC-N2 design to the contextual conditions of Kibera, the sensor units were run on rechargeable battery packs to overcome a lack of/ unreliable electricity supply. Both pre-sampling and sensor calibration were performed before field sampling, following the approach employed by Pope et. al (2018) and Singh et al. [59]. This approach consisted in calibrating the sensors by using gravimetric measurements of $PM_{2.5}$ and PM_{10}. Gravimetric analysis is deemed ideal for light scattering instruments as it provides an absolute weight measurement [44] and weight can be measured with greater accuracy than other fundamental properties. Gravimetric measurements are also necessary to ensure that calibration is performed under optimum conditions, such as low relative humidity. The calibration was performed for five days at the Institute of Atmospheric Science laboratory of the University of Nairobi (Fig. 5) to collect particulate matter in the regulatory $PM_{2.5}$ and PM_{10} size fractions. Corrections and scaling factors were calculated through the comparison of the mass concentrations from the OPC sensors and the gravimetric instrument (Anderson dichotomous impactor from Sierra Instruments Inc., USA). The observed scaling factors between the OPC-derived $PM_{2.5}$ masses and gravimetric analysis were in the range of 1.8 ± 0.40.

In Kibera, exposure data were obtained from measurements over 48 h using the sensors connected to 20,000mAH power banks. Selected households were located along the stretch of the road from Kibera South Health Centre to the DC's office, within a 100-meter buffer from the centreline of the road on either side (Fig. 4).

Five households per time were equipped simultaneously with the sensors, which provided continuous readings for two days at high temporal resolution (every minute). An additional sensor was kept available during data collection as a backup option. The first cycle was allowed to run for 24 h thereafter, the power banks were changed after 24 h (one day) and replaced with fully charged ones to obtain two complete cycles of 48 h of data sampling. Each OPC sensor was installed inside the house and mounted at least 2 m from the floor of the house and, where possible, the monitors were attached to a wall or hung with strings from the roof. After enumeration and safe unmounting of the monitor at a household, the sensors were switched off and restarted from laptop programs prepping them for set-up in the following household. Data from all monitors were downloaded after the completion of the study and cleaned for analysis. Initial data inspection indicated that one household sampling was not successful with only intermittent data acquisition, which was likely caused by a loose cable. This issue led to reducing the number of households sampled to 14. A questionnaire was also administered to the participants to collect information about their households and to inform the analysis of the air pollution level data collected by the OPC sensors in each household. The survey comprised six sections: 1) Household Identification, 2) Household Characteristics, 3) City-Locality Interaction, 4) Health, 5) Perception of Air Pollution, and 6) Addressing Urban Air Quality Problems. The survey took about 45 min to be completed. The questionnaires were accompanied by a consent form that was signed and stamped in duplicate.

2.2. Community engagement workshop

A community engagement workshop was carried out following the air quality monitoring, to provide feedback to the participants and community members on the results of the air quality monitoring. The feedback was also used as a prompt to validate such findings with the community and also to investigate their views regarding air pollution. The workshop was carried out in January 2020 and included 30 people, comprising participants recruited for the air quality monitoring, community members who were involved in the initial engagement workshop, and members of the research team. The workshop was structured

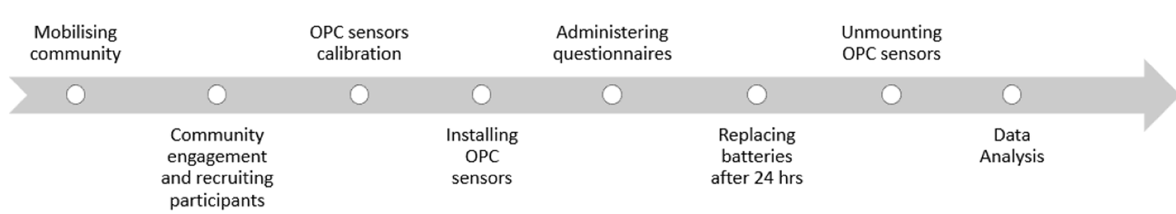

Fig. 3. Overview of the air quality monitoring process.

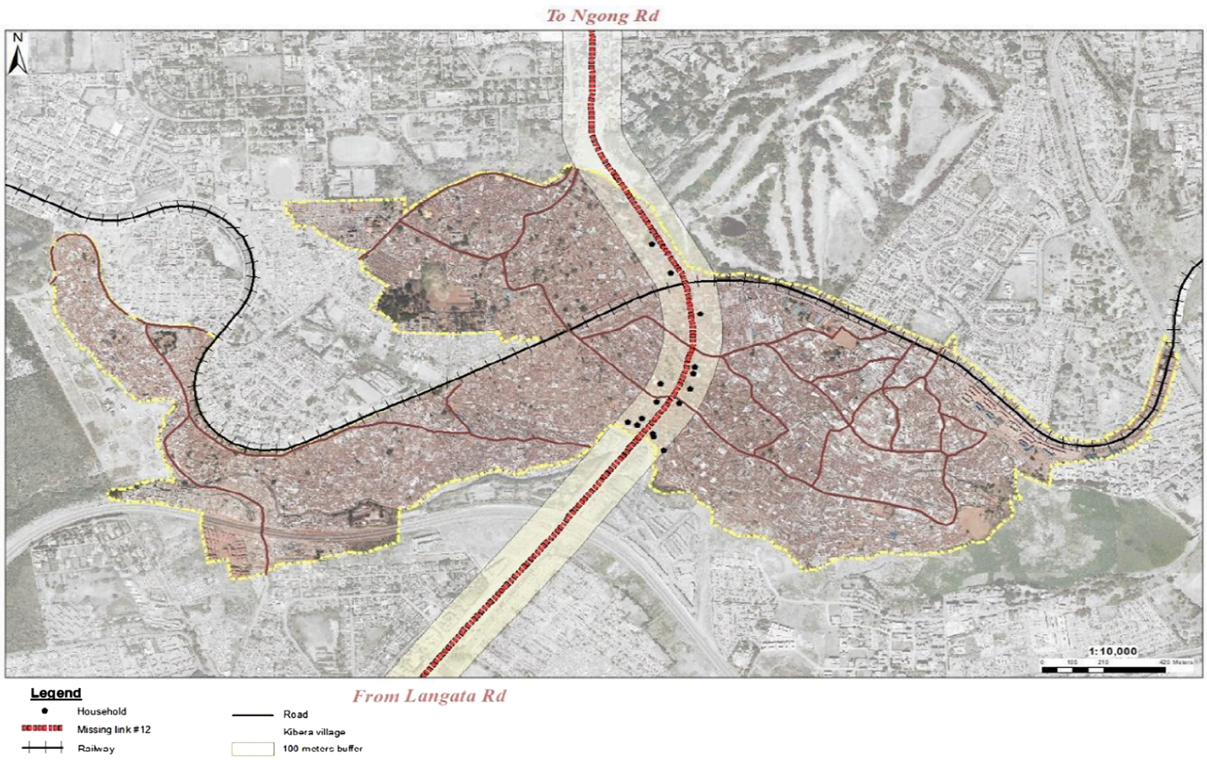

Fig. 4. Approximate household locations (circles) selected for the air quality monitoring.

Fig. 5. Side by side colocation of the OPC sensors with regulatory instruments at the University of Nairobi, for the calibration of sensors in the regulatory size fractions of $PM_{2.5}$ and PM_{10}.

according to the following sessions: 1) community understanding of the causes and effects of air pollution; 2) findings from the air quality monitoring; 3) community engagement with the research program and 4) community strategies to reduce air pollution exposure.

The workshop took place in a community building in Kibera. At the beginning of the session, participants were informed about the aim of the discussion and required to provide verbal consent to be involved in the project. At the end of the session, participants were thanked for their contribution with a "care package" including 2 kg of sugar. The sessions were audio-recorded with consent from participants, transcribed into Swahili and then translated into English for analysis. Qualitative thematic coding and analysis were carried out using the procedure outlined in Robson and McCartan [51], which involved 1) collecting participants' statements, 2) grouping and coding extracts of text with similar content; 3) developing the initial set of categories and 4) refining the initial set of categories into the final set of themes and sub-themes.

2.3. Follow-on survey questionnaire

A questionnaire survey was carried out between July and August 2021 to investigate the wider impacts caused by ML#12 upon the community of Kibera. The survey involved 452 households recruited according to a stratified random sample based on the geographical location from ML#12: 1) 25 m buffer; 2) 75 m buffer and 3) 150 m buffer. The recruitment process involved the following stages: 1) Random selection of structures within buffer zones at required density (from remote); 2) Community information to raise awareness of surveys amongst residents and local leadership; 3) Field census of selected - structures to record their status, number of households within each structure, and destination of use (residential/business); 4) Random selection of residential households (from remote); 5) Definition of a physical address system with development of structure and household codes; and 6) Recruitment of participants with collection of consent forms and contact numbers to participate in the survey. Table 1 provides an overview of the respondents' socio-demographic characteristics.

The survey explored the level of outdoor air pollution in Kibera, changes in air quality, vulnerability and exposure to air pollution, and potential health symptoms developed since the construction of the bypass. Similarly, indoor pollution was investigated by exploring sources of fuel for cooking and lighting in the participants' households. Finally, the survey investigated the levels of noise pollution, changes in noise quality and associated causes since the development of the bypass, but results for this part of the survey are omitted in this paper as secondary measurement and overall not relevant to the overall context. Similarly to the community workshop, survey participants have been thanked for their contribution with a "care package" including a shop voucher of the value of 200 KES (approximately 2 US dollars).

3. Results

3.1. Measuring air pollution exposure levels

Fig. 6 provides the $PM_{2.5}$ and PM_{10} distributions for the 14 measured households as individual boxplots for the 48 h of measurements in each household. Hourly averaged data is used in the figure so comparison with the WHO recommendations for 24 h average can be made. The boxplots are colour coded with respect to the primary fuel type of each household. The majority of households use kerosene (n = 10), with two households using LPG, one charcoal, and one firewood/sawdust as their primary fuel. However, most households used multiple sources of fuel. For example, all the households using kerosene as their primary fuel, use charcoal as a secondary fuel source. The 'energy ladder' concept suggests that as households become affluent, they use cleaner fuels, with the primary fuel types observed in this study typically being in order of cleanliness: LPG > kerosene > charcoal > firewood/sawdust [76]. In particular, solid fuels (charcoal and firewood/sawdust in this study) are found to be more heavily polluting than kerosene and LPG. There is some evidence in Fig. 6 that households using charcoal and firewood/sawdust as their primary fuel have greater indoor air pollution, but the sample size is too small to be definitive. The lack of information about when primary and secondary fuel sources were used further complicates interpretation. Each household was measured for 48 h in two 24-hour blocks. Table 2 provides the summary statistics of the average hourly $PM_{2.5}$ and PM_{10} mass concentrations averaged over all monitored households.

Overall, the analysis highlights that measured median average concentrations of $PM_{2.5}$ and PM_{10} are significantly above WHO annual average recommendations of 5 and 15 $\mu g/m^3$ for $PM_{2.5}$ and PM_{10}, respectively. It is noted that since the measurements were for only 48 h this extrapolation is not definitive. Many households' median hourly concentrations also exceed the WHO 24 hourly recommendation levels of 15 and 45 $\mu g/m^3$ for $PM_{2.5}$ and PM_{10}, respectively, Interrogation of individual household data indicates that household air pollution increases during the preparation of the main meals, which includes breakfast (7.00–9.00 am), lunch (12.00–1.00 pm) and dinner (7.00–10.00 pm).

Fig. 7 provides an example diurnal profile obtained from one household which used kerosene and charcoal as their primary and secondary fuels for cooking, respectively. Lighting within this household came from electricity so should not contribute to the household air pollution. Significant peaks in $PM_{2.5}$ and PM_{10} are seen at lunchtime and dinnertime. A further peak in PM_{10} is also seen in the afternoon which is not seen in the $PM_{2.5}$ signal. This suggests an additional source of coarse PM. Coarse particles are defined as $PM_{10} – PM_{2.5}$, and fine particles are represented by $PM_{2.5}$. Larger particles are often associated with mechanical processes such as the resuspension of dust from roads, especially non-paved roads [47,63].

To assess the role of the road construction upon household air pollution levels, the ratio of coarse particles to fine particles was investigated. Fig. 8 provides the ratio of coarse to fine particle mass concentration averaged over all households as a function of the hour of the day. The coarse-to-fine particle mass concentration ratio is higher during daylight hours when the new, but unfinished bypass road, which is close to the households, is typically used by informal traffic, including pedestrians, bicycles, motorcycles and other motorized vehicles. This suggests that the road in its unfinished state is already a significant contributor to household air pollution in the monitored households. This measurement is corroborated by qualitative evidence from the community engagement workshop, where household participants expressed the need to add extra curtains and other barriers to their households to filter and reduce the ingress of the increased dust from the road.

3.2. Air pollution, community engagement and associated perspectives

In late January 2020, the research team held a workshop for the participants from the air quality monitoring households, and other community members interested in air quality. The workshop was held with the twofold aim of providing feedback on early findings from the air quality monitoring, and discussing the overall implications of air

Table 1
Overview of respondents' socio-demographic characteristics.

Name	Variables	N	%
Gender	Female	284	62.7
	Male	168	37.3
Age	18–25 y.o.	116	25.7
	26–35 y.o.	155	34.4
	36–45 y.o.	97	21.5
	46–55 y.o.	54	12.0
	Above 55 y.o.	29	6.4
Marital status	Single	138	30.6
	Married/living with partner	313	69.4
Household members	1–3 people	145	32.2
	4–7 people	277	61.4
	8 or more people	29	6.4
Monthly income[*]	Below 5000 KES	89	28.8
	5001–7500 KES	106	34.3
	7501–10000 KES	75	24.3
	Above 10,000 KES	39	12.6
Health problems	No	417	92.5
	Yes	34	7.5
Type of fuel used for cooking	Kerosene	265	33.2
	Charcoal	222	27.9
	LPG	268	33.6
	Electricity	42	5.3
Location indoor cooking	Indoor kitchen	223	49.3
	Room used for living/sleeping	186	41.2
	Kitchen detached from house	18	4.5
Household distance from ML#12	Buffer 25 m	147	32.6
	Buffer 75 m	157	34.7
	Buffer 150	148	32.7

[*] 100 KES approximately 1 US Dollar.

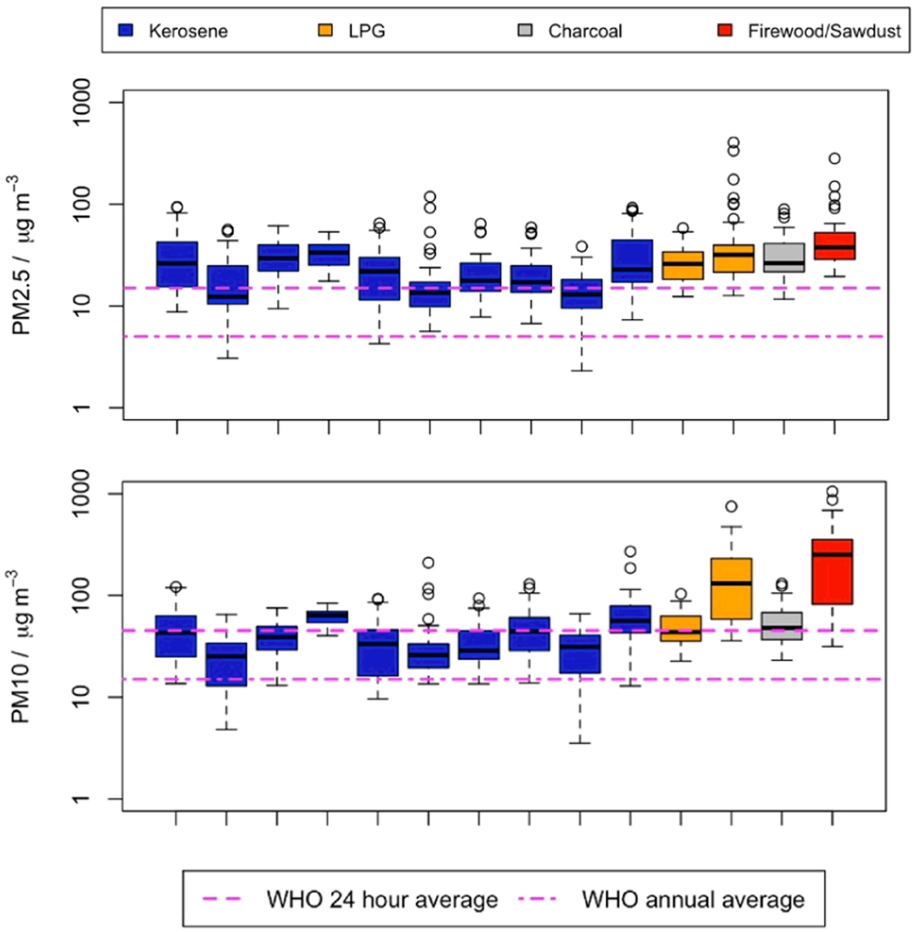

Fig. 6. Boxplots showing the distributions of $PM_{2.5}$ (upper panel) and PM_{10} (lower panel) air pollution measured in the 14 households.

Table 2
Summary statistics of hourly averaged data over all measured households (n = 14). All values are in mass concentration in μg/m^3.

Pollutants	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum
$PM_{2.5}$	2.3	14.4	23.1	28.7	34.3	404.5
PM_{10}	3.5	27.4	43.0	63.5	64.2	1053.8

pollution with the community.

Following the presentation of the findings from the analysis of the air quality monitoring, several themes emerged from the participants of the study. The overarching theme was the increase in awareness about air pollution among the community members and particularly its health implications. The findings from the sensors showed participants the poor air quality in their households and backed up their assumption that this was related to respiratory illnesses such as cough, bronchitis and tuberculosis: *"I was happy to see the sensor machine in my house. Our*

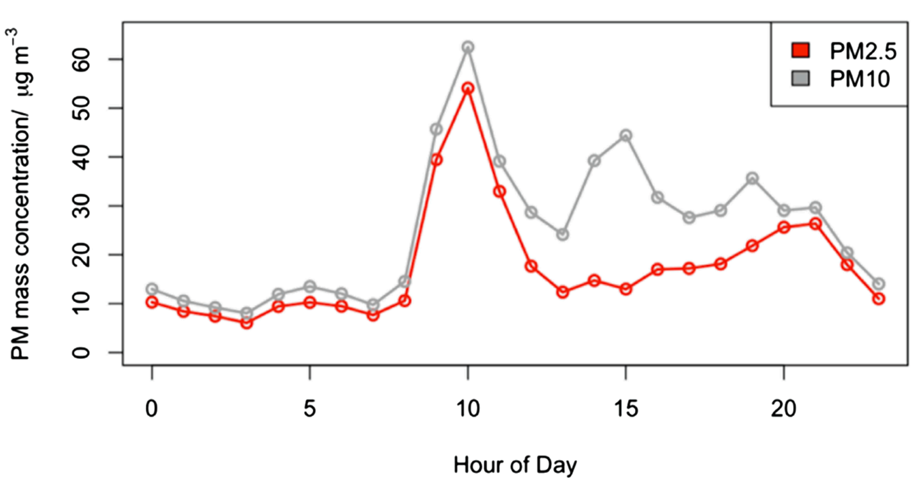

Fig. 7. Example diurnal profile $PM_{2.5}$ and PM_{10} concentrations within one household which used kerosene and charcoal as their primary and secondary fuels for cooking, respectively.

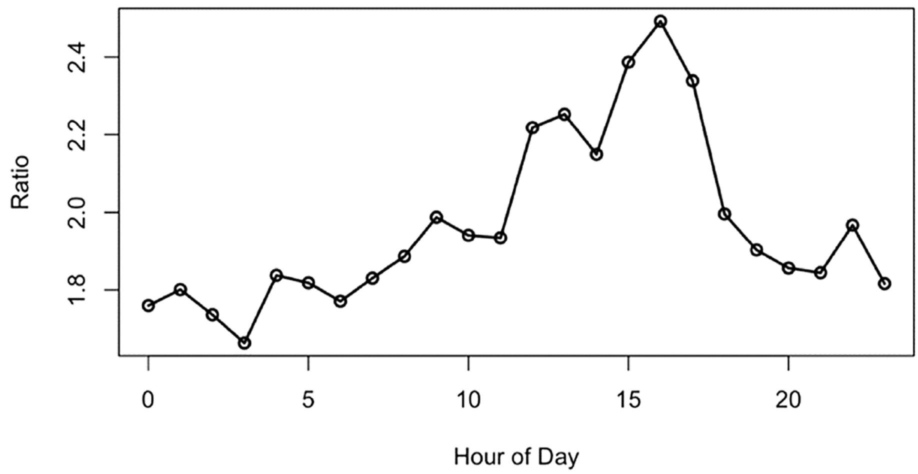

Fig. 8. Diurnal profile of the coarse to fine particulate matter ratio using data from all measured households.

environment is not good, so many diseases are emerging, for example, cough, tuberculosis, and bronchitis. The sensor was helpful as it informed us on the quality of the air we breathe". Moreover, community members stated that having scientific evidence that the air they breathe is contaminated can allow them to lobby for community improvements: "*I believe that the research was like testing for the time. As a pastor, we ask for someone who can intervene to help us get a hospital now that the research tells us the air we breathe is not safe or contaminated"*.

The change in awareness led the participants to discuss how to change the situation and identify a set of actions that would help to reduce air pollution in the community. The main actions that were mentioned included creating awareness of maintaining a clean and healthy environment, cooking outside or in well-ventilated rooms, considering alternative sources of fuel to cook, opening windows to allow a clean inflow of air, wetting the floors before sweeping to reduce the spread of dust, smoking cigarettes outside the house, placing nets on windows, covering the mouth and nose when commuting on boda-bodas (motorcycle taxis) and planting flowers, trees, grasses.

Another important aspect that emerged from the discussion was the awareness of the impacts created by the development of the ML#12 bypass from an environmental perspective. The ML#12 project has had significant social impacts on the community members of Kibera, especially from a social point of view due to eviction, relocation and loss of livelihood. However, very little was considered from an environmental perspective. The participants acknowledged that the construction of the bypass is affecting them (and will do in the future) and discussed what should be changed: *"The engagement process was good, we felt we were not abandoned. At least we will know how the road will affect us and what we have to change"*. It emerged that the road construction has increased their vulnerability towards air pollution by polluting the air they breathe and also chances of respiratory complications*: "The road construction road has polluted the air we breathe thus resulting in disease-related outbreak. Gases like carbon monoxide, when inhaled in high concentration and because of the poor ventilation, can cause death"*.

Moreover, the topic of the construction of ML#12 led to a wider discussion about its environmental impacts, and the implications associated with infrastructure development in general. One clear message that emerged from the workshop is that the community is concerned with a range of environmental factors in addition to air pollution, including flooding, water management (drinking water quality, sewerage treatment, inadequate toilet), noise, heat and household lighting.

A follow-on survey involving 452 households in Kibera outlined that, overall, 45% of respondents stated that the air quality in Kibera in the proximity of the ML#12 is poor. The vast majority of respondents (89%) reported that the air quality in Kibera has changed since the beginning of the construction of the bypass. Around three-quarters of respondents mentioned that air quality deteriorated, with 28% a little worse and 43% much worse. In terms of vulnerability, almost two-thirds of the respondents felt vulnerable to air pollution, with 42% and 22% feeling vulnerable and extremely vulnerable, respectively. Considering proximity, participants living within the buffer of 25 m from ML#12 felt more affected by the development of the road compared to those living within a buffer of 75 m and 150 (Fig. 9). Indeed, participants living closer to the road reported having higher levels of feeling extremely vulnerable to air quality (36%), expressed that the air quality had got much worse since the starting of the construction (59%) and overall the air quality in Kibera is poor (50%).

Looking at indoor air quality, 95% of respondents had access to electricity supply in their households, which was used as their main source of lighting. Other sources of lighting mentioned included candles (19%) and kerosene (12%). For cooking, data indicate that the most used fuel options were liquid petroleum gas (62%), kerosene (61%) and charcoal (51%). More specifically, participants reported using such fuels according to a variety of combinations, such as kerosene and charcoal (20%), kerosene and liquid gas petroleum (14%) and charcoal and liquid gas petroleum (12%). About half of the respondents usually cook in a kitchen inside the house (52%), while most of the remaining participants do it in a room that is used also for living and sleeping inside the house (43%). Participants were also asked if they had developed any symptoms since the beginning of the construction of the bypass. Main symptoms reported were dry cough (56%), productive cough (36%) and eye problems (20%). A geographical differentiation showed again that respondents living closer to the road (buffer 25 m) mentioned suffering more from dry cough (21%), eye problems (9%) and allergies (9%) compared to those living more distant from the road.

A data disaggregation by socio-demographic characteristics revealed that people living with health impairments/issues feel more vulnerable to air pollution (82% vs 63%). People aged 45–54 years old and those above 55 years old experienced more deterioration and changes in air quality since the development of ML#12, with the latter also feeling more vulnerable to air compared to all others (72% vs 64%). On opposite, people earning more than 10,000 KES per month felt less vulnerable than the other income groups. Participants with a monthly income below 5,000 KES were found to rely more on charcoal and kerosene (for both cooking and lighting) and less LPG compared to higher income groups. Similar trends were found also for people aged above 55 years old. Overall, no specific patterns were identified with regard to gender, marital status and the number of people living in the household.

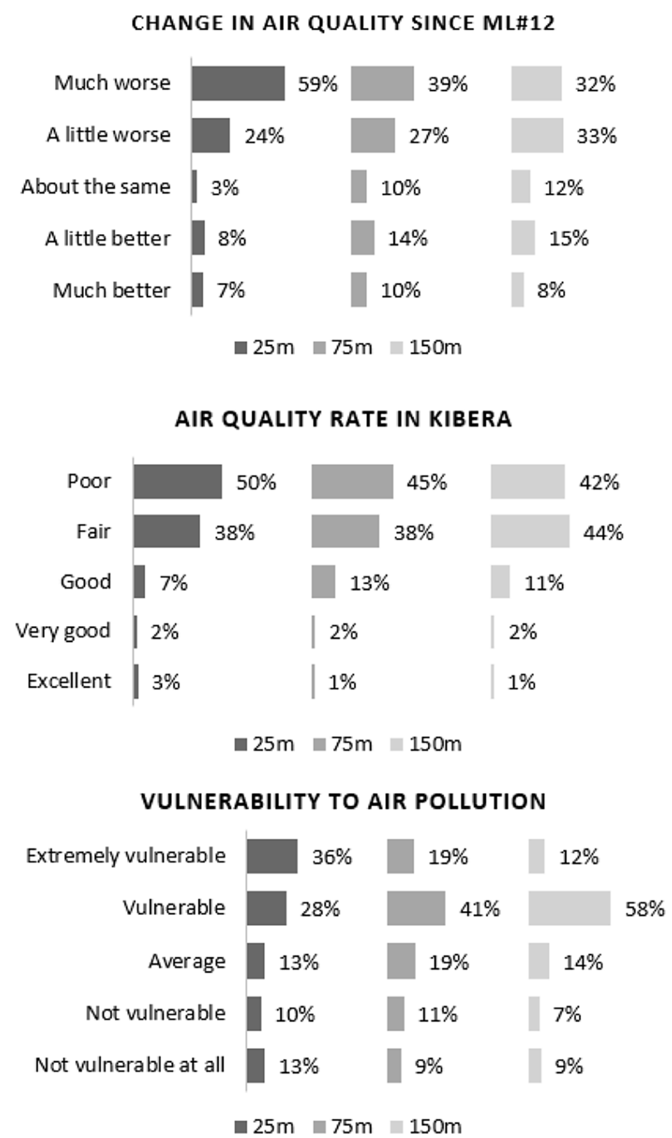

Fig. 9. Perceived air pollution impacts by geographical distance from ML#12.

4. Discussion

In this study, we have shown the validity of a citizen science approach for air quality monitoring to understand the impacts of HVT road infrastructure development. This approach allowed local-based actors, with expert support, to collect data from low-cost sensors to measure the baseline air quality situation before the new road becomes used for its formal purpose. The overarching finding from the study is that community members involved in the study in Kibera improved their overall understanding of the risk of poor air quality. The residents that were engaged in reflecting upon and thinking differently about air pollution increased their awareness regarding personal exposures to air pollution, sources of pollution, vulnerability to poor air quality, and associated implications for their health. In a context like Kibera, where residents face constantly significant and more “tangible” challenges due to the contextual conditions in which they live, increasing awareness of the implications associated with air pollution assumes even more relevance. Whilst residents may be more concerned about issues such as accessing job opportunities and services and exposure to environmental hazards (flooding and fire outbreaks), the disproportioned impact of poor air quality on vulnerable and low-income areas and households is a matter of significant concern causing death and illness, with also associated economic costs.

The use of citizen science for air quality monitoring was found also to contribute to a better understanding of local environmental issues that can potentially drive constructive and progressive dialogues between communities and local authorities. Such dialogues, that consider the impacts of air pollution on health, should help shape urban infrastructure planning and development to improve outcomes for residents. The air quality monitoring coupled with the outcomes of the quantitative survey data showed that the new bypass road was likely causing significant increases in household air pollution, especially within households in the proximity of the new road. During the data collection stage, the road was under construction and largely unpaved, hence extremely prone to resuspend dust when vehicles, using it informally, travelled upon it. The completion of the new bypass will involve the dressing of the road surface, which will reduce the resuspension of dust per vehicle. However, the number of vehicles that will use the road will increase dramatically as its use turns from informal to formal use. More vehicles will mean more exhaust emissions and potentially more non-exhaust emissions dependent on how road dust suspension is affected by higher vehicle use on a less dusty surface. The effect on overall air pollution levels is yet unknown, but this study provides useful baseline data with which to assess the effect on the Kibera community. Such findings also confirm that air pollution is a potential hazard in HVT infrastructure development in Nairobi, as highlighted by Da Silva and Charles [12], and that health impacts from air pollution due to road building should be assessed from the design stage, and monitored during and after the construction.

Certified air quality monitoring is a well-acknowledged financial challenge for governmental, environmental, and local authorities/organisations in the Global South context. The use of low-cost sensors can be a valid option to create a reliable and cost-effective air quality network to monitor pollution, as shown by Code for Africa [10]. This is particularly valid in the context of HVT infrastructure development. Low-cost sensors can provide a dynamic network tailoring hotspots where specific measurements are required, or monitor locations affecting vulnerable groups of society. Previous research in the East Africa context (see [47;59]) has shown that traffic-related emissions are among the main contributors to urban air pollution. Our study provides baseline data to monitor the changing levels of air pollution in households as ML#12 continues to be constructed and ultimately used. Source apportionment techniques allowed for the disaggregation of the outdoor and indoor sources of air pollution, allowing for an ambient air quality index baseline to be established. The availability of real-time monitoring at one-minute intervals over 48 h using low-cost devices enabled the reporting of detailed temporal pollutant patterns including the characterization of peak exposure periods among the different households. Employing a 48-hour measurement allowed for collecting data from two complete cycles in each specific household, making it possible to identify specific trends and patterns. Moreover, the use of rechargeable batteries reduced considerably the delays in monitoring and sped up the protocol to set up the sensors in the following households. As our study highlights, road emissions do not concern only road users, but also contribute to indoor air quality, especially for those living in proximity of transport infrastructure. In this sense, although the air quality monitoring was employed primarily to explore the impacts of the ML#12 construction, it allowed the community to identify and understand the issues they experience on daily basis through cooking and heating, and the health implications associated with such practices.

This research tackled also three SDGs against road building development and citizen science practices for air quality monitoring, namely SDG11, SDG3 and SDG17. *SDG11. Sustainable cities and communities* - Cities that undertake irresponsible development and generate unacceptable levels of air pollution cannot be considered sustainable. This project provided the Kibera community with a voice on the effects of road development and air pollution, allowing them to lobby and demand better actions to tackle pollution more effectively. *SDG3. Good health* *and well-being* - There is a lack of empirical research that explores the impacts of air pollution on the health and well-being of specific low-income and vulnerable communities, and how health inequalities arise within these communities. This project provides the baseline data for the role of the new road, and infrastructure, on air quality within the Kibera community. *SDG17. Partnerships for the Goals* – This research capacity fostered the collaboration between the UK and Kenyan academics and stakeholder organisations to explore air quality issues. The project generated significant knowledge translation and transfer from academic silos into communities, allowing communities to understand the causes and effects of air pollution and providing the required information for bottom-up grassroots organizations to argue for better air quality.

This study has the limitation of having collected the data for a short period of time (48 h per household) from the air quality sensors during the Kenyan short rainy season (between October and December), and therefore it does not take into account any potential season variation in the data (i.e. differences with dry season). Moreover, the participants for the deployment of the sensors have been recruited through a purposive sampling technique, making the sample potentially not representative in terms of differences in sources used for cooking and lighting, location of cooking and ventilation conditions. Potential participants were also informed during the recruitment process about the “care package”, which might have increased community members’ participation, but at the same time introduced bias in the data collection. Some additional challenges also emerged during the preliminary stages while engaging the community, as potential participants expressed concerns about the monitors breaching their privacy, fearing that the devices could make audio or picture recordings, or safety issues linked with the sensors.

Overall, the findings from the study are in line with the reviews from Commodore et al. [11] and Ward et al. [71]. In addition to increased awareness about the implications of air pollution and developing coping strategies, the community engaged in the study enhanced their capability to gain and use scientific tools to address issues at a local level and lobby to solve them. An example in this sense was provided during the community workshop when it was discussed how the health impacts of high levels of HAP and AAP are leading to poor outcomes for residents, and health services should respond to this issue. This led the community members to discuss and identify a set of actions that could help reduce their vulnerability to air pollution, including considering alternative sources and the location for cooking, increasing ventilation and reducing the spread of dust. Finally, the study has also provided a strategy to strengthen local capacity for the community members to get practice for air quality monitoring and has also forged connections with the research team to lay the groundwork of trust and reciprocity for future work.

5. Conclusion

Many Sub-Saharan African cities are experiencing significant growth in urbanization, with consequent deterioration in air quality in part due to increasing vehicular traffic and poor vehicle regulation. However, the lack of reliable and long-term data on the air pollution associated with roads, in addition to the costs required for environmental authorities to carry out high-quality air quality measurements, are additional issues in tackling air pollution in African cities. This paper explored how citizen science can be an effective approach to tackling air pollution and enhancing awareness among communities about the implications associated with poor air quality. The study engaged the community living in the informal settlement of Kibera in Nairobi, to explore the likely environmental impact associated with the development of the ML#12 bypass. Fourteen households were equipped with low-cost OPC sensors to collect data for indoor and outdoor air quality over a 48-hour period of time. Citizen science resulted in an effective approach to engaging communities to carry out air quality measurements and understand issues at the local level. The study allowed participants to enhance their awareness of the risk linked with air pollution and engage the community in thinking differently about this issue and what they can do to reduce it.

In the context of HVT infrastructural development in African cities, citizen science can be an effective tool to collect valuable data and monitor the impact of air pollution associated with infrastructure development during and after the construction stages. The study provided local-based actors, with expert support, to use low-cost sensors to measure the baseline air quality situation before the new road becomes opened for its formal purpose. Such an approach provides information for both the local community to allow for bottom-up community action, but also offers easy-to-digest evidence for city officials allowing for top-down action. The approach used in the study has the distinct characteristic of being centred on community needs and interests and focuses specifically on local problems. We demonstrate that such an approach leads to the promotion of a community-centred understanding of air pollution, including personal exposures, sources of pollution, and vulnerability to poor air quality. We advocate for citizen science and participatory mechanisms for air quality monitoring approaches to be taken up more broadly and embedded in planning processes in African cities. Community-based and participatory mechanisms can create more context-related interventions and inclusive place-making, particularly in the case of informal settlements, where formal top-down planning often fail to understand the impacts of its processes and how community create their alternative-substitute place-making [1].

The findings presented in this paper are based on a small-scale project. Further research in informal settlements should consider involving a wider variety of community members and different stakeholders, especially local authorities, organizations and healthcare institutions. Engaging official authorities could be also beneficial during projects’ implementation to make sure environmental regulations are followed and guarantee transparency mechanisms concerning the community potentially affected. Similarly, different ways to boost sensitization to increase knowledge and awareness of the effects of air pollution among community members should be explored.

CRediT authorship contribution statement

Talib Manshur: Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Carlo Luiu:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **William R. Avis:** Conceptualization, Methodology, Writing – review & editing, Project administration. **Vera Bukachi:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Michael Gatari:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Joe Mulligan:** Writing – review & editing, Supervision. **David Ng’an’ga:** Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing. **Jonathan Radcliffe:** Writing – review & editing, Supervision. **Ajit Singh:** Software, Validation, Formal analysis, Investigation, Writing – review & editing. **Ezequiel Waiguru:** Software, Validation, Formal analysis, Investigation, Writing – review & editing. **Amos Wandera:** Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Project administration. **Francis D. Pope:** Conceptualization, Methodology, Software, Formal analysis, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This study was supported by the Royal Academy of Engineering through the Frontier of Engineering for Development scheme (FoDSF \1819\1\12).

The authors are grateful for funding from The Institute for Global Innovation/ Institute of Advanced Studies (IGI/IAS) of the University of Birmingham, and the Global Challenges Research Fund, which has helped support this project.

The authors would like to thank all participants that contributed to this study.

References

[1] Andres L, Bakare H, Bryson JR, Khaemba W, Melgaço L, Mwaniki GR. Planning, temporary urbanism and citizen-led alternative-substitute place-making in the Global South. Reg Stud 2021;55(1):29–39. https://doi.org/10.1080/00343404.2019.1665645.

[2] Avis W, Bartington S. Monitoring Air Quality in Low- Income and Lower Middle-Income Countries. K4D Helpdesk Report. Brighton, UK: Institute of Development Studies; 2020.

[3] Avis W, Wodajo B, Getaneh Z. Community Engagement in Digital Innovation: Evidence from past experience in the Global South (Digital Air Quality East Africa). Birmingham, UK; 2020.

[4] Awe Y, Hagler G, Kleiman G, Klopp J, Pinder R, Terry S. Filling the Gaps: Improving Measurement of Ambient Air Quality in Low and Middle Income Countries; 2017. Retrieved from http://pubdocs.worldbank.org/en/425951511369561703/Filling-the-Gaps-White-Paper- Discussion-Draft-November-2017.pdf.

[5] Brickle MB, Evans-Agnew R. Photovoice and Youth Empowerment in Environmental Justice Research: A Pilot Study Examining Woodsmoke Pollution in a Pacific Northwest Community. J Community Health Nurs 2017;34(2):89–101. https://doi.org/10.1080/07370016.2017.1304148.

[6] Brody JG, Morello-Frosch R, Zota A, Brown P, Pérez C, Rudel RA. Linking exposure assessment science with policy objectives for environmental justice and breast cancer advocacy: the northern California household exposure study. Am J Public Health 2009;99(S3):S600. https://doi.org/10.2105/AJPH.2008.149088.

[7] Cacari-Stone L, Wallerstein N, Garcia AP, Minkler M. The promise of community-based participatory research for health equity: A conceptual model for bridging evidence with policy. Am J Public Health 2014;104(9):1615–23. https://doi.org/10.2105/AJPH.2014.301961.

[8] Cashman SB, Adeky S, Allen AJ, Corburn J, Israel BA, Montaño J, et al. The power and the promise: Working with communities to analyze data, interpret findings, and get to outcomes. Am J Public Health 2008;98(8):1407–17. https://doi.org/10.2105/AJPH.2007.113571.

[9] Centers for Disease Control and Prevention. (1997). Principles of community engagement. *Atlanta, GA: CDC/ATSDR Committee on Community Engagement*.

[10] Code for Africa. (2021). Inexpensive tech to help air pollution survey in Kenya. *Medium.Com*. Retrieved from https://medium.com/code-for-africa/cheap-tech-to-help-air-pollution-survey-in-kenya-787977f0dff3.

[11] Commodore A, Wilson S, Muhammad O, Svendsen E, Pearce J. Community-based participatory research for the study of air pollution: a review of motivations, approaches, and outcomes. Environ Monit Assess 2017;189(8):1–30. https://doi.org/10.1007/S10661-017-6063-7/FIGURES/3.

[12] Da Silva J, Charles A. Risk beyond the red line: Urban risk and large scale infrastructure projects in Kenya. Nairobi, Kenya; 2018. Retrieved from https://www.unequalscenes.com/.

[13] Hosgood HD, Boffetta P, Greenland S, Lee Y-C, McLaughlin J, Seow A, et al. In-home coal and wood use and lung cancer risk: A pooled analysis of the international lung cancer consortium. Environ Health Perspect 2010;118(12):1743–7. https://doi.org/10.1289/ehp.1002217.

[14] Devarakonda S, Sevusu P, Liu H, Liu R, Iftode L, Nath B. In: Real-time air quality monitoring through mobile sensing in metropolitan areas. New York, New York, USA: ACM Press; 2013. https://doi.org/10.1145/2505821.2505834.

[15] Dutta P, Aoki PM, Kumar N, Mainwaring A, Myers C, Willett W, Woodruff A. Demo abstract: Common sense - Participatory urban sensing using a network of handheld air quality monitors. Sensor Systems, SenSys 2009:349–50. https://doi.org/10.1145/1644038.1644095.

[16] English PB, Olmedo L, Bejarano E, Lugo H, Murillo E, Seto E, et al. The Imperial County Community Air Monitoring Network: A Model for Community-based Environmental Monitoring for Public Health Action. Environ Health Perspect 2017;125(7):074501. https://doi.org/10.1289/EHP1772.

[17] Franchini M, Mannucci PM, Harari S, Pontoni F, Croci E. The Health and Economic Burden of Air Pollution. Am J Med 2015;128(9):931–2. https://doi.org/10.1016/J.AMJMED.2015.03.021.

[18] Fuller R, Landrigan PJ, Balakrishnan K, Bathan G, Bose-O'Reilly S, Brauer M, et al. Pollution and health: a progress update. The Lancet Planetary Health 2022;6(6). https://doi.org/10.1016/S2542-5196(22)00090-0.

[19] Garfias Royo M, Parikh P, Mutwiri F, Harper J, Bukachi V, Mulligan J. Using Future Scenario Planning as a tool for informed decision making on infrastructure interventions in Kibera, Nairobi in Kenya. Habitat Int 2018;79:30–41. https://doi.org/10.1016/j.habitatint.2018.07.009.

[20] Gaventa J, Barrett G. So What Difference Does it Make? Mapping the Outcomes of Citizen Engagement. IDS Working Papers 2010;2010(347):01–72. https://doi.org/10.1111/j.2040-0209.2010.00347_2.x.

[21] Gordon SB, Bruce NG, Grigg J, Hibberd PL, Kurmi OP, Lam K, bong H, et al. Respiratory risks from household air pollution in low and middle income countries. Lancet Respirat Med. 2014. https://doi.org/10.1016/S2213-2600(14)70168-7.

[22] Groulx N, Urch B, Duchaine C, Mubareka S, Scott JA. The Pollution Particulate Concentrator (PoPCon): A platform to investigate the effects of particulate air pollutants on viral infectivity. Sci Total Environ 2018;628–629:1101–7. https://doi.org/10.1016/j.scitotenv.2018.02.118.

[23] Hauser C, Buckley A, Porter J. Passive samplers and community science in regional air quality measurement, education and communication. Environ Pollut 2015;203:243–9. https://doi.org/10.1016/j.envpol.2014.12.028.

[24] Jiao W, Hagler G, Williams R, Sharpe R, Brown R, Garver D, et al. Community Air Sensor Network (CAIRSENSE) project: Evaluation of low-cost sensor performance in a suburban environment in the southeastern United States. Atmos Meas Tech 2016;9(11):5281–92. https://doi.org/10.5194/amt-9-5281-2016.

[25] Johnston JE, Juarez Z, Navarro S, Hernandez A, Gutschow W. Youth Engaged Participatory Air Monitoring: A "Day in the Life" in Urban Environmental Justice Communities. Int J Environ Res Public Health 2019;17(1). https://doi.org/10.3390/IJERPH17010093.

[26] Kenya National Bureau of Statistics. (2019). *2019 Kenya Population and Housing Census Volume 1: Population by County and Sub-County. 2019 Kenya Population and Housing Census* (Vol. I). Retrieved from https://www.knbs.or.ke/?wpdmpro=2019-kenya-population-and-housing-census-volume-i-population-by-county-and-sub-county.

[27] Kondo MC, Mizes C, Lee J, McGady-Saier J, O'Malley L, Diliberto A, et al. Towards Participatory air pollution exposure assessment in a goods movement community. Prog Community Health Partnersh 2014;8(3):291–304. https://doi.org/10.1353/cpr.2014.0047.

[28] Kurmi OP, Semple S, Simkhada P, Cairns S, Smith W, Ayres JG. COPD and chronic bronchitis risk of indoor air pollution from solid fuel: A systematic review and meta-analysis. Thorax 2010;65(3):221–8. https://doi.org/10.1136/thx.2009.124644.

[29] Landrigan PJ, Fuller R, Acosta NJR, Adeyi O, Arnold R, Basu N (Nil). The Lancet Commission on pollution and health. The Lancet. Lancet Publishing Group 2017. https://doi.org/10.1016/S0140-6736(17)32345-0.

[30] Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: A systematic analysis for the Global Burden of Disease Study 2010. Lancet 2012;380(9859):2224–60. https://doi.org/10.1016/S0140-6736(12)61766-8.

[31] Loh P, Sugerman-Brozan J, Wiggins S, Noiles D, Archibald C. From asthma to AirBeat: Community-driven monitoring of fine particles and black carbon in Roxbury, Massachusetts. Environ Health Perspect 2002;110(SUPPL. 2):297–301. https://doi.org/10.1289/EHP.02110S2297.

[32] Luiu C, Wandera A, Radcliffe J, Pope FD, Bukachi V, Mulligan J. COVID-19 Impacts on Mobility in Kenyan Informal Settlements: A Case Study from Kibera , Nairobi. Transport Findings; 2022. https://doi.org/10.32866/001c.37571.

[33] Mahajan S, Kumar P, Pinto JA, Riccetti A, Schaaf K, Camprodon G, et al. A citizen science approach for enhancing public understanding of air pollution. Sustain Cities Soc 2020;52:101800. https://doi.org/10.1016/j.scs.2019.101800.

[34] Mazzeo A, Burrow M, Quinn A, Marais EA, Singh A, Ng'ang'a D, et al. Evaluation of the WRF and CHIMERE models for the simulation of PM2.5in large East African urban conurbations. Atmos Chem Phys 2022;22(16):10677–701. https://doi.org/10.5194/acp-22-10677-2022.

[35] Minkler M, Vasquez V, Chang C. Promoting healthy public policy through community-based participatory research: Ten case studies. UC Berkeley School of Public Health and PolicyLink; 2008. Berkeley, CA. 2009. Retrieved from https://www.policylink.org/resources-tools/promoting-healthy-public-policy-through-community-based-participatory-research-ten-case-studies.

[36] Minkler M. Linking science and policy through community-based participatory research to study and address health disparities. Am J Public Health 2010;100(SUPPL. 1):81–7. https://doi.org/10.2105/AJPH.2009.165720.

[37] Mitra S, Mulligan J, Schilling J, Harper J, Vivekananda J, Krause L. Developing risk or resilience? Effects of slum upgrading on the social contract and social cohesion in Kibera. Nairobi *IIED* 2017;29(1):103–22. https://doi.org/10.1177/0956247816689218.

[38] Mulligan J, Bukachi V, Clause JC, Jewell R, Kirimi F, Odbert C. Hybrid infrastructures, hybrid governance: New evidence from Nairobi (Kenya) on green-blue-grey infrastructure in informal settlements. Anthropocene 2020;29:100227. https://doi.org/10.1016/j.ancene.2019.100227.

[39] Mulligan J, Harper J, Kipkemboi P, Ngobi B, Collins A. Community-responsive adaptation to flooding in Kibera, Kenya. Proc Inst Civil Eng - Eng Sustain 2017;170(5):268–80. https://doi.org/10.1680/jensu.15.00060.

[40] Nairobi City County. (2019). *Air Quality Action Plan*. Retrieved from https://www.eci-africa.org/wp-content/uploads/2019/05/Nairobi-Air-Quality-Action-Plan_Final_ECI_31.12.2018.pdf.

[41] Nairobi City County. (2020). The Nairobi City County Air Quality Policy. Nairobi, Kenya. Retrieved from https://nairobiassembly.go.ke/ncca/wp-content/uploads/paperlaid/2020/SESSIONAL-PAPER-NO.-2-ON-NAIROBI-CITY-COUNTY-AIR-QUALITY-POLICY.pdf.

[42] Nairobi City County. (2021). The Nairobi City County Air Quality Bill. Kenya: Kenya Gazette Supplement.

[43] Njuguna HN, Cosmas L, Williamson J, Nyachieo D, Olack B, Ochieng JB, et al. Use of Population-based Surveillance to Define the High Incidence of Shigellosis in an Urban Slum in Nairobi, Kenya. PLoS One 2013;8(3):e58437. https://doi.org/10.1371/journal.pone.0058437.

[44] O'Connor S, O'Connor PF, Feng HA, Ashley K. Gravimetric Analysis of Particulate Matter using Air Samplers Housing Internal Filtration Capsules. Gefahrstoffe, Reinhaltung Der Luft = Air Quality Control 2014;74(10):403–10.

[45] Odbert C, Mulligan J. The Kibera Public Space Project - Participation, Integration and Networked Change. In: Jeffrey Hou KY, Spencer B, Way T, editors. Now Urbanism. Routledge; 2014. p. 177–92. https://doi.org/10.4324/9781315753065-24.

[46] Pope FD, Blake R. ASAP-East-Africa Reading Pack (No. 1) Air Quality in Low to Middle Income Countries. Birmingham; 2017.

[47] Pope FD, Gatari M, Ng'ang'a D, Poynter A, Blake R. Airborne particulate matter monitoring in Kenya using calibrated low-cost sensors. Atmos Chem Phys 2018;18 (20):15403–18. https://doi.org/10.5194/acp-18-15403-2018.

[48] Pun VC, Tian L, Ho K-F. Air Pollution From Resuspended Soil/Road Dust And Increase Risk Of Emergency Respiratory Hospitalizations. ISEE Conference Abstracts 2015;2015(1):1959. https://doi.org/10.1289/ISEE.2015.2015-1959.

[49] Rajé F, Tight M, Pope FD. Traffic pollution: A search for solutions for a city like Nairobi. Cities 2018;82:100–7. https://doi.org/10.1016/J.CITIES.2018.05.008.

[50] Rickenbacker H, Brown F, Bilec M. Creating environmental consciousness in underserved communities: Implementation and outcomes of community-based environmental justice and air pollution research. Sustain Cities Soc 2019;47: 101473. https://doi.org/10.1016/J.SCS.2019.101473.

[51] Robson C, McCartan K. Real world research. John Wiley & Sons; 2016.

[52] Rodriguez A, Brickley E, Rodrigues L, Normansell RA, Barreto M, Cooper PJ. (2019, November 1). Urbanisation and asthma in low-income and middle-income countries: a systematic review of the urban-rural differences in asthma prevalence. *Thorax*. BMJ Publishing Group Ltd. doi:10.1136/thoraxjnl-2018-211793.

[53] Rubin CL, Allukian N, Wang X, Ghosh S, Huang C-C, Wang J, et al. We make the path by walking it": Building an academic community partnership with boston chinatown. Prog Community Health Partnersh 2014;8(3):353–63. https://doi.org/10.1353/cpr.2014.0046.

[54] Sadd J, Morello-Frosch R, Pastor M, Matsuoka M, Prichard M, Carter V. The Truth, the Whole Truth, and Nothing but the Ground-Truth: Methods to Advance Environmental Justice and Researcher-Community Partnerships. Health Educ Behav 2014;41(3):281–90. https://doi.org/10.1177/1090198113511816.

[55] Schwarze PE, Øvrevik J, Låg M, Refsnes M, Nafstad P, Hetland RB, et al. Particulate matter properties and health effects: Consistency of epidemiological and toxicological studies. Hum Exper Toxicol 2006;25(10):559–79. https://doi.org/10.1177/096032706072520.

[56] Singh A, Avis WR, Pope FD. Visibility as a proxy for air quality in East Africa. Environ Res Lett 2020;15(8):084002. https://doi.org/10.1088/1748-9326/ab8b12.

[57] Singh A, Bakare H, Mazzeo A, Avis WR, Ng'ang'a D, Gatari M, et al. Urban diagnostics and a systems approach to air quality management: Pathways towards sustainable economic development and a healthy Nairobi, Kenya. Front Environ Sci 2022;10. https://doi.org/10.3389/fenvs.2022.978002.

[58] Singh A, Ng'ang'a D, Gatari MJ, Kidane AW, Alemu ZA, Derrick N, et al. Air quality assessment in three east african cities using calibrated low-cost sensors with a focus on road-based hotspots. Environ Res Communcations 2021;3(7):075007. https://doi.org/10.1088/2515-7620/ac0e0a.

[59] Singh A, Ng'ang'a D, Gatari MJ, Kidane AW, Alemu ZA, Derrick N, et al. Air quality assessment in three East African cities using calibrated low-cost sensors with a focus on road-based hotspots. Environ Res Communications 2021;3(7):075007. https://doi.org/10.1088/2515-7620/ac0e0a.

[60] Stave KA. Using system dynamics to improve public participation in environmental decisions. Syst Dyn Rev 2002;18(2):139–67. https://doi.org/10.1002/SDR.237.

[61] Stockholm Environment Institute. (2022). Legislation for clean air in Kenya. In Stockholm Environment Institute (Ed.), *Action and accountability - Annual report*. Stockholm. Retrieved from https://www.sei.org/publications/annual-report-2021/.

[62] Taylor FE, Millington JDA, Jacob E, Malamud BD, Pelling M. Messy maps: Qualitative GIS representations of resilience. Landsc Urban Plan 2020;198:103771. https://doi.org/10.1016/j.landurbplan.2020.103771.

[63] Thorpe AJ, Harrison RM, Boulter PG, McCrae IS. Estimation of particle resuspension source strength on a major London Road. Atmos Environ 2007;41 (37):8007–20. https://doi.org/10.1016/J.ATMOSENV.2007.07.006.

[64] Thurston GD, Kipen H, Annesi-Maesano I, Balmes J, Brook RD, Cromar K, et al. A joint ERS/ATS policy statement: What constitutes an adverse health effect of air pollution? An analytical framework. Eur Respirat J Eur Respiratry Soc 2016;49(1): 1600419. https://doi.org/10.1183/13993003.00419-2016.

[65] Tongco MDC. Purposive sampling as a tool for informant selection. Ethnobot Res Appl 2007;5:147–58. https://doi.org/10.17348/era.5.0.147-158.

[66] UN-HABITAT. (2006). *Nairobi Urban Sector Profile*. Nairobi. Retrieved from http://www.unhabitat.org.

[67] USAID. (2019). *LMIC Urban Air Pollution Solutions*. Retrieved from https://breathelife2030.org/wp-content/uploads/2019/08/USAID_APSolutionsDoc_070219.pdf.

[68] Valavanidis A, Fiotakis K, Vlachogianni T. Airborne Particulate Matter and Human Health: Toxicological Assessment and Importance of Size and Composition of Particles for Oxidative Damage and Carcinogenic Mechanisms. 2008;26(4), 339–362. doi:10.1080/10590500802494538.

[69] Van Brussel S, Huyse H. Citizen science on speed? Realising the triple objective of scientific rigour, policy influence and deep citizen engagement in a large-scale citizen science project on ambient air quality in Antwerp. J Environ Plan Manag 2019;62(3):534–51. https://doi.org/10.1080/09640568.2018.1428183.

[70] Vellalassery A, Pillai D, Marshall J, Gerbig C, Buchwitz M, Schneising O, et al. Using TROPOspheric Monitoring Instrument (TROPOMI) measurements and Weather Research and Forecasting (WRF) CO modelling to understand the contribution of meteorology and emissions to an extreme air pollution event in India. Atmos Chem Phys 2021;21(7):5393–414. https://doi.org/10.5194/ACP-21-5393-2021.

[71] Ward F, Lowther-Payne HJ, Halliday EC, Dooley K, Joseph N, Livesey R, et al. Engaging communities in addressing air quality: a scoping review. Environ Health : A Global Access Sci Source 2022;21(1). https://doi.org/10.1186/s12940-022-00896-2.

[72] WHO. (2016). Health as the Pulse of the New Urban Agenda. United Nations Conference on Housing and Sustainable Urban Development Quito – October 2016.

[73] WHO. (2022a). Ambient (outdoor) air pollution. Retrieved March 24, 2023, from https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health.

[74] WHO. (2022b). Household air pollution. Retrieved March 24, 2023, from https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health.

[75] Wing S, Horton RA, Muhammad N, Grant GR, Tajik M, Thu K. Integrating epidemiology, education, and organizing for environmental justice: Community health effects of industrial hog operations. Am J Publ Health 2008;98(8):1390–7. https://doi.org/10.2105/AJPH.2007.110486.

[76] Woolley KE, Bagambe T, Singh A, Avis WR, Kabera T, Weldetinsae A, et al. Investigating the association between wood and charcoal domestic cooking, respiratory symptoms and acute respiratory infections among children aged under 5 years in Uganda: A cross-sectional analysis of the 2016 demographic and health survey. Int J Environ Res Public Health 2020;17(11):3974. https://doi.org/10.3390/ijerph17113974.

[77] World Bank, & Institute for Health Metrics and Evaluation. (2016). *The Cost of Air Pollution. The Cost of Air Pollution*. Washington, DC: World Bank, Washington, DC. https://doi.org/10.1596/25013.