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Air pollution and health in Rwandan and Kenyan schools cooking with polluting fuels: a cross-sectional impact study

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ABSTRACT

School meals across Sub-Saharan Africa are typically prepared using biomass on inefficient stoves, resulting in high air pollution levels that might affect learners and staff. However, there is a paucity of air pollution health-related research in African schools. This study, conducted in seven schools in Rwanda and four schools in Kenya, assessed 1) levels of carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$) in school kitchens, classrooms (three, at different distances from the kitchen), playgrounds and personal among learners and catering staff; and 2) the prevalence of acute air pollution health-related symptoms and knowledge and perceptions of air pollution among learners and staff. For Rwanda and Kenya respectively, median 24-h $PM_{2.5}$ levels were 263 and 1480 μg/m^3 for kitchens and 63 and 68 μg/m^3 for classrooms. In Rwanda, median personal $PM_{2.5}$ exposure levels were 354 μg/m^3 for cooks and 86 μg/m^3 for leaners. In Kenya, median personal $PM_{2.5}$ exposures were 1280 μg/m^3 for cooks and 99 μg/m^3 for leaners. Median CO levels in the kitchens were 1.8 and 23 and for cooks 3 and 14.8 mg/m^3 for Rwanda and Kenya respectively. Surveys with learners (n = 526 and n = 302), catering staff (n = 45 and n = 28), and teachers (n = 21 and n = 12) for Rwanda and Kenya, respectively, demonstrated a high prevalence of self-reported air pollution-related headaches, eye irritation, and cough. The elevated air pollution levels and associated prevalence of health issues underscore the urgent need to accelerate transition to clean energy in African schools.

1. Introduction

Globally approximately 2.1 billion people rely on polluting fuels and technologies such as inefficient cookstoves and traditional three-stone fires that burn wood, charcoal, crop residues or kerosene as their primary means of cooking (IEA; IRENA; UNSD and; World Bank; WHO, 2024). Sub-Saharan Africa (SSA) disproportionately bears the greatest burden with the majority (79%) of the population relying on polluting fuels and technologies (IEA; IRENA; UNSD and; World Bank; WHO, 2024). In Rwanda and Kenya respectively, 91.7% and 70.0% of the population lacks access to clean cooking fuels and technologies (Energy Sector Management Assistance Program, 2024). The incomplete combustion of polluting fuels releases harmful pollutants, including fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), and other toxic compounds, that contribute to household air pollution (HAP). $PM_{2.5}$, in particular, is known to lead to a wide range of adverse health outcomes including stroke (Yu et al., 2020), ischaemic heart disease (McCracken et al., 2012; Pope et al., 2009), chronic obstructive pulmonary disease

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(Kurmi et al., 2010; Po et al., 2011), and lung cancer (Kurmi et al., 2012). Globally, exposure to HAP is responsible for 3.2 million premature deaths annually including 7200 in Rwanda and 23,500 in Kenya (World Health Organization, 2019). Women and children are disproportionately affected by HAP as they spent most of their time near the cookstoves due to domestic duties (Energy Sector Management Assistance Program, 2020). In children less than 5 years old, exposure to HAP is responsible for almost half of all pneumonia deaths (World Health Organization). Exposure to air pollution has been linked to impacts on children's health, including increased respiratory symptoms (Dherani et al., 2008), impaired lung function, absences from school, and reduced cognitive and academic performance (Kalisa et al., 2023; Meme et al., 2023). A scoping review on schoolchildren's exposure to indoor and outdoor $PM_{2.5}$ and PM_{10} in Africa showed that children are often exposed to levels exceeding the recommended World Health Organization's (WHO) air quality guidelines (Kalisa et al., 2023). In addition to health impacts, domestic harvesting of firewood also contributes to deforestation and soil degradation. Furthermore, combustion of polluting fuels contributes to climate warming through the production of greenhouse gases (e.g. CO_2, methane) (Energy Sector Management Assistance Program, 2020).

Despite efforts to accelerate the transition to clean cooking and the increase in research in the household setting, few studies have focused on public institutions. Schools, which prepare a high volume of meals, are significant contributors to inefficient cooking practices (World Food Program). In SSA, schools are estimated to use 8 million tons of firewood annually, with resulting emissions of 12–14 million tons of CO_2 equivalent (Energy Sector Management Assistance Program, 2023). A national survey on cooking fuel energy and technologies in public institutions in Rwanda identified schools as the largest consumers of biomass (primarily unstainable harvesting of firewood) (Centre for Economic and Social Studies, 2020). Most of Rwanda's schools are using either firewood (more than 50%) or charcoal (nearly 34%) for cooking. In Kenya, over 90% of primary and secondary schools rely on biomass for cooking (Clean Cooking Association of Kenya and SNV and Netherlands Development Organisation, 2018), whereas the use of alternative cleaner fuels (such as liquefied petroleum gas (LPG), or electricity) in schools is negligible in both countries.

Accelerating access to clean cooking (e.g. LPG, biogas and electricity) is critical to achieving the United Nations 2030 Sustainable Development Goals 7 (SDG7, clean and affordable energy for all) which will have co-benefits in SDG3 (good health and well being), SDG 5 (gender equality), SDG 11 (sustainable cities and communities) and SGD 13 (climate action) while also progressing towards Net Zero 2050 climate goal. There is a paucity of data on the impact of cooking with polluting fuels in schools on air quality and health of catering staff, teachers and learners, despite schools being the second largest consumer of biomass energy after households (Energy Sector Management Assistance Program, 2023). The extent to which air pollution levels from schools affects children's health across Africa, particularly in relation to school cooking practices, is not well understood. More research is needed to address this problem and to protect the health of both students and staff by reducing exposure to harmful air pollutants (Nix et al., 2024).

The aims of this cross-sectional study, conducted in seven schools in Rwanda and four schools in Kenya that use polluting fuels for cooking, were to (i) measure and quantify levels of health damaging air pollution by measuring levels of carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$) in classrooms, school kitchens, and playgrounds, and personal exposure for learners and catering staff and (ii) identify health symptoms and conditions associated with air pollution exposure for school staff and learners as well as (iii) their knowledge and perceptions of air pollution.

2. Methods

2.1. Study design

The study employed a cross-sectional mixed-methods design in seven secondary schools in Rwanda and four secondary schools in Kenya, that were using biomass for cooking and were earmarked for transition to clean cooking technologies (LPG or electricity) under pilot schemes in each country. Baseline data collection took place from March to May 2024 in Rwanda and August to September 2024 in Kenya.

2.2. Studied schools

Seven secondary schools (six boarding and one day school) and four secondary schools (two boarding and two day schools) were selected based on proximity to Kigali and Nairobi city respectively. The schools were chosen having been selected for transitions to clean cooking stoves with LPG (n = 9) or electric pressure cookers (n = 2) under pilot programs. In Rwanda, three schools were located in urban areas and four were in rural areas. In Kenya, all schools were located within the Nairobi metropolitan area. Details of the schools, including demographics, kitchen and classroom layout, kitchen and classroom ventilation, cooking fuels, and stoves and cooking equipment can be found in Supplementary Tables A-F and Supplementary Figures A–B.

2.3. Data collection

2.3.1. Air pollution monitoring

For both countries, indoor and outdoor air pollution measurements were conducted in three classrooms (located at specified distances from the school kitchen), the kitchen, and the playground (ambient). Air quality monitors were placed to sample both 24-h $PM_{2.5}$ and CO on two occasions during a designated school week (representing the full menu and cooking practices of the school). Ambient $PM_{2.5}$ monitoring was conducted at the playground over a five-day period (school week) with monitoring aligned with that for indoor sampling. Personal exposure monitoring of $PM_{2.5}$ and CO was undertaken for the main cook and three learners (randomly selected from the monitoring classroom; one in each classroom) from each school (Supplementary Figure C). The recording period for personal exposure represented the time spent within the school environment (approximately 8-h for cooks, 24-h for learners in boarding schools, and 8-h for learners in day schools).

Measurement of $PM_{2.5}$ was conducted using Ultrasonic Personal Air Samplers v2+ (UPASv2+) with gravimetric assessment of $PM_{2.5}$ mass being undertaken through an inbuilt pump with cyclone collecting $PM_{2.5}$ on a filtering media and a laser/sensor measuring light scatter for real-time data recording (Volckens et al., 2017). Ambient $PM_{2.5}$ was measured using PurpleAir II (light scattering approach for real-time data recording) (PurpleAir). The Purple Air II allowed sampling for the full school week (not possible with UPASv2+ due to gravimetric sampling and shorter battery life of this technology). CO measurements were conducted with Lascar EasyLog EL-USB-CO monitors (LASCAR Electronics) that have an electrochemical sensor to measure CO concentrations in real-time with range between 0 and 300 ppm.

All air quality data were collected by a trained field team according to pre-established sampling protocols following standard operating procedures. Ambient air quality monitoring involved placement of PurpleAir II monitors located at least 10 m away from localised sources of air pollution, trees or tall buildings and at a height of approximately 3 m. Kitchen and classroom monitors were placed at approximately 1.5 m from the floor and at least 1 m from doors and windows. For kitchens, the monitors were placed 1 m from the cooking stove using bespoke stands to support the monitors. Personal exposure was assessed by placing monitors on bespoke tailored vests located in the breathing zone of the wearer (front chest), worn by learners or cooks (Figure SE1, SE2). The UPASv2+ and PurpleAir II light scattering measurements were calibrated using the gravimetric mass concentrations from co-located UPASv2+ monitors in each location. PurpleAir II monitors were further corrected for relative humidity (RH) and temperature (Barkjohn et al., 2022). Teflon filters used in the UPASv2+ were pre- and post weighed after conditioning for 24-h in a temperature and RH controlled room. The pre- and post-weighing were conducted using a gravimetric robot AH500E from Measurement Technology Laboratories (MTL, Minneapolis, USA). Field-blanks were collected twice a week for each school where the UPASv2+ was configured with a filter and was brought to the schools for the whole sampling duration without turning the pump on (Johnson et al., 2022; Shupler et al., 2024). LASCARs were calibrated once during the monitoring period, in a laboratory with zero air and a span CO gas (100 ppm) before their field deployment. All monitoring devices were calibrated before and after the campaign deployment according to manufacturer specifications using standard calibration procedures to ensure accurate measurements. Routine maintenance checks were conducted weekly to identify and rectify any potential issues, such as sensor malfunctions or battery failures, that could affect data quality. Data validation processes, including outlier detection and cross-verification, were performed bi-weekly to maintain the integrity and reliability of the collected data. More details can be found in Supplementary Material A.

2.3.2. Surveys

Surveys were conducted with participants in each of the classrooms being monitored for air quality including 75 learners aged 10 years or older (25 randomly selected from each classroom) and the teachers (one in each classroom). Additional surveys were conducted with all catering staff. Learner surveys collected information on acute air pollution-related health symptoms (and impacts on concentration whilst at school), and knowledge and perceptions of air quality at school and other potential sources of exposure to air pollution external to the school. Surveys for teachers and catering staff explored acute air pollution-related health symptoms and how these symptoms impacted their ability to focus on work/tasks. Additional questions were included on knowledge and perceptions of air quality at school, conditions in the kitchen and classrooms.

2.4. Data analysis

Collected data were subjected to validation processes (outlier detection and cross-verification from different monitoring devices). We calculated pollutant-specific descriptive statistics for valid measurements. We applied a Shapiro- Wilk test to assess normality in the data. Means and standard deviations were reported for continuous variables where data were normally distributed and a Mann-Whitney for the non-parametric data. We applied a Chi square test to the survey data and for categorical variables, frequencies and proportions were used to summarise the data. All data were anonymised and aggregated for analyses. Data were analysed using R, Python and SPSS software.

2.5. Ethical considerations

Ethical approval was granted by the Rwanda National Ethics Committee (RNEC) under reference 349/RNEC/2023, by the Scientific and Ethics Review Unit (SERU) of the Kenya Medical Research Institute under reference KEMRI/SERU/CRDR/091/4704, and the University of Liverpool Central Ethics Committee under reference 12608/CURECD/2023. In Kenya, a research permit was secured from the National Council for Science, Technology and Innovations (NACOSTI) under reference NACOSTI/P/23/27051. Written informed consent was obtained from participants in the local language (Kinyarwanda in Rwanda and Kiswahili in Kenya) by a trained field team. For illiterate participants, the consent form was read aloud in the presence of a witness, ensuring that participation was voluntary. Participants in Rwanda and Kenya received a compensation if they were involved in the air pollution monitoring.

3. Results

3.1. School demographics and cooking practices

Characteristics of the schools, classrooms, kitchens, cooking practices, and menus are described in Table 1, Supplementary Tables A-F, and Supplementary Figures A–B. The number of pupils in each school ranged from 682 to 1503. Only one school in Rwanda used charcoal briquettes as a primary fuel with the rest using wood (with the majority using wood exclusively – just three schools used charcoal as a secondary fuel). The amount of fuel used varied by school according to the number of people cooked for and meals prepared. In Rwanda, most schools prepared porridge for breakfast and beans and vegetables, combined with staple foods (rice, sweet potatoes, or maize flour paste or bread) for lunch and sometimes dinner. Beans and vegetables tended to be cooked simultaneously, while the staple foods were prepared in the morning for lunch or in the afternoon for dinner. In Kenya, all schools except one cooked both breakfast consisting of porridge (one school) or tea and bread (two schools) and lunch and dinner consisting of githeri (beans and maize/corn), ugali (cornmeal porridge), potatoes, cabbage, beans, vegetables, rice, banana, beef, and/or ndengu (green grams stew) depending on the daily menu.

3.2. Air pollution monitoring

The overall 24-h median gravimetric $PM_{2.5}$ concentration in school kitchens was 263 μg/m^3 in Rwanda and 1480 μg/m^3 in Kenya (Table 2). In school classrooms where monitoring was carried out, the average distance of the nearest classroom was 53 m (range: 12–115 m), 79 m (range: 22–125 m) the intermediate and 114 (range: 25–165) the farthest with no clear pollution decays due to distance. The 24-h median gravimetric $PM_{2.5}$ concentrations in classrooms were 63 and 68 μg/m^3 for Rwanda and Kenya, respectively. Personal $PM_{2.5}$ exposure monitoring during the school day (approximately 8-h) for cooks recorded median levels of 354 μg/m^3 and 1280 μg/m^3, for Rwanda and Kenya respectively. For learners, median levels of exposure were 86 μg/m^3 for Rwanda and 99 μg/m^3 for Kenya (Table 2). Median ambient 24-h $PM_{2.5}$ levels measured in school playgrounds were 26 μg/m^3 in Rwanda and 24 μg/m^3 in Kenya.

Mean hourly $PM_{2.5}$ exposures for cooks closely mapped kitchen concentrations during cooking, with similar variations during the 24-h period and exposure spikes observed at 03:00, 6:00, 8:00, 13:00, and 18:00, corresponding to meal preparation and mealtimes. Mean hourly exposure for cooks reached as high as 1287 (95% CI: 1003, 1730) μg/m^3 in Rwanda and 3087 (95% CI: 2090, 4134) μg/m^3 in Kenya (Figs. 1 and 2). Classroom concentrations and learners' mean exposure variations showed consistent spikes between 6:00 to 7:00, 12:00 to 13:00, and 16:30 to 18:00. While these time periods correspond broadly with typical meal preparation times, the data did not allow to attribute these peaks directly to cooking-related emissions or other external air pollution sources. Learners recorded higher levels of exposures during these peaks than the classrooms in both countries with spikes of 140 (95% CI: 133, 149) μg/m^3 and 238 (95% CI: 216, 266) μg/m^3 for learners in Rwanda and Kenya respectively (Figs. 1 and 2). Mean kitchen and classroom concentrations and cook and learner exposures to $PM_{2.5}$ (gravimetric) and CO for each school are displayed in Supplementary Tables H and K, for Rwanda and Kenya respectively. The duration of data monitoring is shown in Supplementary Tables G and J, for Rwanda and Kenya respectively. Light scattering $PM_{2.5}$ data for each school separately can be found in Supplementary Tables I and L. Average hourly $PM_{2.5}$ concentrations in classrooms and kitchens and personal exposures for learners and cooks for each school can be found in Supplementary Figures D–E. The median CO concentrations recorded across all school kitchens were 1.8 mg/m^3 in Rwanda and 23.0 mg/m^3 in

Table 1
Demographic characteristics of Rwandan and Kenyan schools.

	Rwanda							Kenya			
	School 1	School 2	School 3	School 4	School 5	School 6	School 7	School 1	School 2	School 3	School 4
Education level	Secondary boarding school	Secondary boarding school	Secondary boarding school	Secondary day school	Secondary boarding school	Secondary boarding school	Secondary boarding school	Secondary boarding school	Secondary day school	Secondary boarding school	Secondary day school
Number of learners	1150	900	1086	1346	1076	682	1130	1280	1503	1300	1155
Number of classrooms	29	24	22	28	26	12	26	32	24	25	21
Number of catering staff	9	8	8	4	6	4	10	11	4	7	6
Number and type of stoves	5 improved cooking stoves	5 improved cooking stoves	5 improved cooking stoves	7 improved cooking stoves	6 improved cooking stoves	4 improved cooking stoves	8 improved cooking stoves	9 wood stoves (boilers) and 1 LPG stove	4 large boilers and 1 small modern wood jiko	9 large boilers	6 wood stoves
Cooking fuels used	Firewood	Firewood	Firewood	Firewood	Firewood	Firewood	Briquettes, firewood	Firewood, briquettes, LPG (for emergencies)	Firewood, charcoal (occasionally)	Firewood, charcoal briquettes (occasionally)	Firewood

Kenya. The median personal exposure to CO for cooks was 3.0 mg/m^3 in Rwanda and 14.8 mg/m^3 for Kenya. CO concentrations in the classroom and exposures for learners were consistently below 1 mg/m^3 in both countries.

3.3. Learners' health symptoms and perceptions of air quality in school

A total of 526 learners from Rwanda and 302 from Kenya completed the surveys. The average age of the participants was 16.7 years (SD: 2.7) and 16.2 years (SD: 1.1), respectively. In Rwanda, 50.2% of the participants were female, whereas in Kenya, females represented 24.2% of the surveyed learners (Supplementary Table M). In Rwanda, approximately half of the learners had reported experiencing headaches ($n = 306$; 58.2%), eye irritation ($n = 237$; 45.1%), or cough and/or an itchy throat ($n = 262$; 49.8%) in the past month whilst at school (Table 3). Similar results were found in Kenya, with prevalence rates of 65.6% for headaches ($n = 198$), 41.1% for eye irritation ($n = 124$) and 55.6% for cough and/or an itchy throat in the past month. Cooking smoke was reported to be the most common cause of the respiratory symptoms by learners in Kenya, but not in Rwanda, where underlying poor health was reported to be the cause of headaches and coughs and allergy for eye irritation (Supplementary Table M). Wheezing (or whistling in the chest) experienced in the past month was reported less frequently, 18.3% ($n = 96$) in Rwanda and 21.5% ($n = 65$) in Kenya (Table 3). Associations between classroom location and health symptoms are displayed in Supplementary Table N. In Rwanda, eye irritation was significantly lower ($p < 0.05$) in the most distant classroom compared to the nearest classroom, and wheezing was significantly lower ($p < 0.05$) in the most distant classroom than in both the nearest and intermediate classrooms. In Kenya, headaches were significantly lower ($p < 0.05$) in the distant classroom compared to the nearest and intermediate classrooms. However, these findings should be interpreted with caution due to wide variation in the distances between classrooms and the kitchens (Supplementary Table B and E). Most of the learners in Rwanda perceived the air quality in the school environment to be dirty (41.1%) or moderate (33.3%). In Kenya, most learners perceived the school air quality to be clean (30.1%) to moderate (45.0%). Most learners (85.6% in Rwanda and 81.1% in Kenya) reported cooking smoke to be the main source of air pollution at school (Table 4). More details can be found in Supplementary Table M.

3.4. Staff's health symptoms and perceptions of air quality in school

In Rwanda, 66 staff participated in the study (45 catering staff and 21 teachers) and in Kenya, 40 staff completed surveys (28 catering staff and 12 teachers). Responses by the teachers from the surveys are shown in Supplementary Table P. The average age of the catering staff was 34.1 (SD: 9.9) years and 40.9 (SD: 9.3) years for Rwanda and Kenya respectively, with 95.6% and 60.7% being male (Supplementary Table O).

The majority of the cooking staff in Rwanda (92.2%) and Kenya (85.2%) reported wood as the school's primary fuel (Supplementary Table O). The main reason for this unsuitability stemmed from the smoke produced from combustion of the wood and perceived associated negative health impacts.

Headache, eye irritation and coughs or an itchy throat were commonly reported by catering staff in Kenya, with one-month period prevalence rates of 75.0%, 78.6%, and 71.4% respectively (Table 5). A lower prevalence rate was observed for staff in Rwanda, with 53.3% of the surveyed catering staff reporting headache, 55.6% reporting eye irritation, and 42.4% reporting cough or itchy throat. Both eye irritation and cough symptoms in catering staff had a statistically significant relationship ($p < 0.05$) in the two countries while no statistical relationship was observed in headaches and wheezing. Cooking smoke was reported to be the most likely reason for these health symptoms in both Rwanda and Kenya (Supplementary Table O). The occurrence of incidents of burns or scalds was high for catering staff in both countries; (n

Table 2
Gravimetric air pollution levels in different settings in Kenyan and Rwandan schools.

	$PM_{2.5}$ (μg/m^3)				CO (mg/m^3)			
	Mean (SD)	Median (interquartile range)	Range (min - max)	Shapiro-Wilk test p-value	Mean (SD)	Median (interquartile range)	Range (min - max)	Shapiro-Wilk test p-value
Rwanda								
Kitchen (24-h)	893.4 (1373.1)	263.0 (301.5)	191–4223	<0.01	9.2 (11.4)	1.8 (11.6)	0.6–33.7	0.02
Classrooms combined (24-h)	85.0 (53.5)	63.0 (38.0)	34–227	<0.01	0.1 (0.1)	0.0 (0.1)	0.0–0.4	<0.01
Classroom 1	81.1 (51.9)	61.0 (12.0)	50–207	<0.01	0.1 (0.1)	0.1 (0.2)	0.0–0.4	0.06
Classroom 2	108.4 (64.1)	79.0 (70.0)	37–227	0.15	0.1 (0.1)	0.1 (0.1)	0.0–0.3	0.03
Classroom 3	65.6 (28.9)	57.0 (31.5)	34–121	0.29	0.1 (0.1)	0.0 (0.0)	0.0–0.3	<0.01
Cook (8-h)	811.0 (1150.0)	354.0 (477.0)	107–3580	<0.01	8.7 (11.0)	3.0 (10.0)	0.8–33.3	0.01
Learners combined (24-h or 8-h[a])	126.8 (100.7)	86.0 (77.0)	48–520	<0.01	0.1 (0.1)	0.1 (0.2)	0.0–0.4	<0.01
Learner 1	150.7 (153.8)	77.0 (47.5)	71–520	<0.01	0.2 (0.1)	0.2 (0.2)	0.0–0.4	0.16
Learner 2	121.4 (65.8)	92.0 (90.5)	48–221	0.08	0.1 (0.1)	0.0 (0.0)	0.0–0.3	<0.01
Learner 3	108.3 (38.3)	86.0 (45.5)	71–180	0.07	0.1 (0.1)	0.1 (0.2)	0.0–0.3	0.48
Ambient $PM_{2.5}$ (24-h)	27.7 (6.4)	26.0 (11.5)	20.0–36.0	0.24	N/A	N/A	N/A	N/A
Kenya								
Kitchen (24-h)	1471.8 (559.2)	1480.0 (652.2)	693–2234	1	58.3 (68.5)	23.0 (46.6)	10.6–176.5	0.01
Classrooms combined (24-h)	84.7 (69.1)	68.0 (37.0)	25–305	<0.01	0.3 (1.0)	0.0 (0.0)	0.0–3.5	<0.01
Classroom 1	63.8 (24.3)	69.5 (24.8)	25–91	0.65	0.0 (0.0)	0.0 (0.0)	0.0–0.1	<0.01
Classroom 2	63.0 (17.9)	59.5 (27.0)	44–89	0.56	0.9 (1.5)	0.0 (0.9)	0.0–3.5	<0.01
Classroom 3	127.2 (103.4)	76.5 (79.2)	51–305	0.03	0.0 (0.0)	0.0 (0.0)	0–0	1
Cook (8-h)	1307.2 (727.1)	1279.5 (1184.8)	431–2239	0.62	14.5 (7.7)	14.8 (14.7)	6.0–22.4	0.09
Learners combined (24-h or 8-h[a])	100.4 (40.8)	98.5 (46.2)	27–167	0.91	0.3 (0.3)	0.1 (0.4)	0.0–1.0	0.01
Learner 1	101.0 (45.5)	97.0 (55.0)	43–167	0.97	0.3 (0.4)	0.2 (0.3)	0.0–1.0	0.08
Learner 2	103.5 (24.3)	104.0 (44.0)	75–131	0.26	0.3 (0.3)	0.3 (0.4)	0.0–0.6	0.35
Learner 3	96.8 (48.1)	98.5 (34.8)	27–163	0.7	0.2 (0.3)	0.1 (0.2)	0.1–0.7	<0.01
Ambient $PM_{2.5}$ (24-h)	27.2 (10.8)	24.0 (10.2)	16–45	0.44	N/A	N/A	N/A	N/A

[a] 24-h for learners in boarding schools, and 8-h for learners in day schools.

= 15) 33.3% in Rwanda and (n = 19) 67.9% in Kenya reported having ever suffered a burn related injury at the school. In most cases (86.7% in Rwanda and 84.2% in Kenya), the burns or scalds originated from the cooking fuel being used (Table 5).

Most of the catering staff in Rwanda reported the air quality in the school environment to be dirty (n = 27; 60.0%) or moderate (n = 9; 20.0%) (Table 6). Conversely, in Kenya, most catering staff reported the school air quality to be clean (n = 8; 28.6%) or moderate (n = 11; 39.3%). As with the learners, cooking smoke was reported to be the main source of air pollution in the school by the staff (93.3% in Rwanda and 100.0% in Kenya). Other sources of air pollution reported by staff included trash burning (n = 11; 24.4% and n = 10; 35.7%, respectively) and exhaust from local vehicles (n = 6; 13.3% and n = 5; 17.9%, respectively). Catering staff frequently reported the kitchen to be uncomfortably hot (86.7% and 53.6% for Rwanda and Kenya) and smoky/polluted (82.2% and 92.9%, respectively) (Supplementary Table O). To mitigate these uncomfortable conditions, the catering staff reported opening windows or having to leave the kitchen for periods.

4. Discussion

4.1. Main findings

This study assessed the impact of air pollution on health in eleven secondary schools cooking with polluting fuels in Rwanda and Kenya. As with most schools in SSA all of the study schools except one (charcoal) used firewood to prepare the food. School menus in Rwanda predominantly comprised of beans and vegetables, combined with rice, sweet potatoes, or maize flour paste or bread. In Kenya, lunch and dinner mainly comprised staple foods including among others githeri, ugali, beans, and vegetables. Staple foods typically take longer to prepare and cook and require more wood consumption which in turn generates greater $PM_{2.5}$ concentrations. 11 of the 33 school classrooms recorded $PM_{2.5}$ levels above the WHO 24-h interim target 1 (WHO-IT1). Mean $PM_{2.5}$ in school classrooms were 1.1 times greater than the WHO-IT1) of 75 μg/m^3 in both countries. In school kitchens, mean $PM_{2.5}$ concentrations exceeded the 24-h WHO-IT1 target by 11.9 and 19.6 times in Rwanda and Kenya, respectively and also exceed the annual WHO-IT1 (35 μg/m^3). Similarly, mean CO exposures in kitchens were above the

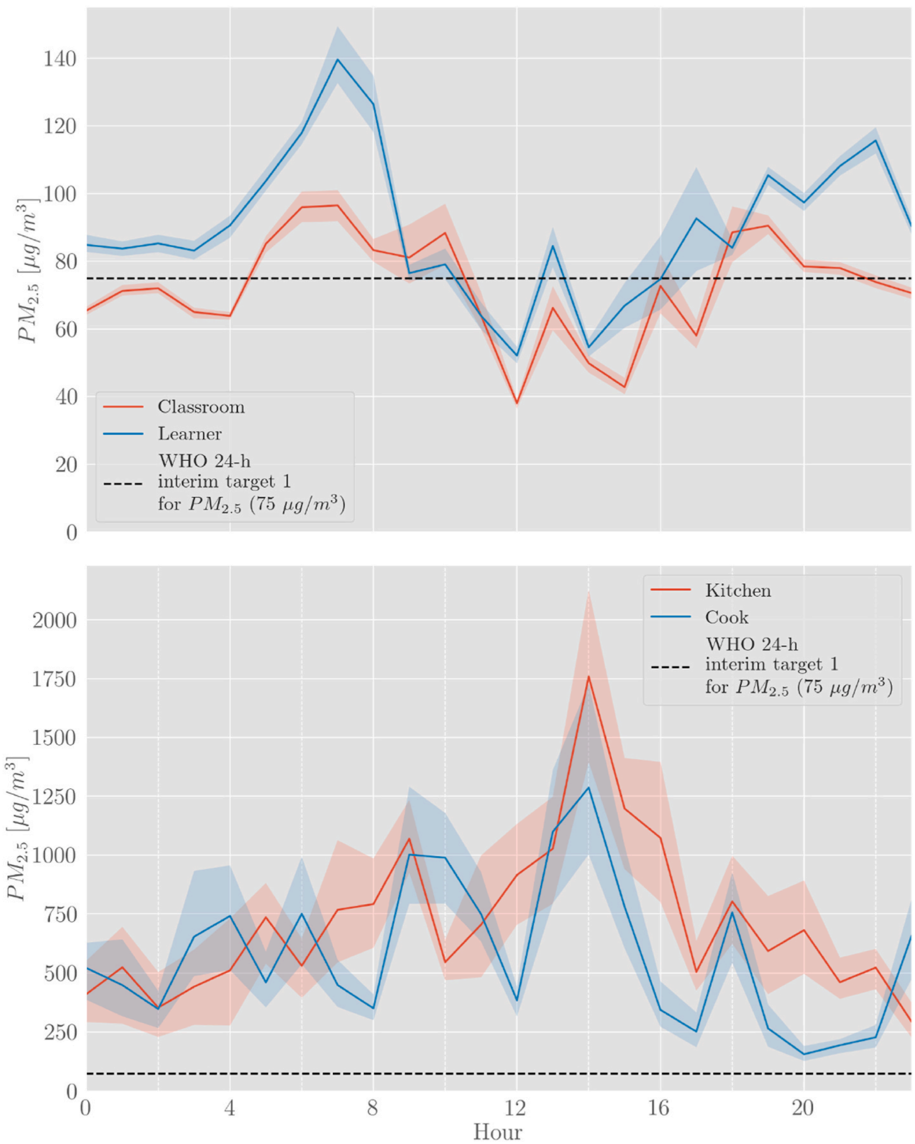

Fig. 1. Mean hourly $PM_{2.5}$ for classrooms (n = 21; red line) and learners (n = 21; blue line), and for kitchens (n = 7; red line) and cooks (n = 7; blue line) in Rwandan schools (light scattering method). Sampling times were approximately 24-h for kitchens, 24-h for classrooms, 8-h for cooks, 8-h for day school learners, and 24-h for boarding school learners. The shaded area represents the 95% confidence interval.

24-h WHO-IT1 target (7 mg/m^3), exceeding it by 1.3 and 8.3 times in Rwanda and Kenya, respectively. The highest $PM_{2.5}$ and CO exposures in kitchens were recorded in schools 3 in Rwanda and school 4 in Kenya, both of which had kitchens with no ventilation. The mean $PM_{2.5}$ levels in these kitchens surpassed the WHO-IT1 24-h target by 56.3 and 29.8 times, while mean CO levels exceeded the recommended limits by 4.8 and 25.2 times for Rwanda and Kenya, respectively. Although our personal $PM_{2.5}$ exposure measurements were not conducted over a full 24-h period, the recorded levels exceeded both the WHO 24-h and annual IT1 levels. Learners in the monitored boarding schools frequently exceeded the WHO 24-h recommended levels during the 24-h monitoring period. The elevated $PM_{2.5}$ concentrations in school kitchens, combined with the relatively low ambient $PM_{2.5}$ levels in playgrounds, indicate that cooking activities are the primary source of air pollution in the school environment rather than traffic or other nearby regional sources. Symptoms observed in day schools may be partially attributed to elevated $PM_{2.5}$ concentrations in learners' home environments, particularly in Rwanda, where 62.3% of learners reported using firewood, charcoal, or kerosene for cooking, compared to only 7.6% in Kenya (Supplementary Table M). Headache, eye irritation, and cough or itchy throat in the past month were common. Cooking smoke was reported to be the main source of air pollution at school by both learners and catering staff in Rwanda and Kenya.

4.2. Comparison to other studies

Our results were much higher than $PM_{2.5}$ concentrations reported in school classrooms in Europe (Rivas et al., 2014), Asia (Che et al., 2021) and USA (Matthaios et al., 2022). We further found that very little research has been conducted on air pollution from cooking in the school environment in low- and middle income countries. A pilot study of three schools in urban Kenya (Nairobi) reliant on wood and charcoal for cooking, reported very high 24-h levels of indoor $PM_{2.5}$, with a mean of 107.6 μg/m^3 in classrooms, 316.2 μg/m^3 in kitchens, 78.4 μg/m^3 in the ambient air, and a mean exposure of 200.9 μg/m^3 for cooks (Nix et al., 2024). For CO, mean concentrations of 8.9 mg/m^3 were measured in kitchens (Nix et al., 2024). These CO levels are similar to our mean measurements in Rwanda but 6.6 times lower than our measurements in Kenya. While we observed slightly lower mean levels of ambient (ranging from 16 to 45 μg/m^3) and classroom (85 μg/m^3)

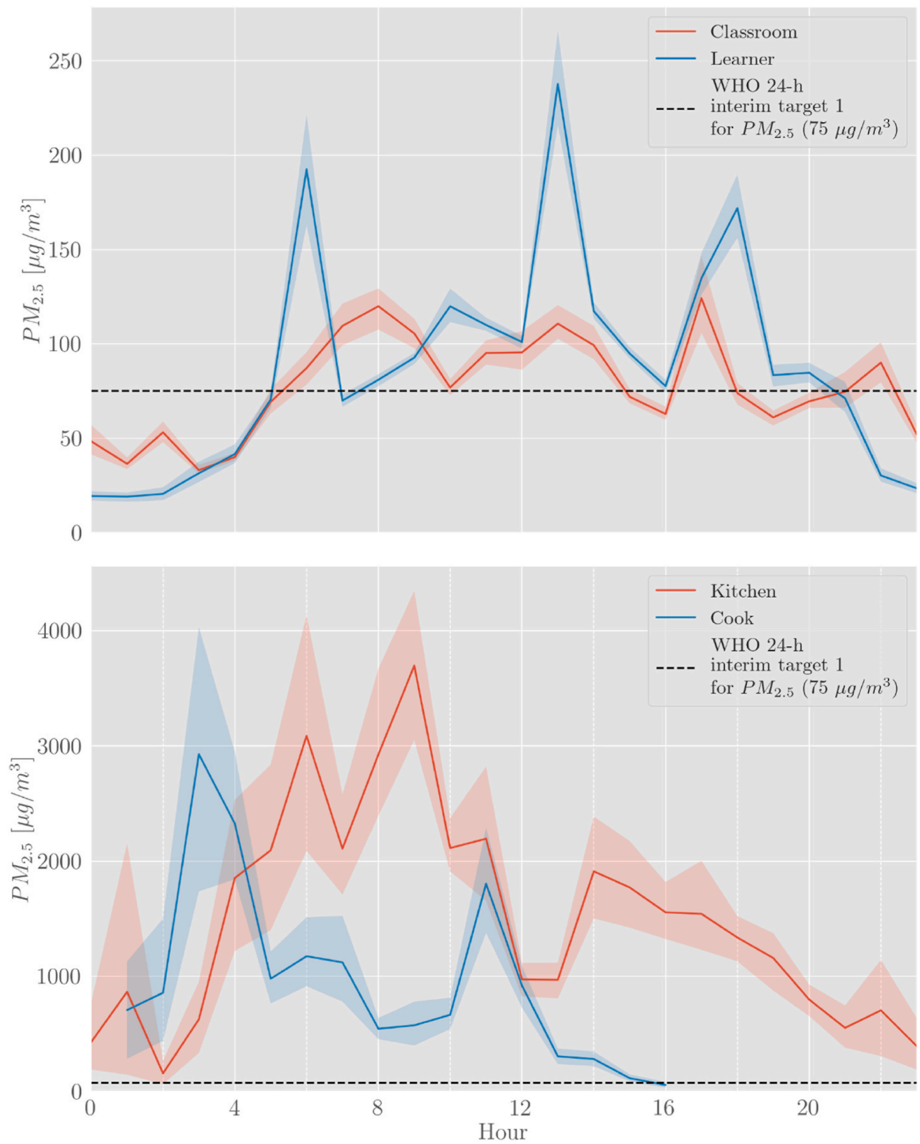

Fig. 2. Mean hourly $PM_{2.5}$ for classrooms (n = 12; red line) and learners (n = 12; blue line), and for kitchens (n = 4; red line) and cooks (n = 4; blue line) in Kenyan schools (light scattering method). Sampling times were approximately 24-h for kitchens, 24-h for classrooms, 8-h for cooks, 8-h for day school learners, and 24-h for boarding school learners. The shaded area represents the 95% confidence interval.

concentrations, mean $PM_{2.5}$, the kitchen levels were 2.8 times (Rwanda) and 4.7 times (Kenya) higher in our study. We also found higher personal exposures for cooks, with levels being 4 times higher in Rwanda and 6.5 times higher in Kenya. Since we measured air pollution using gravimetric sampling (filter-based) rather than light-scattering low-cost sensors, our results may be more representative of the true exposures. A study conducted in Kigali, Rwanda reported annual indoor $PM_{2.5}$ mean concentrations of 40.72 μg/m^3 for the classrooms and 44.87 for $PM_{2.5}$ μg/m^3 for playgrounds (Kalisa et al., 2023a). However, the impact from combustion of cooking fuels within the schools was given minimal consideration. Similarly, a study on asthma symptoms, spirometry and air pollution exposure in schoolchildren in Nairobi, Kenya, did not address the use of school cooking fuels (Meme et al., 2023). The study reported 24-h time weighted average personal $PM_{2.5}$ exposure of 22–39 μg/m^3. A study on school children with asthma in six cities in SSA found daily personal $PM_{2.5}$ exposure levels of 22.9 μg/m^3, but this varied largely from 3.7 μg/m^3 to 213.9 μg/m^3 between children and locations (Lim et al., 2024). School cooking fuels were not identified as a potential source, while the increase of clean fuels for cooking and light in homes was mentioned as an effective change to reduce $PM_{2.5}$ exposures.

4.3. Strengths and limitations

To date, most research on air pollution from reliance on solid fuels in SSA has focused on households, leaving the issue of the use of traditional, polluting cooking fuels in schools and other institutional settings largely understudied. This study offers air pollution and heath insights by investigating school-based cooking practices in one of the regions with the highest access deficit to clean cooking. Our study provides a comprehensive and rigorous air pollution monitoring and assessment of air pollution-related health symptoms in schools in SSA. A few potential shortcomings of the study should be noted. First, health outcomes were self-reported, which might have biased results due to the Hawthorne effect. Moreover, some concepts, such as wheezing, might be difficult to understand for children. Second, we did not investigate the contributions of different sources (e.g. use of polluting cooking fuels, waste burning by residents, industrial emissions, or traffic) to air pollution levels at the school. Likewise, we were unable to incorporate the potential contribution of HAP exposure. Third, the study had a cross-sectional design and therefore we cannot draw any causal relationships between the cooking fuel used by schools, the levels of air

Table 3
Self-reported one-month period prevalence of health symptoms by learners by country.

	Kenya (n = 302)	Rwanda (n = 526)
Headache in past month	n = 198 (65.6%)	n = 306 (58.2%)
Severity		
Very strong	n = 68 (34.3%)	n = 101 (33.0%)
Moderately strong	n = 74 (37.4%)	n = 137 (44.8%)
Just a little	n = 56 (28.3%)	n = 68 (22.2%)
Harder to focus on work/tasks in school	n = 109 (55.1%)	n = 145 (47.4%)
Absence	n = 49 (24.7%)	n = 98 (32.0%)
Eye irritation in past month	n = 124 (41.1%)	n = 237 (45.1%)
Severity		
Mild, no tears	n = 29 (23.4%)	n = 62 (26.2%)
Moderate, some tears, can continue tasks	n = 71 (57.3%)	n = 138 (58.2%)
Severe, with tears, difficult to continue tasks	n = 24 (19.4%)	n = 37 (15.6%)
Harder to focus on work/tasks in school	n = 63 (50.8%)	n = 99 (41.8%)
Absence	n = 19 (15.3%)	n = 51 (21.5%)
Cough or itchy throat in past month	n = 168 (55.6%)	n = 262 (49.8%)
Harder to focus on work/tasks in school	n = 64 (38.1%)	n = 92 (35.1%)
Absence	n = 46 (27.4%)	n = 46 (17.6%)
Wheezing or whistling in the past month	n = 65 (21.5%)	n = 96 (18.3%)
Number of attacks	Mean: 2.6 (SD: 3.1)	Mean: 3.5 (SD: 5.8)
Sleep disturbed due to wheezing		
Never woken with wheezing	n = 22 (33.8%)	n = 22 (22.9%)
Less than one night per week	n = 16 (24.6%)	n = 5 (5.2%)
One or more nights per week	n = 27 (41.5%)	n = 69 (71.9%)
Wheezing severe to limit speech[a]	n = 34 (52.3%)	n = 31 (32.3%)
Harder to focus on work/tasks in school	n = 27 (41.5%)	n = 41 (42.7%)
Absence	n = 15 (23.1%)	n = 23 (24.0%)
Asthma		
Inhalers for breathing problems	n = 13 (4.3%)	n = 41 (7.8%)
Told by doctor to have asthma	n = 14 (4.6%)	n = 29 (5.5%)
Pneumonia		
Told by doctor to have pneumonia	n = 31 (10.3%)	n = 32 (6.1%)

[a] Wheezing severe enough to limit speech to only one or two words at a time between breaths.

Table 4
Learners' perceptions of air quality in school.

	Kenya (n = 302)	Rwanda (n = 526)
Perceptions of air quality in school		
Very clean	n = 3 (1.0%)	n = 10 (1.9%)
Clean	n = 91 (30.1%)	n = 100 (19.0%)
Moderate	n = 136 (45.0%)	n = 175 (33.3%)
Dirty	n = 69 (22.8%)	n = 216 (41.1%)
Very dirty	n = 3 (1.0%)	n = 22 (4.2%)
Don't know	n = 0 (0.0%)	n = 3 (0.6%)
Main sources of air pollution at school (multiple answers allowed)		
Cooking fuel smoke	n = 245 (81.1%)	n = 450 (85.6%)
Trash burning	n = 93 (30.8%)	n = 201 (38.2%)
Car/motorcycle/truck emissions/ exhaust	n = 26 (8.6%)	n = 199 (22.6%)
Nearby industry/plant	n = 1 (0.3%)	n = 7 (1.3%)
Airport	n = 0 (0.0%)	n = 4 (0.8%)
Don't know	n = 5 (1.7%)	n = 2 (0.4%)
Other	n = 62 (20.5%)	n = 54 (10.3%)

pollution, and health symptoms. Fourth, selection bias might have occurred as schools were selected based on their proximity to the city center (e.g. most schools in urban areas). Lastly, due to the kitchen and classroom layouts, sometimes the air pollution instruments were closer to the cooking stoves, windows or doors.

Table 5
Self-reported one-month period prevalence of health symptoms of catering staff by country.

	Kenya (n = 28)	Rwanda (n = 45)
Headache in past month (=yes)	n = 21 (75.0%)	n = 24 (53.3%)
Daily	n = 9 (28.6%)	n = 2 (8.3%)
Weekly	n = 11 (52.4%)	n = 12 (50.0%)
Monthly	n = 1 (4.8%)	n = 10 (41.7%)
Harder to focus on work/tasks in school	n = 13 (61.9%)	n = 10 (41.7%)
Eye irritation in past month (=yes)	n = 22 (78.6%)	n = 25 (55.6%)
Daily	n = 9 (40.9%)	n = 13 (52.0%)
Weekly	n = 9 (40.9%)	n = 8 (32.0%)
Monthly	n = 4 (18.2%)	n = 4 (16.0%)
Severity		
Mild, no tears	n = 2 (9.1%)	n = 5 (20.0%)
Moderate, some tears, can continue tasks	n = 17 (77.3%)	n = 17 (68.0%)
Severe, with tears, difficult to continue tasks	n = 3 (13.6%)	n = 3 (12.0%)
Harder to focus on work/tasks in school	n = 6 (27.3%)	n = 5 (20.0%)
Cough or itchy throat in past month (=yes)	n = 20 (71.4%)	n = 19 (42.4%)
Daily	n = 10 (50.0%)	n = 1 (5.3%)
Weekly	n = 6 (30.0%)	n = 9 (47.4%)
Monthly	n = 4 (20.0%)	n = 9 (47.4%)
Harder to focus on work/tasks in school	n = 7 (35.0%)	n = 8 (42.1%)
Wheezing or whistling in the past month (=yes)	n = 8 (28.6%)	n = 6 (13.3%)
Number of attacks	Mean: 1.2 (SD: 0.4)	Mean: 4.7 (SD: 5.3)
Sleep disturbed due to wheezing		
Never woken with wheezing	n = 3 (37.5%)	n = 2 (33.3%)
Less than one night per week	n = 3 (37.5%)	n = 0 (0.0%)
One or more nights per week	n = 2 (25.0%)	n = 4 (66.7%)
Wheezing severe enough to limit speech[a]	n = 2 (25.0%)	n = 0 (0.0%)
Asthma	n = 0 (0.0%)	n = 1 (2.2%)
Chest sounded wheezy during or after exercise	n = 4 (14.3%)	n = 4 (8.9%)
Dry cough at night, apart from cough associated with cold or chest infection, in the past 12 months	n = 13 (46.4%)	n = 10 (22.2%)
Rhinitis (in the past month)		
Problems with sneezing or runny/blocked nose when not having a cold or the flu	n = 14 (50.0%)	n = 20 (44.4%)
Noise problem accompanied by itchy-watery eyes	n = 9 (64.3%)	n = 10 (50.0%)
Interference of nose problem with daily activities		
Not at all	n = 5 (35.7%)	n = 5 (25.0%)
A little	n = 3 (21.4%)	n = 11 (55.0%)
A moderate amount	n = 5 (35.7%)	n = 3 (15.0%)
A lot	n = 1 (7.1%)	n = 1 (5.0%)
Ever had hay fever	n = 4 (14.3%)	n = 1 (2.2%)
Eczema		
Ever had itchy rash which was coming and going for at least six months	n = 2 (7.1%)	n = 2 (4.4%)
Burns and scalds at school	n = 19 (67.9%)	n = 15 (33.3%)
Burn/scald caused by cooking fuel	n = 16 (84.2%)	n = 13 (86.7%)
Fuel involved in burn/scald	Firewood: n = 14 (87.5%) Charcoal: n = 1 (6.3%) Other: n = 1 (6.3%)	Firewood: n = 12 (92.3%) Other: n = 1 (7.7%)

[a] Wheezing severe enough to limit speech to only one or two words at a time between breaths.

4.4. Recommendations for future research and practice

Future research should investigate the impact of clean fuel interventions in schools, including LPG, biogas, and electric cooking (eCooking), on various outcomes, including but not limited to, air pollution levels, air-pollution related health symptoms, fuel and time savings, safety of cooks, labour and physical strains on kitchen staff, leaners absenteeism, and health service use by cooks and learners. A cost-benefit analysis would be valuable to estimate the investment - and recurrent fuel costs.

Table 6
Perceptions of air quality in schools by catering staff.

	Kenya (n = 28)	Rwanda (n = 45)
Perceptions of air quality in school		
Very clean	n = 0 (0.0%)	n = 0 (0.0%)
Clean	n = 8 (28.6%)	n = 8 (17.8%)
Moderate	n = 11 (39.3%)	n = 9 (20.0%)
Dirty	n = 7 (25.0%)	n = 27 (60.0%)
Very dirty	n = 2 (7.1%)	n = 1 (2.2%)
Main sources of air pollution at school (multiple answers allowed)		
Cooking fuel smoke	n = 28 (100%)	n = 42 (93.3%)
Trash burning	n = 10 (35.7%)	n = 11 (24.4%)
Car/motorcycle/truck emissions/exhaust	n = 5 (17.9%)	n = 6 (13.3%)
Other	n = 3 (10.7%)	n = 1 (2.2%)
Nearby industry/plant	n = 1 (3.6%)	n = 1 (2.2%)
Airport	n = 0 (0.0%)	n = 0 (0.0%)
Ways to avoid/change the conditions (multiple answers allowed)		
Leave kitchen	n = 15 (53.6%)	n = 29 (64.4%)
Open windows	n = 14 (50.0%)	n = 32 (71.1%)
Wear glasses	n = 0 (0.0%)	n = 0 (0.0%)
Wear protective clothing	n = 3 (10.7%)	n = 2 (4.4%)
Drink milk	n = 10 (35.7%)	n = 0 (0.0%)

The study underlines the necessity for interventions to reduce air pollution levels and exposure in schools and to improve health among staff and learners. Most initiatives in Rwanda and Kenya currently focus on improved cookstoves, fuelled by either firewood or charcoal (Centre for Economic and Social Studies, 2020; Clean Cooking Association of Kenya and SNV and Netherlands Development Organisation, 2018). However, research has shown that only clean fuels (such as LPG, ethanol, and eCooking) could consistently achieve kitchen $PM_{2.5}$ levels at or below the annual WHO interim target of 35 $\mu g/m^3$ (Pope et al., 2021). As a recent study on perceptions of air pollution by staff in three schools in Kenya identified that air pollution was often perceived to be dominated by the local environmental surroundings and socio-cultural context (Saligari et al., 2025), it is preferable to use a holistic approach jointly targeting ambient air pollution and the use of cooking polluting fuels. Schools that are currently unable to switch to clean fuels should implement strategies to reduce exposure, e.g. by improving ventilation or using dry wood. Preliminary findings suggest that symptoms among learners may be reduced when classrooms are located farther away from the school kitchen. Therefore, relocating kitchens at a distance greater than 100 m away from classrooms could be a potential strategy to reduce health symptoms for learners. Successful delivery of policies and programs that promote clean fuels at schools depend on effective implementation strategies. Policy planning should therefore address issues identified in previous initiatives, such as limited awareness of available solutions, insufficient user training, lack of upfront financing, inadequate technical support and maintenance, and incompatibility with local cooking practices (Energy Sector Management Assistance Program, 2023). Another challenge to consider in the transition is that firewood is frequently included as part of parents' in-kind contributions (Energy Sector Management Assistance Program, 2023). Successful implementation requires a multi-stakeholder approach, engaging stakeholders such as the Ministry of Education, the Ministry of Infrastructure, school management, finance providers, and clean fuel technology suppliers.

Both Rwanda and Kenya have made some progress in advancing sector policies and regulations. The Rwandan School Feeding Operational Guidelines were approved in 2019. The guidelines account for biomass in costing school meals and specify the use of fuel-efficient stoves as minimum kitchen requirements (Ministry of Education (MINEDUC and); Republic of Rwanda). Furthermore, the government has pledged to reduce the reliance of institutions on wood biomass for cooking and heating by supporting and encouraging institutions to use alternative cooking technologies with emphasis on electricity, LPG, and green charcoal (Rwanda Ministry of Infrastructure and Ministry of Environment). In 2023, the Kenyan President stated that all schools should transition to LPG by 2025 (Okata, 2023; Kenya Ministry of Energy).

5. Conclusion

This study demonstrated high levels of $PM_{2.5}$ and CO along with high prevalences of air pollution-related health issues in Rwandan and Kenyan schools that use polluting fuels for cooking. Given the severe health effects associated with exposure to these pollutants, our findings highlight the urgent need to accelerate the transition to clean cooking in schools, preferably in a holistic approach jointly targeting ambient air pollution and the use of polluting cooking fuels. As schools are the second-largest consumers of biomass energy after households, supporting their transitioning to clean cooking fuels, such as LPG or electric cooking, could lead to significant health improvements for both staff and learners, enhancing their overall health and well-being, and have climate co-benefits due to reduced consumption of unsustainable biomass.

CRediT authorship contribution statement

Willah Nabukwangwa: Writing – original draft, Investigation. **Révérien Rutayisire:** Writing – original draft, Investigation. **Esther A. Kalkman-Boudewijns:** Writing – original draft, Supervision, Formal analysis, Conceptualization. **Federico Lorenzetti:** Writing – review & editing, Visualization, Software, Formal analysis, Data curation. **Emily Nix:** Writing – review & editing, Methodology, Conceptualization. **Bernard Mutariyani:** Investigation. **Gohole Arthur-Akaranga:** Investigation. **Betty Koech:** Investigation. **Joan Kinya:** Investigation. **Matthew Shupler:** Writing – review & editing. **Ghislaine Rosa:** Writing – review & editing, Methodology, Conceptualization. **Elisa Puzzolo:** Writing – review & editing, Funding acquisition. **Claude Mambo Muvunyi:** Writing – review & editing. **Theoneste Ntakirutimana:** Writing – review & editing. **Daniel Pope:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Clarisse Musanabaganwa:** Writing – review & editing. **James Mwitari:** Writing – review & editing, Supervision, Funding acquisition. **Vasileios N. Matthaios:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

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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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.122619.

Data availability

Data will be made available on request.

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