



Air Pollution and Urban Green Space: Evidence of Environmental Injustice in Adama, Ethiopia

Erin Flanagan^{1*}, Kristoffer Mattisson¹, John Walles^{2,3}, Asmamaw Abera^{4,5}, Axel Eriksson⁶, Festina Balidemaj¹, Anna Oudin¹, Christina Isaxon⁶ and Ebba Malmqvist¹

¹ Division of Occupational and Environmental Medicine, Department of Laboratory Medicine, Faculty of Medicine, Lund University, Lund, Sweden, ² Clinical Infection Medicine, Department of Translational Medicine, Faculty of Medicine, Lund University, Malmö, Sweden, ³ Department of Infectious Diseases, Central Hospital Kristianstad, Kristianstad, Sweden, ⁴ Water and Public Health Department, Ethiopia Institute of Water Resources, Addis Ababa University, Addis Ababa, Ethiopia, ⁵ Department of Non-Communicable Diseases, Armauer Hansen Research Institute, Addis Ababa, Ethiopia, ⁶ Division of Ergonomics and Aerosol Technology, Department of Design Sciences, Faculty of Engineering, Lund University, Lund, Sweden

While air pollution data in Ethiopia is limited, existing studies indicate high levels of both ambient and household air pollution; rapid urbanization also threatens the preservation of urban green spaces. In this study, environmental injustice, or the disproportionate burden of environmental exposures on persons of lower socioeconomic status (SES), was explored among women in Ethiopia using a mother and child cohort from the city of Adama. Land-use regression models were previously developed for modeling ambient nitrogen dioxide (NO₂) and nitrogen oxides (NO_x) throughout Adama, while household air pollution (cooking fuel type) and the presence of green space were assessed through questionnaires and home visits, respectively. The odds of being exposed to these environmental factors were analyzed in association with two SES indicators, education and occupation, using logistic regression. Our results indicate the presence of environmental injustice in Adama, as women with lower SES shouldered a higher burden of air pollution exposure and enjoyed less urban green space than their higher SES counterparts. These findings encourage the prioritization of air quality control and urban planning resources toward policy action within lower SES areas. From a societal perspective, our results also support more upstream interventions, including investment in educational and occupational opportunities. Still, a human rights approach is emphasized, as governments are responsible for protecting the right to a clean environment, especially for those disproportionately exposed. To the best of our knowledge, this is the first study on environmental injustice in Ethiopia, and the first in Sub-Saharan Africa to investigate the inequalities of ambient and household air pollution exposure as well as urban green space access in the same cohort.

Keywords: environmental injustice, exposure inequality, socioeconomic status, ambient air pollution, household air pollution, urban green space

INTRODUCTION

Expansive scientific literature on air pollution and health has led to an understanding of its role in countless illnesses and diseases (World Health Organization, 2016a; Landrigan et al., 2017), such as respiratory disease (World Health Organization, 2013a,b; Castro et al., 2017), cardiovascular (Chen and Hoek, 2020) and cerebrovascular disease

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*Correspondence:

Erin Flanagan
erin.flanagan@med.lu.se

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(Niu et al., 2021), pregnancy complications (Pedersen et al., 2014), adverse birth outcomes (Stieb et al., 2012; Perera et al., 2019), childhood asthma (Khreis et al., 2017), neurological and developmental disorders (Chun et al., 2020), dementia (Carey et al., 2018), and even death (Hoek et al., 2013; Huangfu and Atkinson, 2020). Indeed, it is estimated that mortality due to ambient air pollution alone is likely to increase by 50% or more by 2050 if no aggressive mitigating actions are taken (Lelieveld et al., 2015).

In Sub-Saharan Africa, one of the greatest contributors to ambient air pollution is traffic (Hitchcock et al., 2014), particularly from an old and poorly maintained vehicle fleet (Panyacosit, 2000). Many countries, including Japan and European nations, regularly export cars to Africa that no longer meet their own environmental standards, so-called “super-emitters” (Brunekreef, 2005), oftentimes after removing their particle filters and catalytic converters (Naidja et al., 2018). Samples of particulate matter (PM) taken from roadsides in Addis Ababa, Ethiopia, for example, were found to contain toxic elements including lead, zinc, cadmium, and chromium (Embiale et al., 2019), yet emissions from vehicle exhaust are not systematically regulated in most African countries (Naidja et al., 2018). Another important source of outdoor air pollution is solid waste burning (Naidja et al., 2018), as waste collection and transport services are often lacking (Solomon, 2011). This practice emits harmful pollutants, such as heavy metals (Wang et al., 2017), polycyclic aromatic hydrocarbons (PAHs) (Hsu et al., 2016), and dioxins (Li et al., 2019).

Household air pollution is also a prominent issue in Sub-Saharan Africa, as pollutive biomass fuels are often used for cooking and heating (Mead et al., 2008; World Health Organization, 2016b; Naidja et al., 2018). Burning solid fuels like wood, charcoal, animal dung, and crop residue in traditional cooking stoves emits high levels of PM, PAHs, and carbon monoxide (CO) (Naidja et al., 2018). Studies from Addis Ababa, Ethiopia, have identified indoor PM concentrations of 818–905 $\mu\text{g}/\text{m}^3$ (Keil et al., 2010; Sanbata et al., 2014), which is ~ 30 times higher than residential averages in high-income countries (Morawska et al., 2013). These exposures tend to disproportionately affect women, whom are most often tasked with cooking, and their children (Okello et al., 2018; Mocumbi et al., 2019).

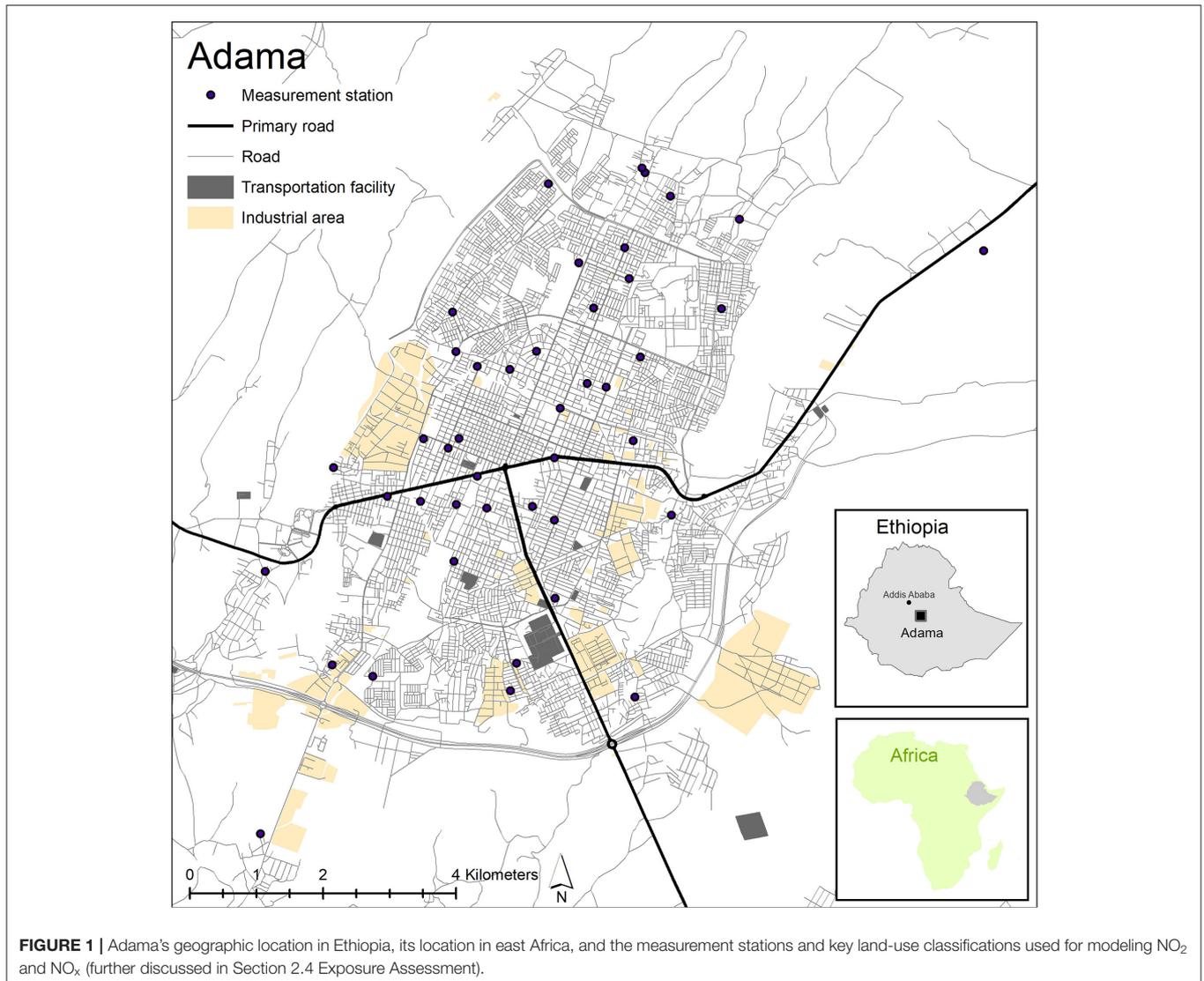
Importantly, household and ambient air pollution co-exist: emissions from cooking contribute to overall ambient air pollution levels, and ambient air pollution contributes to household air pollution (Bo et al., 2017; Balmes, 2019), especially when homes are not well-insulated or home filtration systems of the outdoor air are not available. While air pollution data in Ethiopia is limited, existing studies indicate high levels of both ambient and household air pollution to be a significant problem (Tefera et al., 2016).

Moreover, rapid urbanization occurring throughout Sub-Saharan Africa (UNEP, 2014; Pieterse et al., 2015) can intensify environmental burdens. Fueling this urbanization is general population growth, with the region as a whole experiencing an annual population growth of 2.6% as of 2020 (The World Bank, 2021). Anthropogenic sources of air pollution, such as traffic,

waste burning, solid fuel combustion, and industry, and their subsequent health effects (Owili et al., 2017), are likely to increase with an increasing urban population. Additionally, this growth often happens faster than infrastructure can accommodate. The potential “coordination deficit” (Hill et al., 2014) poses a risk to urban green areas and existing biodiversity there within (Güneralp et al., 2017; Ofori et al., 2018), as buildings and other supporting structures are constructed- at times without adequate planning. Studies from other parts of the world (Lee and Maheswaran, 2011; Saule and La Torre, 2011) and South Africa (Tomita et al., 2017) have found that green spaces, particularly in urban environments, have ameliorating effects on mental health and well-being and facilitate physical activity and social contact (World Health Organization, 2016c). Unfettered urban development that cuts into greenery can also exacerbate the heat island effect (Taha, 1997; Mohajerani et al., 2017), which negatively impacts both human health and the climate. Despite its importance, relatively few studies have been conducted in Sub-Saharan Africa investigating green space in connection to humans, such as residential access and health benefits.

Environmental injustice, or environmental inequity, is the unequal distribution of environmental burdens among areas characterized by lower socioeconomic status (SES). A 2015 global review reported a consistent air pollution exposure gradient among studies conducted in North America, Asia and Oceania, with exposure increasing as SES decreased (Hajat et al., 2015). Only findings from European settings appeared to be mixed (Hajat et al., 2015), as historic city centers, sometimes having higher levels of air pollution, increase property values and attract higher-income residents (O’Neill et al., 2003). Most research concerning environmental injustice has been conducted in high-income or upper-middle-income countries despite lower-income countries (LICs) and lower-middle-income countries (LMICs) often facing higher air pollution exposure and greater threats to urban green space retention. A recent study in India adds new evidence on this relationship within LMICs: areas populated by persons of lower castes, whom have been traditionally marginalized, and neighborhoods with poor sanitation and housing conditions were subjected to higher concentrations of PM with an aerodynamic diameter $< 2.5 \mu\text{m}$ ($\text{PM}_{2.5}$) (Chakraborty and Basu, 2021).

A clear knowledge gap exists, as few studies on environmental injustice related to air pollution exposure have been conducted in Africa. Of 37 studies evaluated in a global review on environmental injustice (Hajat et al., 2015), only one conducted in Africa was identified. Based in Ghana, its results indicated that higher SES areas were associated with lower concentrations of $\text{PM}_{2.5}$ and PM with an aerodynamic diameter $< 10 \mu\text{m}$ (PM_{10}) (Rooney et al., 2012). Regarding the unequal experience of urban green areas, a study from Nigeria demonstrated that 65% of persons living in low-income residential areas were dissatisfied with their access to green space, whereas dissatisfaction dropped to 28% in middle-income neighborhoods and to only 8% in high-income areas (Ochodo et al., 2014). An understanding of the socioeconomic differences in exposure can shape future health impact assessments, inform policy decisions, and identify priority intervention groups. To the best of our knowledge, no study to



date has investigated environmental injustice, nor included all of these environmental exposures (ambient air pollution, household air pollution, and urban green space access), in Ethiopia. Including all three illustrates the multitude of environmental exposures humans face simultaneously and captures a more comprehensive picture of environmental injustice's reach. The aim of this study is to explore environmental injustice, specifically the associations between SES and (1) ambient air pollution, (2) household air pollution, and (3) urban green space access, in Adama, Ethiopia.

MATERIALS AND METHODS

Study Setting

Adama is the fourth largest city in Ethiopia with an estimated 214,000 inhabitants and is located southeast of the capital, Addis Ababa (see **Figure 1**). Situated along the Pan African Highway linking the harbor in Djibouti with Addis Ababa, Adama experiences a large amount of freight transport by trucks.

Although a relatively new road has been built outside the city center to divert this heavy transit, it is a toll road, which many drivers choose to avoid. The vehicle fleet in Adama is comprised of cars and trucks that are often old and lack exhaust treatment systems, such as catalytic converters (Brunekreef, 2005; Adama City Administrative Office, 2019). In recent years, polluting rickshaws no longer permitted in Indian cities have been exported to Adama (Adama City Administrative Office, 2019). Additionally, waste is often burned outside homes or in empty lots because formal public waste collection services are not available (Teshome, 2021). Furthermore, many households lack reliable, affordable electricity for cooking, and even when electricity is available, women may continue to use solid fuels to uphold traditional cooking practices (Keil et al., 2010).

Study Population

The Adama Mother and Child cohort is a prospective cohort (ClinicalTrials.gov identifier number NCT03305991) of 2,085 pregnant women. These women were recruited from three

public antenatal care clinics (Adama Hospital, Adama Health Centre, and Geda Health Centre) in urban Adama, Ethiopia, from November 2015 to February 2018 (Tesfaye et al., 2020). Women were eligible for participation at the first antenatal care visit for the current pregnancy if they consented to study procedures, including tracing by phone and home visits, and if they were residing in the uptake area for the duration of the pregnancy. At inclusion, interviews and questionnaires were administered to obtain obstetric, health-related, demographic, and socioeconomic data as well as information on cooking practices, such as fuel type(s) used. Physical examinations and blood sampling were also conducted at this time. Later, home visits were performed to collect the GPS coordinates of each woman's residence during pregnancy, additional characteristics of the home, and features of the immediate environment, including urban greenery. This cohort has previously been used to study infectious diseases (König Walles et al., 2018; Tesfaye et al., 2020; Walles et al., 2020). See **Supplementary Figure 1** for the flowchart detailing all cases excluded from the study population with respect to environmental exposure data.

Socioeconomic Status Indicators

Self-reported data on education and occupation was derived from the aforementioned questionnaires. Education had the following categories: illiterate, less than grade 6, grades 6–12, or more than grade 12. These were collapsed into two variables, including one with three categories: “illiterate and < grade 6” ($n = 676$), “grades 6–12” ($n = 1,172$), and “> grade 12” ($n = 231$) and one dichotomized into “low education” (illiterate and < grade 6; $n = 676$) and “high education” (grades 6–12 and > grade 12; $n = 1,403$). The latter reflects the separation of primary and secondary education in Ethiopia. Occupation alternatives included daily laborer, permanent employment, student, homemaker, unemployed, and self-employed. Here, occupations not comprising paid employment (homemaker, unemployed, and student) were excluded from analysis. The remaining occupations were dichotomized into “daily laborer” ($n = 248$) and permanent employment and self-employed (hereafter referred to together as “permanent employment”; $n = 437$). As ~63% ($n = 1,319$) of the women in this study were homemakers, this reduced the sample size for occupation-related analyses substantially.

Exposure Assessment

Ambient Air Pollution

Land-use regression (LUR) models for nitrogen dioxide (NO₂) and nitrogen oxides (NO_x) throughout Adama have been developed previously and published (Abera et al., 2021). These particular air pollutants are commonly used as proxies to capture air pollution exposure generated by combustion. In short, NO₂ and NO_x concentrations were measured at more than 40 sites (**Figure 1**) over the course of 6 days during both the wet and dry seasons. The measured mean NO₂ and NO_x levels for the entire city were 13.1 μg/m³ and 29.0 μg/m³, respectively. Traffic measurement sites had the highest NO₂ and NO_x averages of 17.5 μg/m³ and 45.0 μg/m³, respectively. The lowest mean values were found at the regional background measurement

sites: 5.0 μg/m³ of NO₂ and 11.0 μg/m³ of NO_x. The LUR models included geographical predictor variables related to roads, industries (NO₂ only), and transportation administration areas (NO_x only) (**Figure 1**). Further details on the full models can be found in Abera et al. (2021). Approximately 75% of the NO₂ variance and 68% of the NO_x variance could be explained by the developed LUR models (Abera et al., 2021). In addition to the measurements taken with passive samplers, we were granted access to time-resolved NO₂ and NO_x data collected with a Thermo Scientific NO-NO₂-NO_x analyzer (model 42i) at the Ethiopian Meteorological Institute site in Adama from January 2017 through December 2018. Although the data had many gaps, air pollution concentrations did not appear to fluctuate considerably between the two years, so no temporal adjustments were made (Abera et al., 2021).

Local personnel, instructed on how to use a handheld Garmin GPS-tracker, were able to collect the geographical coordinates of 1,656 (79.4%) women's home residences during the home visit; others could not be reached ($n = 428$). Women whose geographical coordinates were not correctly recorded ($n = 31$) or fell outside of the area with available geographical predictor data ($n = 17$) were excluded. To preserve a large enough sample size, coordinates that were written as degree, minute, and second ($n = 238$) instead of degree and minute were retained in the main analyses, but a sensitivity analysis excluding them was performed. Information regarding geographical predictor variables included in the LUR models was then extracted from around the home residence of each woman and used to model both NO_x and NO₂ exposure in ArcGIS version 10.5.1 (Redlands, CA, USA). The LUR model predicted one woman's NO_x exposure to have a negative value, which was subsequently excluded. The resulting modeled mean exposure levels of NO₂ and NO_x (13.7 μg/m³ and 29.9 μg/m³, respectively), were used to create the final, dichotomized exposure variable: “low exposure” (below the mean) and “high exposure” (above the mean). Additionally, NO₂ and NO_x were dichotomized into emission levels below and above 20 μg/m³, which corresponds to the cutoff previously used to study environmental injustice in Sweden (Flanagan et al., 2019).

Household Air Pollution

Questions regarding the type of fuel(s) that participants used for cooking allowed for multiple answers and included the following options: electricity, gas/kerosene, wood/charcoal, cow dung, cylinders (liquid petroleum gas, LPG), and other. The “other fuel(s)” alternative was excluded from analyses due to a low response rate ($n = 1$). The remaining fuel types were grouped into three categories, “clean fuel” (electricity/gas/kerosene/LPG only; $n = 488$), “solid fuel” (wood/charcoal/cow dung only; $n = 988$), and “mixed fuel types” (a combination of clean and solid fuels; $n = 593$).

Samples of wood, charcoal, and cow dung were collected in Adama, imported to Sweden, and analyzed in the Lund University Aerosol Laboratory (manuscript in preparation). The fuels were burned in a controlled set-up and the chemical composition of the smoke was measured, as were time-resolved mass concentrations, size distributions, and PM collection for

subsequent analysis. Carbon dioxide (CO₂) measurements, used to estimate the emitted PM_{2.5}, were measured with a tapered element oscillating microbalance (TEOM) per kg of fuel through carbon mass balance, which facilitated exposure assessment by fuel type. Assumptions for these calculations included the following: four 1-h cooking events (including coffee making) a day; 300 g of charcoal is used at each event; and the cooking is conducted in a 180 m³ home with an air exchange rate of 15 h⁻¹. This relatively high air exchange rate was chosen because the building envelope of mud houses is highly penetrable due to gaps between the roof and walls and uncovered openings often serving as windows and doors. Additionally, exposure measurements of 28 women’s breathing zones during coffee making, all using charcoal, in Adama were conducted using TSI® DustTrak, and the amount of charcoal burned was weighed (Edlund, 2019).

Urban Green Space

A subjective assessment of the presence of urban green space in the residential area was collected from the women (“yes”; *n* = 945 and “no”; *n* = 668) during the home visit, for which a portion of the study population (*n* = 428) could not be reached. Additional questions on residential characteristics were also asked at this time.

Statistical Analysis

All analyses were conducted with SPSS Statistical Software version 25 (IBM®, Armonk, NY, USA) using logistic regression. Associations between SES indicators (education and occupation) and ambient air pollution (dichotomous NO₂ and NO_x exposure below/above Adama’s mean concentrations and below/above 20 µg/m³), household air pollution (fuel type used for cooking), and the presence of green space (yes/no) were investigated and described as odds ratios (ORs) with 95% confidence intervals (CIs). SES reference categories included “> grade 12,” “high education,” and “permanent employment.”

A sensitivity analysis was conducted pertaining to ambient air pollution, where all women with GPS coordinates written as degree, minute, and second (*n* = 238) instead of degree and minute were excluded.

Ethical Considerations

Approval for this study was granted by the Ethical Review Board of the Ministry of Science and Technology, Addis Ababa, Ethiopia (310-046-2015) and the Lund University Ethical Committee (Registration numbers: 2015/364 and 2016/576 [amendment]). Written informed consent was obtained from all participants prior to any study procedures. Data was collected and processed strictly under code and stored in a REDCap (www.project-redcap.org) database hosted by the Faculty of Medicine, Lund University, Sweden, to preserve data integrity and maintain study participants’ confidentiality.

RESULTS

Most women in the Adama Mother and Child cohort were between 18 and 29 years old, median 25 years, and virtually all were married (~96%). A slight majority (~56%) had completed

TABLE 1 | Demographic information on the women comprising the Adama mother and child cohort (*n* = 2,085) including both household and residential characteristics.

	<i>n</i> (% of total)
PERSONAL CHARACTERISTICS	
Age	
< 18	19 (0.9)
18–24	917 (44.0)
25–29	812 (38.9)
30–34	256 (12.3)
≥ 35	75 (3.6)
Missing	6 (0.3)
Marital status	
Single	64 (3.1)
Married	1,994 (95.6)
Divorced	16 (0.8)
Widowed	3 (0.1)
Missing	8 (0.4)
Education	
Illiterate	266 (12.8)
< Grade 6	410 (19.7)
Grades 6–12	1,172 (56.2)
> Grade 12	231 (11.1)
Missing	6 (0.3)
Occupation	
Daily laborer	248 (11.9)
Permanent employment	274 (13.1)
Self-employed	163 (7.8)
Homemaker	1,319 (63.3)
Student	42 (2.0)
Unemployed	29 (1.4)
Missing	10 (0.5)
HOUSEHOLD CHARACTERISTICS	
Fuel used for cooking*	
Electricity	1,005 (48.2)
Gas or kerosene	79 (3.8)
Charcoal or wood	1,564 (75.0)
Animal dung	9 (0.4)
LPG cylinder	15 (0.7)
Other	1 (0.05)
Missing	15 (0.7)
Electricity	
Yes	1,984 (95.2)
Missing	17 (0.8)
Running water	
Yes	1,863 (89.4)
Missing	8 (0.4)
Material used for walls	
Mud	751 (36.0)
Concrete blocks	580 (27.8)
Stone	260 (12.5)
Wood	20 (1.0)
Missing	474 (22.7)

(Continued)

TABLE 1 | Continued

	<i>n</i> (% of total)
RESIDENTIAL AREA CHARACTERISTICS	
Traffic intensity on nearest road	
Heavy	525 (25.2)
Medium	910 (43.6)
Light	164 (7.9)
Missing	486 (23.3)
Traffic intensity on nearest major road	
Heavy	1,359 (65.2)
Medium	193 (9.3)
Light	45 (2.2)
Missing	488 (23.4)
Industry coverage	
Large	4 (0.2)
Medium	325 (15.6)
Small	1,298 (62.3)
Missing	458 (22.0)
High population density	
Yes	1,456 (69.8)
Missing	452 (21.7)
Urban green spaces	
Yes	945 (45.3)
Missing	472 (22.6)

*Participants could select multiple alternatives. LPG, liquid petroleum gas.

schooling between grades 6 through 12, with the most prominent occupation being homemaker (~63%). Most households had electricity and running water, and homes were typically built using mud (a mixture of dried soil and organic materials) or concrete blocks. Regarding their residential areas, most women reported heavy to medium traffic nearby but only a small presence of industrial sites. Additionally, the majority of women lived in areas perceived to have a high population density, while ~45% considered their neighborhood to have green space present. See **Table 1** for further details.

Ambient Air Pollution

Women of the Adama Mother and Child cohort were, on average, exposed to 13.70 $\mu\text{g}/\text{m}^3$ of NO_2 and 29.89 $\mu\text{g}/\text{m}^3$ of NO_x (minimum: 4.09 and 0.44 $\mu\text{g}/\text{m}^3$, maximum: 37.72 and 126.61 $\mu\text{g}/\text{m}^3$, respectively). These modeled exposure concentrations, which have been published previously in Abera et al. (2021), are illustrated in **Figure 2**.

The odds of being exposed to either ambient NO_2 or NO_x concentrations above Adama's mean values steadily increased with decreasing education level (**Table 2**). When education was dichotomized, this trend continued; however, statistical significance remained only for NO_x . Daily laborers appeared to have slightly higher odds of experiencing greater exposure to NO_2 and NO_x , but these results were not statistically significant ($p = 0.35$ and $p = 0.39$, respectively). For exposure to NO_2

above 20 $\mu\text{g}/\text{m}^3$ (**Table 3**), stronger effects were observed for both SES indicators, especially when education was divided into three categories, albeit with wider confidence intervals. The corresponding odds were generally smaller for NO_x exposure above 20 $\mu\text{g}/\text{m}^3$ and with greater statistical insignificance. The sensitivity analysis excluding coordinates written as degree, minute, and second produced similar results but with slightly lower ORs (**Supplementary Tables 1, 2**).

Household Air Pollution

The likelihood of cooking with solid fuels only as compared to clean fuels only was closely linked to education levels. Women who attended less than grade 6 of schooling and those who attended grades 6–12 were ~13 times and 4 times more likely to cook with solid fuels only, respectively, compared to those who attended school past grade 12 (**Table 4**). When education level was dichotomized, those with primary school education (low education) had about 3.6 times greater odds of using solid fuels only as compared to those who attended secondary school (high education). Concerning occupation, women employed as daily laborers were 5 times more likely to cook with solid fuels only compared to those with permanent employment. Similar trends, though with lower ORs, were seen for the use of solid fuels only vs. a mix of clean and solid fuels. Even when considering the odds of using a combination of clean and solid fuels against clean fuels only, lower SES women tended to have slightly greater odds of using the dirtier option (mixed fuels) than their higher SES counterparts, though some statistical insignificance was present.

Cooking with charcoal generated an estimated indoor 24-h average exposure of 260 $\mu\text{g}/\text{m}^3$ of $\text{PM}_{2.5}$ in addition to any outdoor exposures. The emission factor obtained for charcoal combustion in a ceramic Mirchaye stove was 3.3 g/kg fuel. Wood combustion generated several times higher $\text{PM}_{2.5}$ emissions of varying chemical composition per kg fuel compared to charcoal, and dung gave twice the emissions per kg compared to wood in our experiments. As a greater amount of fuel is needed per day for wood- and dung-fired cooking compared to charcoal, $\text{PM}_{2.5}$ exposure increases even more: by approximately one order of magnitude (a factor of 10) for wood and twice that for dung, assuming indoor cooking.

Urban Green Space

Women with an education below grade 6 were nearly 3 times more likely to report a lack of green space around their residency than those with education levels above grade 12, and those who had attended grades 6–12 had double the odds of experiencing a lack of green space compared to the most highly educated women (**Table 5**). A similar trend remained when education level was dichotomized. Further, those who worked as daily laborers were more than twice as likely to report a lack of green space in their residential area compared to those who had permanent employment.

DISCUSSION

Environmental injustice was found to be present in Adama, as women of lower socioeconomic status had consistently greater

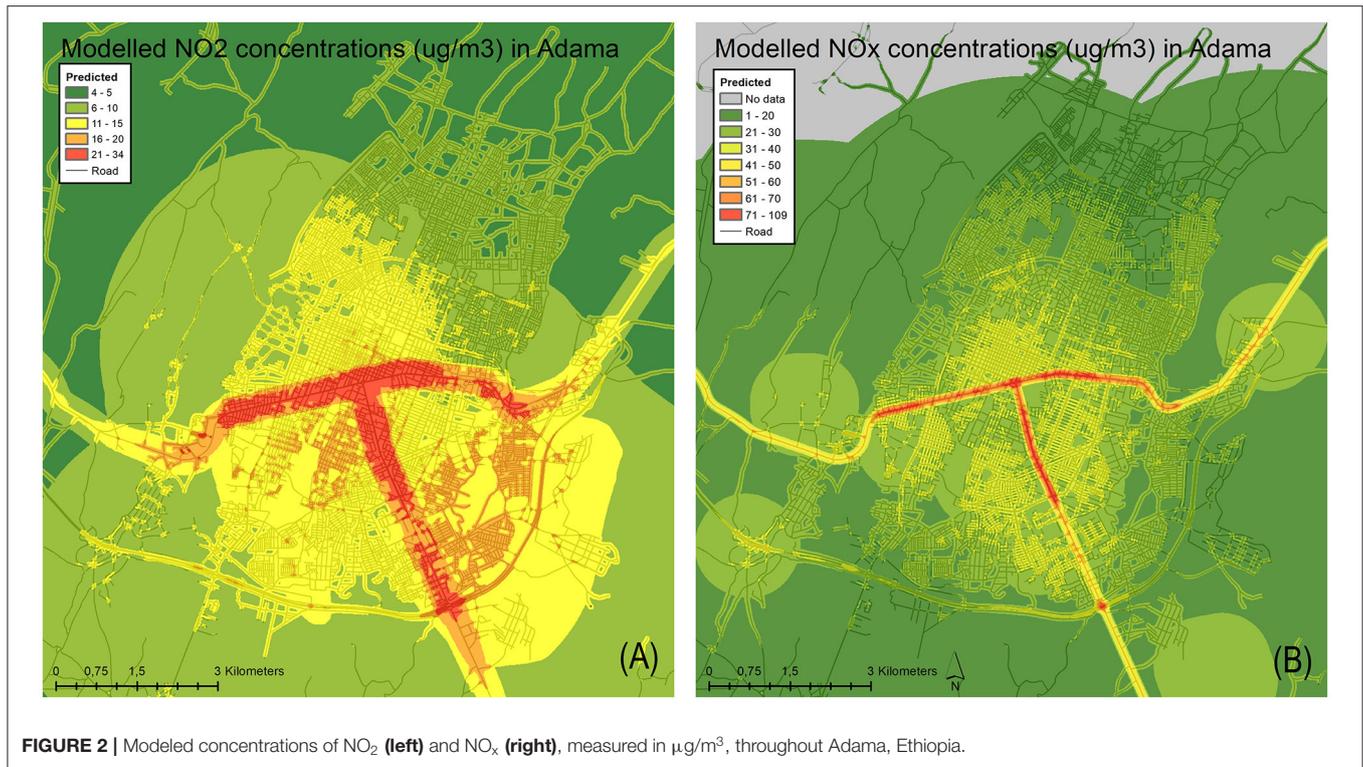


FIGURE 2 | Modeled concentrations of NO₂ (left) and NO_x (right), measured in µg/m³, throughout Adama, Ethiopia.

TABLE 2 | Odds of being exposed to levels of NO₂ and NO_x above the mean (13.70 and 29.89 µg/m³, respectively) associated with education level and occupation among women in the Adama Mother and Child cohort.

	OR (95% CI)	
	NO ₂ N = 1,606	NO _x N = 1,605
Education level		
Illiterate and < Grade 6	1.71 (1.19–2.45)**	2.14 (1.49–3.09)**
Grades 6–12	1.65 (1.17–2.32)**	1.88 (1.33–2.67)**
> Grade 12	REF	REF
Education level^a		
Low	1.13 (0.91–1.40)	1.26 (1.02–1.56)*
High	REF	REF
Occupation		
Daily laborer	1.19 (0.83–1.70)	1.17 (0.82–1.66)
Permanent employment	REF	REF

Number of included participants (N) is presented.
OR, Odds ratio; CI, Confidence interval. ^aLow = Illiterate and < Grade 6, High = Grades 6–12 and > Grade 12. REF, reference category. *p ≤ 0.05. **p ≤ 0.01.

TABLE 3 | Odds of being exposed to levels of NO₂ and NO_x above 20 µg/m³ associated with education level and occupation among women in the Adama Mother and Child cohort.

	OR (95% CI)	
	NO ₂ N = 1,606	NO _x N = 1,605
Education level		
Illiterate and < Grade 6	5.80 (2.77–12.16)**	1.33 (0.82–2.14)
Grades 6–12	4.45 (2.15–9.24)**	1.71 (1.09–2.69)*
> Grade 12	REF	REF
Education level^a		
Low	1.53 (1.16–2.01)**	0.87 (0.62–1.20)
High	REF	REF
Occupation		
Daily laborer	1.61 (0.98–2.64)	1.38 (0.72–2.64)
Permanent employment	REF	REF

Number of included participants (N) is presented.
OR, Odds ratio; CI, Confidence interval. ^aLow = Illiterate and < Grade 6, High = Grades 6–12 and > Grade 12. REF, reference category. *p ≤ 0.05. **p ≤ 0.01.

odds of being exposed to higher levels of ambient NO₂ and NO_x concentrations, using solid fuels that produce high levels of PM_{2.5}, and living in areas that lack green space. Moreover, odds were stronger for ambient NO₂ exposure when using a higher exposure concentration cut-off (20 µg/m³), which we

have previously used when studying environmental injustice in Sweden (Flanagan et al., 2019), as opposed to Adama’s mean (13.7 µg/m³), illustrating lower SES persons’ increasing risk of exposure to even higher levels of air pollution. These results are also in line with the few environmental injustice studies

TABLE 4 | Odds of using solid fuels for cooking associated with education level and occupation among women in the Adama Mother and Child cohort.

	OR (95% CI)		
	Solid vs. clean fuels	Solid vs. mixed fuels	Mixed vs. clean fuels
Education level	N = 1,476	N = 1,581	N = 1,081
Illiterate and < Grade 6	12.88 (8.30–19.98)**	7.04 (4.63–10.72)**	1.83 (1.24–2.69)**
Grades 6–12	4.49 (3.01–6.69)**	3.70 (2.48–5.52)**	1.21 (0.88–1.67)
> Grade 12	REF	REF	REF
Education level^a	N = 1,476	N = 1,581	N = 1,081
Low	3.55 (2.73–4.62)**	2.26 (1.80–2.82)**	1.58 (1.17–2.12)**
High	REF	REF	REF
Occupation	N = 486	N = 507	N = 367
Daily laborer	5.31 (3.39–8.30)**	3.73 (2.50–5.55)**	1.42 (0.86–2.37)
Permanent employment	REF	REF	REF

Number of included participants (N) is presented. OR, Odds ratio; CI, Confidence interval. Solid fuels = wood/charcoal/cow dung only. Clean fuels = electricity/gas/kerosene/liquid petroleum gas cylinder only. Mixed fuels = a combination of clean and solid fuels. ^aLow = illiterate and < Grade 6, High = Grades 6–12 and > Grade 12. REF, reference category. *p ≤ 0.05. **p ≤ 0.01.

conducted in Sub-Saharan Africa. In Accra, Ghana, for instance, higher SES areas were associated with lower concentrations of PM_{2.5} and PM₁₀ (Rooney et al., 2012). Considering urban green areas in Nakuru, Nigeria, dissatisfaction with available green spaces rose in a stepwise manner as SES decreased (Ochodo et al., 2014). This is parallel to our results of the reported lack of green space in women’s residential areas increasing incrementally as education decreased and being more likely among daily laborers compared to those with permanent employment. Thus, any investigation and mitigation efforts concerning environmental exposures Sub-Saharan African cities should not assume equal exposures across the population, but rather consider the complex and nuanced exposure gradients that exist in relation to socioeconomic status.

Ambient Air Pollution

The regulation and governance of air pollution has proven to be an immense challenge in LICs and LMICs, particularly in Sub-Saharan Africa (Amegah and Agyei-Mensah, 2017; Makoni, 2020; Mir Alvarez et al., 2020). For instance, a study found that most African countries have not incorporated the World Health Organization’s (WHO) air pollution guidelines into their national legislations, and 45% of African countries did not have any air pollution regulations whatsoever (Joss et al., 2017). In Ethiopia, proclamation No. 300/2002 on “Environmental Pollution Control” specifies standards for ambient air quality,

TABLE 5 | Odds of experiencing a lack of green space in the residential area associated with education level and occupation among women in the Adama Mother and Child cohort.

	OR (95% CI)
	Lack of green space
Education level	N = 1,610
Illiterate and < Grade 6	2.93 (2.02–4.25)**
Grades 6–12	2.06 (1.44–2.94)**
> Grade 12	REF
Education level^a	N = 1,610
Low	1.59 (1.29–1.97)**
High	REF
Occupation	N = 540
Daily laborer	2.27 (1.58–3.25)**
Permanent employment	REF

Number of included participants (N) is presented. OR, Odds ratio; CI, Confidence interval. ^aLow = illiterate and < Grade 6, High = Grades 6–12 and > Grade 12. REF, reference category. *p ≤ 0.05. **p ≤ 0.01.

yet no documents outlining national or regional strategies to translate these policies into practice exist (Mitike et al., 2016). As a result, there are inadequate implementation processes to encourage adherence and manage enforcement (Mitike et al., 2016). While air quality control may be sparse, mean modeled NO₂ exposure levels in Adama (13.70 μg/m³) appeared to fall well below the current WHO and European Union air quality guideline of 40 μg/m³ (annual average) (EU, 2008; World Health Organization, 2018). Still, the maximum NO₂ exposure levels modeled in Adama (37.72 μg/m³) approach this limit, which is currently under revision by WHO and is likely to be lowered (World Health Organization, 2018).

Household Air Pollution

As women in Adama with lower education and daily laborer employment had consistently greater odds of cooking with pollutive solid fuels, the case for prioritizing women of lower SES for initiatives involving cleaner fuel supplementation and subsidization is strong. Further, charcoal was found to generate 24-h average exposure levels of PM_{2.5} that exceeded the WHO’s indoor exposure guideline (25 μg/m³) (World Health Organization, 2010) by a factor of 10. Still, this fuel type was the least polluting of the three studied, and cow dung, the cheapest fuel, was the most polluting. This illustrates that providing people in low-income countries the possibility of substituting their energy source, even with respect to solid fuels, could contribute to a relative improvement in indoor air quality. On the other hand, charcoal production itself leads to emissions elsewhere, and the substitution of solid fuels with gas or electricity is a more sustainable alternative.

While significant efforts have been made to curb household air pollution from cook stoves (Pilishvili et al., 2016; Puzzolo

et al., 2016; Yip et al., 2017), not all interventions have been effective (Tsephel et al., 2009; Eshetu, 2014; Sanbata et al., 2014; Quansah et al., 2017; Jürisoo et al., 2018). An alternative to the traditional approach of stand-alone, household-scale delivery of products is the utility-scale service model (Ray and Smith, 2021). This may include reliable electricity from regulated mini-grids or cost-efficient distribution of liquefied petroleum gas (LPG) (Ray and Smith, 2021). The former is applicable to our study setting, where ~95% of women have electricity in their household but still use solid fuels (74%)- often due to electricity being more expensive and/or not in continuous supply (Kapsalyamova et al., 2021). Further, supplying households in India and the Kyrgyz Republic with gas, particularly LPG, reduced solid fuel use (Kapsalyamova et al., 2021). A similar utility transition is a promising option for Adama, where the use of gas, kerosene or LPG is low (4.5%). While the need for individual behavior change is acknowledged, people's ability to choose is often constrained by their circumstances (Ray and Smith, 2021). If universal access and uptake of cleaner energy is the goal, services should be planned and delivered such that the health-promoting option becomes the default (Ray and Smith, 2021). State investment in clean, domestic energy services would require the historical inefficiencies, corruption, and poor governance of energy production and delivery to be addressed (Ray and Smith, 2021). With this, the utility-scale service model underscores the importance of political will and government action for large-scale, long-term improvement in indoor air quality (Ray and Smith, 2021).

Urban Green Space

Most research on urban green space has been conducted in higher-income countries (Rupprecht and Byrne, 2014; Kabisch et al., 2015), but this has recently expanded to include lower-income countries in Sub-Saharan Africa (Chamberlain et al., 2019; Vancampfort et al., 2019; Sardeshpande and Shackleton, 2020; Yessoufou et al., 2020). Of particular interest is urbanization, which drives a rapid shift in land-use, including the removal of natural vegetation and the construction of housing, infrastructure, and industry. These coalesce to drive land surface temperature increases, as demonstrated in urban Nigeria (Fashae et al., 2020) and the Ethiopian highlands (Yohannes et al., 2020). In Ethiopia's capital city Addis Ababa, green spaces, including urban forest and urban agriculture, have undergone a rapid decline (Teferi and Abraha, 2017; Azagew and Worku, 2020), and only 0.37 m² of park space per capita is available to residents (Azagew and Worku, 2020). Indeed, the reduction of overall vegetation cover in Addis Ababa and the reported ~16% increase in built-up area from 1985 to 2015 is considered to have contributed to the land surface temperature of the city increasing 3–8°C over the same time period (Worku et al., 2021). Adama, on the other hand, has 2.1 m² of park space per capita (Azagew and Worku, 2020), but this still falls short of the standards provided by the WHO (9 m²) (World Health Organization, 2016c) and the Ethiopian Urban Green Infrastructure Standard (15 m²) (Ministry of Urban Development Housing, 2015). Despite master plans with the intention of protecting, expanding, or creating new urban

green spaces, such objectives rarely become reality in most Ethiopian cities due to low enforcement of development plans, pressured expansion of built-up areas, weak prioritization of urban green spaces, financial constraints, lack of professional knowledge, and insufficient public involvement (Girma et al., 2019; Azagew and Worku, 2020). Fortunately, it appears that a greater understanding of the positive benefits of urban vegetation and green space is emerging (Herslund et al., 2018). Protecting and expanding these spaces remains one of the most promising climate change adaptations strategies that can help reduce the urban heat island effect and improve human health (Teferi and Abraha, 2017).

A Societal and Human Rights Approach

From a societal perspective, the present results underline the importance of educational and occupational opportunities. These upstream determinants, rather than policy regulations or technical solutions, offer an additional pathway through which individual risk of air pollution exposure can be reduced and access to urban green space can be improved (Ahlers, 2016). Furthermore, higher educational attainment can contribute to greater awareness of environmental exposures. Several studies conducted in Sub-Saharan Africa have noted awareness of air pollution exposure and its health effects to rise as education increased (Egondi et al., 2013; Omanga et al., 2014; Nwankwo et al., 2018; Odonkor and Mahami, 2020). Such awareness is essential to promote individual behavioral change (Muindi et al., 2014; Nwankwo et al., 2018), stimulate grassroots engagement, and generate public demand for policy creation. Addressing these environmental exposures, however, requires governmental action (Ngo et al., 2015; Breathelife, 2016; Bahino et al., 2018). Utilizing a human rights perspective would provide governments with clear, legally enforceable obligations to act, as ambient and household air pollution and dwindling urban green space violates the right to good health (Boyd, 2019). Indeed, Ethiopia's own constitution recognizes access to clean and healthy environments as a fundamental right for which the government is responsible (Article 44/1 Proclamation No. 1/1995). This protection is especially necessary for those disproportionately exposed.

Methodological Considerations

A key strength of this study is the LUR models developed specifically for assessing ambient air pollution exposure in Adama, which successfully capture the spatial variability of NO₂ and NO_x (Abera et al., 2021). Additionally, the aerosol chamber analysis of cooking fuel samples taken directly from the study area increase the reliability of our inferences regarding household air pollution exposure. The Adama Mother and Child cohort has been successfully utilized in previous studies, and the geographic location of each woman's home residence was manually collected, which helped reduce the risk of exposure misclassification for those women included in analyses. The use of in-depth questionnaire data for SES (< 1% missing) is considered an additional strength, as official registers maintained by governmental agencies are lacking. Furthermore, antenatal care facilities offer a unique opportunity for epidemiological studies, where a representative sample of otherwise healthy

women can be accessed. Our study population was quite diverse, capturing a range of education levels and occupations, and ~96% of the households could be characterized by married women expecting a child. We, therefore, believe that this study is representative of, and the results generalizable to, families residing in urban Ethiopia, with the exception of extremes in wealth and poverty. Finally, this is a novel study, as very few studies on environmental injustice in LICs and LMICs have been conducted. To the best of our knowledge, this is also the first study on environmental injustice in Ethiopia and the first in Sub-Saharan Africa to investigate the inequalities of several environmental exposures in the same cohort.

Several limitations are also present. Common to all air pollution epidemiology studies, exposure misclassification is a possible limitation. The use of well-performing LUR models and individual residential addresses can help decrease this bias. Even so, data on some important geographical predictor variables was not available, which is further discussed in Abera et al. (2021). As previously mentioned, a number of residential address coordinates were registered as degree, minute, and second ($n = 238$); these were treated as degree and minute in the main analysis and, thereby, introduced some uncertainty. However, our sensitivity analysis demonstrated that their inclusion did not substantially alter the results (Supplementary Tables 1, 2). Not reaching 428 women for home visits is also a limitation, but these women did not seem to differ greatly in terms of socioeconomic status compared to those who were able to be reached (Supplementary Table 3).

Using cooking fuel type as a proxy for household air pollution may also increase the risk of exposure misclassification (Odo et al., 2021). Nevertheless, the response-rate for fuel type was high, with < 1% missing. It should be noted that the category “solid fuels” comprises three fuel types whose emissions differ greatly. Charcoal appeared to be the most commonly used fuel in Adama from previous field visits. The estimated exposure from cooking also has its limitations; for instance, the estimations were based on the fuel alone, excluding any additional exposure from the food and cooking oil; all emissions were assumed to mix into the residence volume uniformly and instantaneously; and many homes have a volume smaller than that assumed in the model. This may have led to an underestimation of the true cooking emissions. Still, the exposure concentrations from the laboratory experiments were in line with the calculated 24-h average of $262 \mu\text{g}/\text{m}^3$ from DustTrak measurements taken in the breathing zone of charcoal-fueled coffee preparation by women in Adama (Edlund, 2019), despite the model being greatly simplified.

Responses regarding the presence of green space were subjective, but such accounts have been suggested to be preferable when evaluating the quality or experience of greenness as opposed to an objective measure of the quantity of green space (Leslie et al., 2010). The reliance on self-reported data for SES indicators and cooking fuel type may have contributed to response bias. Furthermore, the decision

to limit occupation-related analyses to only positions with paid employment significantly reduced the sample population, which might have led to decreased power and increased uncertainty for the results concerning this particular SES indicator. Missing data on urban green space (~23%) can also be seen as a limitation. There was a slight tendency for women identifying as illiterate to be missing more data on green space compared to the most highly educated (> 10% difference); however, the percent missing among the occupation categories studied were relatively similar (Supplementary Table 4).

Future Research

Future studies, especially health impact assessments, in Ethiopia and other countries in Sub-Saharan Africa investigating environmental exposures and their health effects would benefit from stratifying their analyses by SES. Not doing so could incorrectly homogenize exposures and potentially mask an existing gradient, which would, consequently, derive inaccurate risk assessments. This stratification would also provide insight into practical strategies for policy implementation- demonstrating where interventions are most needed and for whom they would most benefit. Additionally, participatory research methods that directly involve members of the community should be prioritized to further improve awareness and inspire agency; this is important for long-term engagement and to generate momentum for political change (Ngo et al., 2017).

CONCLUSIONS

We found evidence of environmental injustice in Adama, Ethiopia, as residents with less education and/or employment as daily laborers experienced higher exposure to ambient and household air pollution than their more educated, permanently employed counterparts. These lower SES women were also more likely to lack urban green space in their residential areas. Considering socioeconomic differences in environmental exposures is important to better understand existing exposure gradients and to help identify priority populations for policy planning and applied interventions. From a societal perspective, these results also support investment in educational and occupational opportunities; however, governments are ultimately responsible for the protection of the human right to a clean environment for all.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: The ethical permissions granted for this project outline restrictions that limit dataset access to only those researchers involved in the project, as sensitive information on individual exposure levels of air pollution, socioeconomic status, demographics, and health is present. Requests to access these datasets should be directed to Ebba Malmqvist, ebba.malmqvist@med.lu.se.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethical Review Board of the Ministry of Science and Technology, Addis Ababa, Ethiopia (310-046-2015) and the Lund University Ethical Committee (Registration numbers: 2015/364 and 2016/576 [amendment]). Written informed consent to participate in this study was provided by the participants; if the participant was a minor, their legal guardian/next of kin provided written informed consent.

AUTHOR CONTRIBUTIONS

CI and EM were responsible for the conceptualization of this study and funding acquisition. EM was responsible for project administration. Data curation was performed by JW, CI, KM, AA, EM, and AE. Preliminary investigations were conducted by JW, CI, KM, AA, EM, AE, and FB. Formal analysis was performed by EF, AO, and EM. EF wrote the original draft of the manuscript. All authors aided in manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frsc.2021.728384/full#supplementary-material>

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