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Indoor and Outdoor Air Quality for Sustainable Life: A Case Study of Rural and Urban Settlements in Poor Neighbourhoods in Kenya

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Abstract: This paper reports on the indoor and outdoor air quality in informal urban and rural settlements in Kenya. The study is motivated by the need to improve consciousness and to understand the harmful health effects of air quality to vulnerable people, especially in poor communities. Ng'ando urban informal settlement and Leshau Pondo rural village in Kenya are selected as representative poor neighborhoods where unclean energy sources are used indoor for cooking, lighting and heating. Filter based sampling for gravimetrical, elemental composition and black carbon (BC) analysis of particulate matter with an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) is performed. findings from Ng'ando and Leshau Pondo showed levels exceeding the limit suggested by the world health organization (WHO), with rare exceptions. Significantly higher levels of $PM_{2.5}$ and black carbon are observed in indoors than outdoor samples, with a differences in the orders of magnitudes and up to 1000 μg/m^3 for $PM_{2.5}$ in rural settlements. The elemental composition reveals the presence of potentially toxic elements, in addition to characterization, emission sources were also identified. Levels of Pb exceeding the WHO limit are found in the majority of samples collected in the urban locations near major roads with heavy traffic. Our results demonstrate that most of the households live in deplorable air quality conditions for more than 12 h a day and women and children are more affected. Air quality condition is much worse in rural settlements where wood and kerosene are the only available fuels for their energy needs.

Keywords: particulate matter; black carbon; TXRF; indoor; outdoor; air quality; human health; biomass; fossil fuel

1. Introduction

Good indoor air quality plays an essential role in human health and comfort. However, depending on indoor human activities and houses' structural designs, air quality can easily be compromised [1]. The first-ever World Health Organization (WHO) global conference on air pollution and health held in Geneva in 2018 reported that over 91% of the world population lives in conditions where the air quality exceeds the recommended limits. It was also emphasized that globally, one in every nine deaths is due to air pollution. The conference's main objective was to agree on ways of reducing the annual 7 million deaths due to air pollution as well as in contributing to addressing sustainable development goals (SDGs) by 2030 [2].

Household air pollution is a passive killer and is linked to 3.8 million deaths annually [3]. Deaths due to air pollution can be traced from acute respiratory infections, lung cancer and chronic obstructive pulmonary disease. Cataracts and blindness, tuberculosis,

premature births and low birth weight, headaches and back pains have also been attributed to indoor air pollution [4–6]. Kenya economic survey 2019 reported that 21.8 million people suffered from respiratory diseases in 2018 [7], which indicates that air pollution could be of major concern in Kenya.

Globally, it is estimated that three billion people rely on biomass fuel. In sub-Saharan Africa, over 700 million households still use simple stoves and open fires for cooking and heating with biomass fuel [8]. In the Kenyan households, 80% of the population, especially those living in the informal settlement, still use solid fuels [9] and kerosene stoves as a key energy source for cooking lighting [10]. Increased indoor air pollution levels have led to detrimental health effects and negative impact on the national economies [11–15]. This is mainly attributed to high poverty levels, low penetration of cleaner energy sources like electricity, and low awareness of associated health risks. Incomplete combustion of fuels leads to emissions of particulate matter (PM), black carbon (BC), inorganic and gases such as carbon monoxide, sulfur dioxide, ammonia and nitrogen oxides, including poly-aromatic and mono-aromatic hydrocarbons [16].

To control air pollution and its potential effects, governments and health institutions have set limits of exposure. For instance, the WHO and European Union (EU) have set averaged 24 h guideline exposure for $PM_{2.5}$ at 25 $\mu g/m^3$ [17,18]. In implementing the requirement of article 42 in the Constitution of Kenya 2010, Kenya Government provides that every person has a right to clean and healthy environment and introduced air quality regulations in 2014. This was an implementation of the Environment and Natural Resources Strategic Plan of 2006–2010 [19] and Environmental Management and Co-ordination Act (EMCA) 1999 [20], which was aligned to the Constitution as EMCA 2015. It set a 24 h ambient exposure tolerable limit at 75 $\mu g/m^3$ for industrial areas. How effectively these regulations are implemented or understood by users remains questionable. In Kenya, the set regulations' implementation is inhibited by lack of baseline air quality measurementsair quality measurements across the country, budgetary constraints, and lack of political goodwill.

According to the United Nations human settlement program (UN-HABITAT) [21], more than half of the population that resides in Kenyan urban cities live in informal settlements [22]. The poor cannot afford cleaner sources of energy; hence, they rely on low grade and inefficient fuels. Low-income Kenyan households areas, are particularly exposed to indoor air pollution since cooking activities are carried out inside the houses, characterized by poor ventilation and incomplete combustion of fuels. This results to millions of people being exposed to severe health risks, mostly women and children who spend most of their time inside the house and or near the fireplace. There are also high outdoor air pollution levels, which is contributed by the current construction boom, absence of waste collection systems by the authorities, open burning of wastes, industries, and vehicle emissions. Indoor pollution can also affect outdoor air quality and even possible transportation of the particles of an aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$) by winds from one region to another [23].

$PM_{2.5}$ are reparable, they are made of a mixture of inorganic and organic compounds in solid and liquid particles from both natural and anthropogenic sources. These particles can penetrate deep into the respiration system [24] and to the bloodstream causing lung inflammation, cardiovascular and respiratory diseases [14,25]. $PM_{2.5}$ mass concentration is a relevant parameter to state the condition of indoor and outdoor air quality The particles' elemental composition can determine their toxicity and lead to an estimate of possible sources of the particles.

Heavy and trace metals can occur naturally from the earth's crust while others are due to anthropogenic activities. Heavy metals can be either essential or non-essential, depending on the metal and its concentration [26]. Ambient concentration limits have been set for some elements with known health effects. For instance, the WHO air quality guidelines and the EU air quality directive have an annual limit of 0.5 $\mu g/m^3$, 6 ng/m^3, 20 ng/m^3 and 5 ng/m^3 respectively for Pb, As, Ni, and Cd [27]. In Kenya limits exists only

for Pb that are set at 1.0 μg/m^3, 0.75 μg/m^3 and 0.5 μg/m^3 for industrial, residential and controlled areas respectively [28].

Black carbon (BC) is a component of PM$_{2.5}$ emitted during incomplete combustion of fossil and biomass fuels [29]. The size and the hydrophobic property of BC particles promote long-distance transport in the human body that have detrimental effects on human health. It carries along with its poly-aromatic hydrocarbons to the lungs. Due to its size, it can take a long time in the lungs' alveolar region. These particles can enter into the circulatory system and extrapulmonary organs such as the liver [30]. In this study, BC in PM$_{2.5}$ samples is analysed to differentiate between BC of biomass (BBC) and fossil (FBC) origin.

In the recent past, X-ray fluorescence (XRF) spectrometry techniques have become a trend in multi-elemental analysis in filters [31–34]. These techniques allow the determination of low quantities of trace elements due to their low detection limits over a wide range of elements simultaneously. XRF is a non-destructive technique leaving the sample intact for further analysis using other techniques. Bilo et al. [35] reported a comprehensive semi qualitative comparison of X-ray fluorescence techniques for outdoor sampled filters from a known Mn source, prepared using SMART STORE® (SMART Solutions s.r.l., 25124, Brescia, Italy) device.

In Kenya, air quality studies have been done [11,36–39], some recording heavy metal contamination of particulate matter [40–45]. Most of these studies focus on qualitative analysis and social impact with suggested solutions. The primary objective of this study is to quantitatively determine PM$_{2.5}$ levels, chemical composition using TXRF and black carbon concentration using a light absortion technique from low economic households in an informal urban and rural setting.

The findings will be recommended and presented as evidence of air pollution to public health department in the ministry of health and policymakers while raising awareness of possible health risks to the public. It will also add valuable data on air pollution that is needed to understand and improve air quality status in Kenya and Sub Saharan Africa in general, while providing necessary data to categorize fuel types with their respective pollution levels. This study will also contribute to achieving sustainable development goal on health and well-being (SDG 3) and clean energy (SDG 7) These goals can be achieved simultaneously through common strategies and interventions at the policy level, within households and other stakeholder engagement and actions.

2. Materials and Methods

This study was conducted in an informal settlements in Nairobi (N'gando) and a rural village (Leshau Pondo) in Kenyan south East region. The region has two rainy seasons in March–June and October–November, with an annual rainfall ranging between 800–2000 mm. the dry months December–March are the hottest (21–26 °C) while coldest periods are in June–September (5–12 °C) [46].

N'gando is approximately 5 km from the central business district Nairobi, Kenya capital city. Nairobi has a landmass of 696 square kilometres and at 1°17′11″ S, 36°49′2″ E with a population of approximately 4.3 million and 1.5 million households [47]. In the urban informal settlements, no housing standards are enforced, this, results in poor infrastructure and housing structures leading to congestion Iron sheets are the main building materials for the walls and roofs and each house would have a single window and a door. The majority of residents in N'gando are either unemployed or employed in unskilled manual labour occupations. An average of five people live in a single room house of approximately 10 m^2, this roomoperate as the bedroom, kitchen and living room. They have an electricity connection mainly for lighting. Sampling sites are shown in the map of Figure 1a.
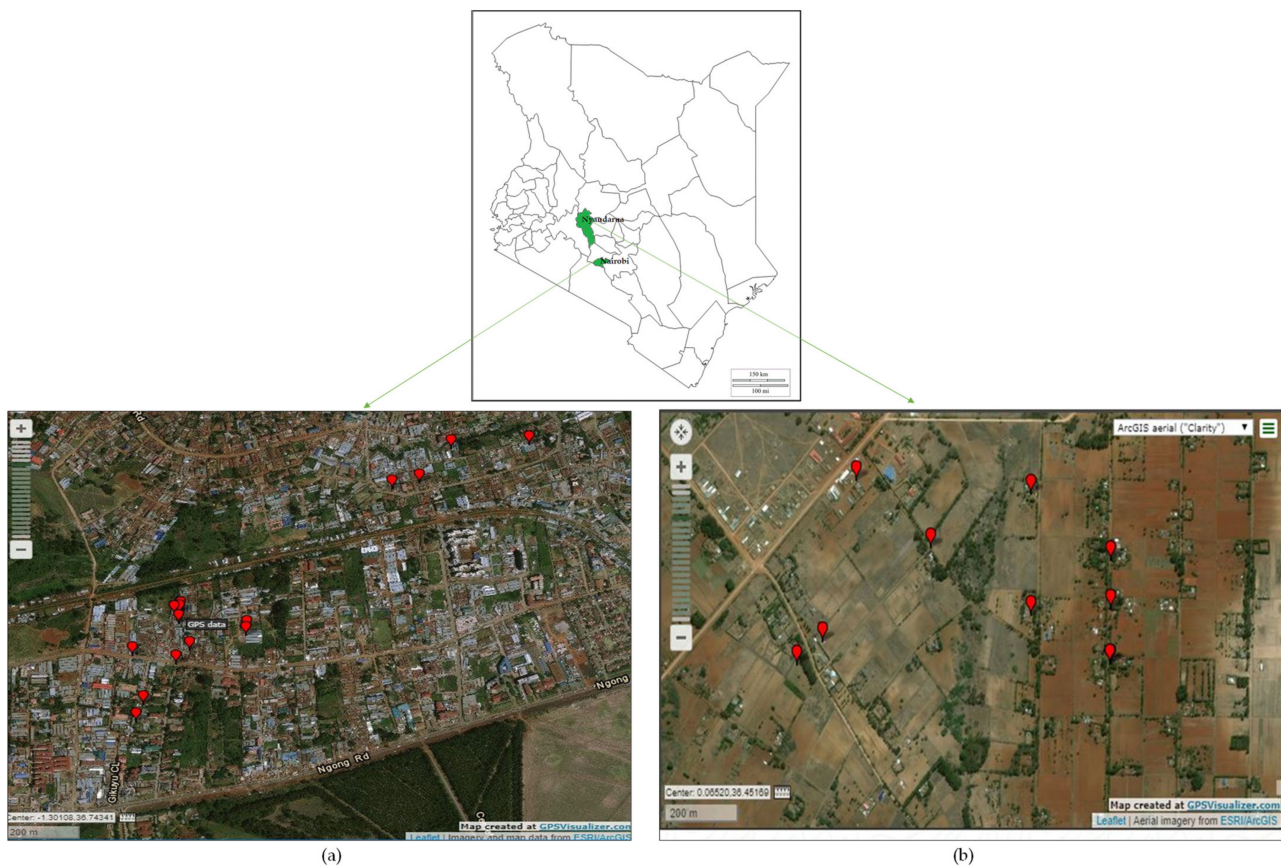
Figure 1. Google maps of the two sampling sites (**a**) N'gando—Urban infomal settlement (**b**) Leshau Pondo—Rural village and their position in Kenya.

Leshau Pondo village in Mathingira ward is a typical rural village in Nyandarua County in central Kenya and the northwest of the Aberdare ranges. It is approximately 220 km from Nairobi city. Nyandarua lies within a landmass area of 3300 km² at 0°33′0″ S, 36°37′0″ E with a population of approximately 636,000 and 180,000 households [47]. Land ownership is regulated where a person can own a minimum of three (3) acres hence there is enough space for the homesteads. The weather conditions allow small scale agriculture where farmers engage in crop farming and livestock rearing. The sampling sites are shown in the map of Figure 1b. Seven of the houses sampled are made of wood and iron sheets roofs while R5 is made of mud and an iron sheet roof, and the R6 is made of iron sheets on both the walls and roof.

This study was done in selected households where the participants were willing to participate and equipment safety was guaranteed. Necessary documentation was filed with the local administration office through the area chiefs before the actual research work was carried out. For the security of the researcher and the equipment, a guard from the police was provided by the local administration. Due to this insecurity, sampling sessions were conducted during the day's active hours from 7 a.m. to 7 p.m. Sampling would start during or before cooking breakfast and would stop after cooking dinner where possible. All the GPS locations, the type of fuel used and activities logs were recorded. The sampling was performed without altering normal household activities and cooking stoves operations, fuel types and cooking techniques.Household sampling, especially in the informal settlements is relatively costly, logistically very difficult and intensive compared to other open sites and laboratory-controlled measurements. Therefore, small data sizes per site and fuel types are covered in this study. 15 households in Ng'ando informal settlement were involved in this campaign conducted from 4 April to 1 May 2019. The type of cooking fuels used are liquefied petroleum gas (LPG), charcoal and kerosene, In Leshau Pondo, nine

households were involved in this campaign conducted from 8 to 18 August 2019. Wood was the primary source of cooking fuel and kerosene was the main lighting fuel used in lantern lamps.

The $PM_{2.5}$ sampler loaded with a clean filter was calibrated by coupling a mass flow meter and a rotameter to the sampler loaded with a filter and adjusting the pump's flow rate to obtained six different flow rates. This procedure helps to electronically control the valve for a constant mass flowrate [48]. These points facilitated developing a calibration graph used to establish the correct average sample flow before and after the field campaign.

$PM_{2.5}$ was sampled using cyclone pump samplers (BGI 400S) with geometry and airflow that allows collection of $PM_{2.5}$ on pre-weighed Teflon filters (PTFE membrane), 37 mm in diameter with a pore size of 2 µm (R2PJ037, Pall, Port Washington, NY, USA). Filter pore diameter of 2 µm was considered to be appropriate in this study due the expected sampling duration and pollution levels. Long sampling hours and high pollution levels would clog a filter with smaller pore diameter which would result to pressure drop hence low filter collection efficiency [49,50]. In addition particle of smaller diameter than the pore size of the filter can still be collected [51].The flow rate was set at 4 LPM. The sampler have a rechargeable battery that made it convenient for use in households with no electricity. The battery was recharged with an external solar charged battery bank or in a charging outlet in the nearby shopping centre. After sampling, the filter were offloaded from the filter cassette and placed in carefully in a sealed airtight petri dishes to avoid contamination during storage and transportation for further laboratory analysis.

Each household sampled had two (2) $PM_{2.5}$ samplers running simultaneously to collect indoor and outdoor $PM_{2.5}$. The indoor sampler was placed approximately at 1.5 m height from the ground level, corresponding to the appropriate breathing zone. In Leshau Pondo, the outdoor sampler would be attached on a long stick approximately 3 m above the ground level approximately 20 m from the kitchen. Due to congestion of the houses in Ng'ando, the outdoor sampler was placed between the roofs where there was no obstruction to ensure free air flow. Details of the collected samples are reported in Table 1. The outdoor filter U4 was damaged during the sampling campaign hence it is not considered for $PM_{2.5}$ mass concentration.

$PM_{2.5}$ mass was determined gravimetrically with a microbalance in relative humidity and temperature-controlled room. The mass difference of the filter before and after sampling is used to obtain particulate matter's mass. The mass concentration of $PM_{2.5}$ is then obtained by dividing the $PM_{2.5}$ mass by the volume of sampled air. In this study, filters were weighed three times but on different days and the average mass was consider. Mass concentration uncertainty was propagated from the weighing balance is at 0.00005 g and volume of air through the filter at 0.0005 m^3 uncertainties.

Elemental analysis was determined by total reflection X-ray fluorescence (TXRF) spectrometer S2 PICOFOX (Bruker AXS Microanalysis GmbH, Berlin, Germany). Before analysing the filter for elemental content, it is first prepared using the SMART STORE®, an automatic device for sample preparation, classification and storage [35]. The resulting sample is placed onto a quartz reflector carrier for TXRF measurements. The sample was irradiated for 600 s live time and measured five times. The TXRF is equipped with a Mo tube, operating at 50 kV and 1.750 µA, a multilayer 2 monochromator (17.5 keV), and a silicon drift detector (SDD). The spectral fitting and spectral deconvolution was done considering K, L, and M line series using the instrument software. This software performs the quantification procedure on each measured spectrum. Low detection limits (LLD) (a few ng/cm^2) can be achieved for elements with atomic numbers greater than 13 (Al). LLD and relative standard errors were calculated as indicated in Borgese et al. [34]. The quantification procedure is done by single point calibration using the NIST 2783 certified reference material. The relative standard deviations were about 20% for all the elements.

Table 1. Ng'ando and Leshau Pondo samples with household code (HH), geographical locations and fuel used per household.

HH	Fuel	Latitude	Longitude
U1	LPG	1.30131	36.7401
U2	LPG	1.30105	36.74
U3	LPG	1.30364	36.73926
U4	LPG	1.30105	36.74012
U5	Kerosene	1.30096	36.74016
U6	Charcoal	1.30225	36.739
U7	Charcoal	1.30248	36.74003
U8	Kerosene	1.3021	36.74035
U9	Kerosene	1.30149	36.74172
U10	LPG	1.30167	36.7417
U11	Kerosene	1.29729	36.7458
U12	Charcoal	1.29745	36.74515
U13	Kerosene	1.2962	36.7484
U14	Charcoal	1.29631	36.74653
U15	Kerosene	1.30413	36.7391
R1	Wood + kerosene	0.065269	6.453133
R2	Wood + kerosene	0.067746	36.45313
R3	Wood + kerosene	0.066642	36.4507
R4	Wood + kerosene	0.066396	36.45505
R5	Wood + kerosene	0.064255	36.44747
R6	Wood + kerosene	0.064288	36.45506
R7	Wood + kerosene	0.064288	36.45504
R8	Wood + kerosene	0.068024	36.4489
R9	Wood + kerosene	0.064728	36.44809

Black carbon (BC) in the $PM_{2.5}$ samples was analysed using a Multi-wavelength Absorption Black Carbon Instrument (MABI, Australian Nuclear Science and Technology Organisation, Locked Bag 2001, Kirrawee DC NSW 2232, Australia). The instrument has a preassembled optical component, sample holder slot, light shutter and detector. This instrument works on the Beer-Lambert law principle. That the intensity light passing through the filter before and after sampling produces an absorption coefficient of the particle - filter system. To obtain BC concentration (ng/m^3), the filter's collection surface area, mass absorption coefficient at each wavelength, volume of air sampled, and the collection time are considered [52], and a relative standard deviation of $\pm9\%$ is used. BC is analysed using the absorption technique at seven (7) wavelengths: 405 nm, 465 nm, 525 nm, 639 nm, 870 nm, 940 nm and 1050 nm [53]. Using this technique, it is possible to determine the BC fraction originating from biomass (BBC) and fossil fuels (FBC). BBC is determined by using the concentration at the wavelength of 639 nm while FBC is the difference between the concentrations at 405 nm and 1050 nm wavelengths. [54].

Statistics and calculations of data from the study were processed using the Microsoft Office® Excel 2016 program (Redmond, WA, USA). Data were further analysed using the JMP statistical software (Version 15, SAS Institute, Via Darwin 20/22, 20143, Milan, Italy). Principal Component Analysis (PCA) was used to investigate the data structure, detect clusters, identify the presence of outliers, give a visual representation of detect clusters, identify outliers, and visualize the relationships between the variables [55]. Furthermore, to support PCA and to have a more explicit visual representation of the cluster, a hierarchical cluster analysis was carried out. Cluster determination was performed employing Euclidean distance to measure the similarity between observations [56,57].

It was not possible to record weather conditions on-site or access the weather data from the Kenya metrological department. Therefore, this study, rainfall values used were obtained from a free online database (http://www.worldweatheronline.com, accessed on 23 September 2020). The GPS points from the sampled locations are used to generate the

site maps by an available free web service (http://gpxviewer.1bestlink.net, accessed on 23 September 2020).

3. Results

3.1. PM$_{2.5}$ Levels

Figure 2 shows the distribution of PM$_{2.5}$ mass concentration in Ng'ando and Leshau Pondo. Only a few households have PM$_{2.5}$ mass concentrations below the value recommended by the WHO of 25 μg/m^3. All the median values are also above the Kenyan set industrial area limit of 75 μg/m^3. Majority of the recorded values are significantly higher than the reported outdoor background levels in a study in Nairobi (Urban) and Nanyuki (Rural) sites, compared to this study as a reference [39]. The comparison clearly shows that air quality indoor is worse than outdoor, especially in rural areas.
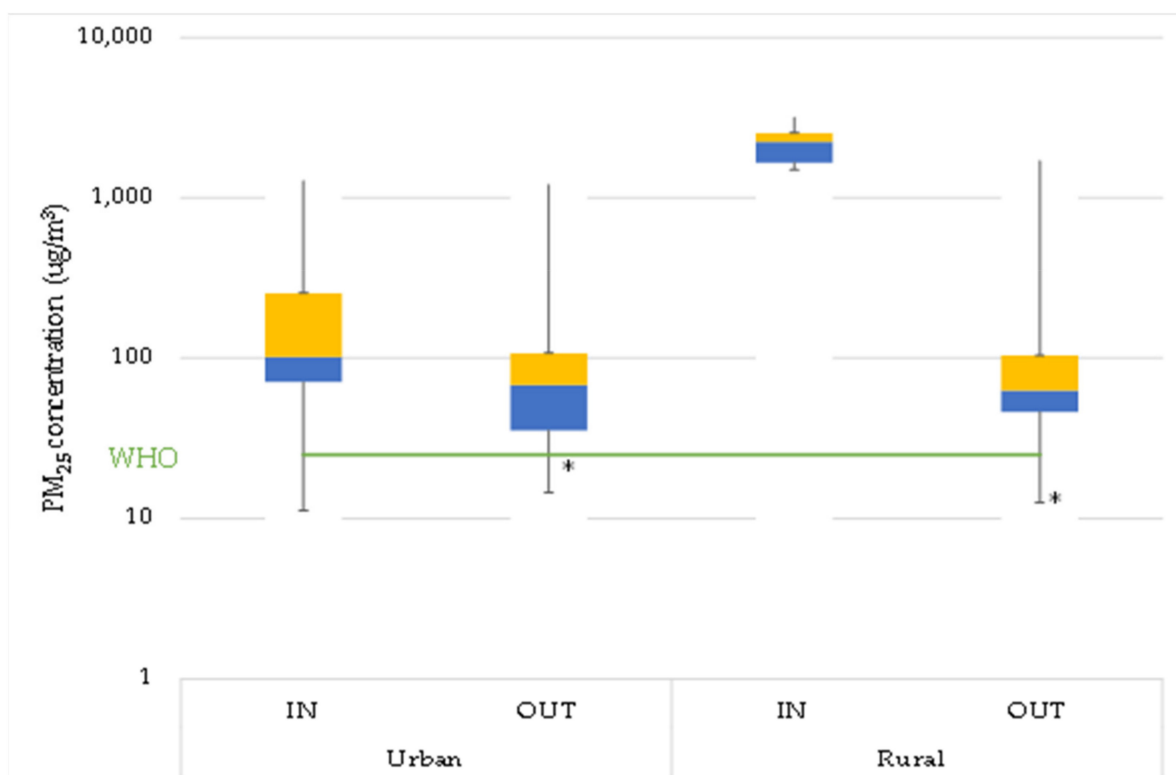

Figure 2. Distribution of PM$_{2.5}$ mass concentration in Ng'ando (Urban) and Leshau Pondo (Rural). The red line represents the WHO recommended limit, and stars (*) the literature reported background mean [39].

Figure 3 shows a comparison of all the measured PM$_{2.5}$ mass concentrations. Outdoor levels are similar in the two areas. Indoor levels are much higher than outdoor at each household, with values exceeding the WHO guideline about two orders of magnitude in the rural area.

In the informal urban settlement, outdoor PM$_{2.5}$ mass concentrations range from 14.5 to 1205.5 μg/m^3 with a mean of about 164.8 μg/m^3, approximately 6 times higher than the WHO guideline. The lowest concentration is found in household U7_OUT collected after and during rainfall. Light rainfall of about 3.4 mm recorded the previous night (7 May 2019) and 1.0 mm rainfall on the sampling day (8 May 2019). The highest value is found in U15_OUT located near a busy unpaved road (Mama Wahu road), an access road with small shops that serve most Ng'ando residents. A wide range of indoor PM$_{2.5}$ mass concentration is observed. Values range from 11.2 to 1276.6 μg/m^3, with a mean of 235.3 μg/m^{3,} approximately 10 times higher than the WHO guideline. Sample U5_IN has the lowest concentration, and it is recorded where there was an open window near the

cooking space that remained open throughout the whole day to enhance air circulation in the room. The maximum is observed in U7_IN where a charcoal cooking stove was used for 7 h continuously while boiling cereals.
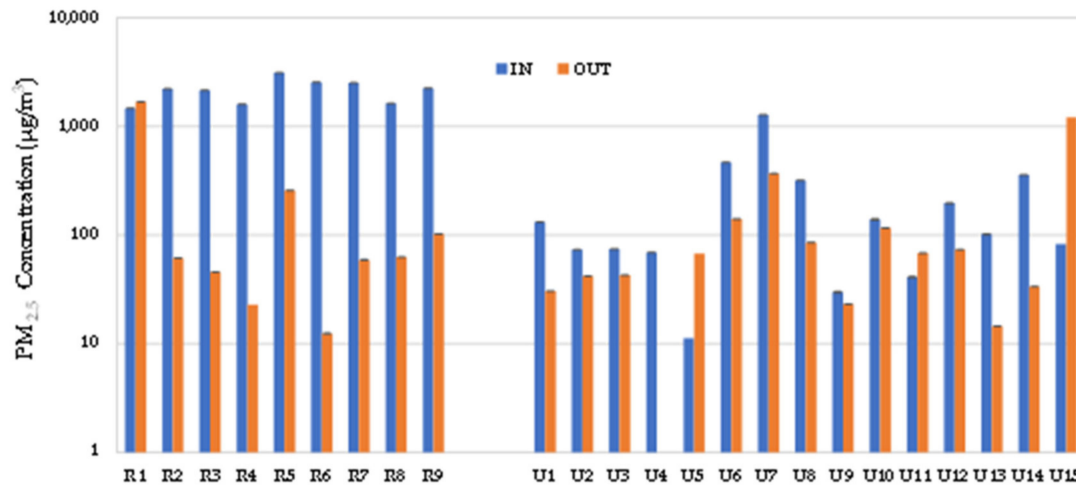

Figure 3. Indoor (IN) and outdoor (OUT) PM$_{2.5}$ mass concentration collected in Leshau Pondo (R) and Ng'ando (U).

In the rural settlement, outdoor PM$_{2.5}$ mass concentrations range from 12.62 to 1700.91 µg/m^3 with a mean of 259.4 µg/m^3, approximately 10 times above the WHO guideline. The lowest concentration is found in household R6_OUT collected after and during rainfall. About 15.8 mm, moderate rainfall recorded the previous day (13 August 2019) and 14.9 mm mm rainfall on the sampling day (14 August 2019). The highest value is found in R1_OUT is not considered representative as the filter was placed near the kitchen roof, where the particles collected were interfered with by the emissions from the kitchen. The indoor PM$_{2.5}$ mass concentration range of 1495.43 to 3174.6 µg/m^3 with a mean of 2200.4 µg/m^3 approximately 100 times above the WHO guideline. The indoor activities noted during indoor sampling was cooking. Sample R1_IN has the lowest concentration. It is collected in a household where walls are made of wood, where there are many spaces in between these woods and the gambrel roof design made of iron. The highest values are observed in sample R5_IN, collected in the house where the walls are made of mud and a flat roof. In both locations, kitchens had windows of approximately 50 cm by 60 cm, which remained open throughout the day.

Figure 4 indicates the indoor PM$_{2.5}$ mass concentration distributions calculated grouping the samples according to the fuel type used in the households, irrespective of their urban or rural location. Results clearly show that the highest values are present when the wood is used for cooking and kerosene for lighting at night, followed by charcoal. Both with wide concentration ranges about 1679 and 1080 µg/m^3 respectively, and kerosene with range 305 µg/m^3. The narrowest distribution obtained for LPG lays within one of kerosene.

3.2. Elemental Composition

In total 14 elements are identified in PM$_{2.5}$ samples: K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Rb, Ba and Pb. The minimum, maximum and averages of element concentrations in Ng'ando and Leshau Pondo are shown in Table 2. All data is available as Supplementary Materials (Table S1). In Ng'ando, the observed trend of elemental mass concentration is following: K > Fe > Ca > Ti > Mn > Ba > Zn > Rb > Pb, suggesting that one or more similar sources are contributing to the elemental composition. Elements associated with crustal dust K, Fe Ca, Ti, Mn has a higher concentration compared to elements associated with anthropogenic activities Zn, Pb, and Ba. Indoor concentrations of all elements are higher than the outdoor except for V, Ni, Cu, Cr, and As are below the detection limit. In Leshau

Pondo, only the 3 elements with the highest concentration have the same trend where K > Fe > Ca > Zn for both indoor and outdoor. Ti, V, Cr, Mn, Ni, Cu, As, Ba and Pb are below the detection limit. Some potentially toxic elements regulated by the WHO identified are: Pb, As and Ni. The recorded 8 h averages are lower than the annual set limits. However, some concentration peaks occur in samples U7_IN and U3_OUT for Pb, and R2_IN for Ni.
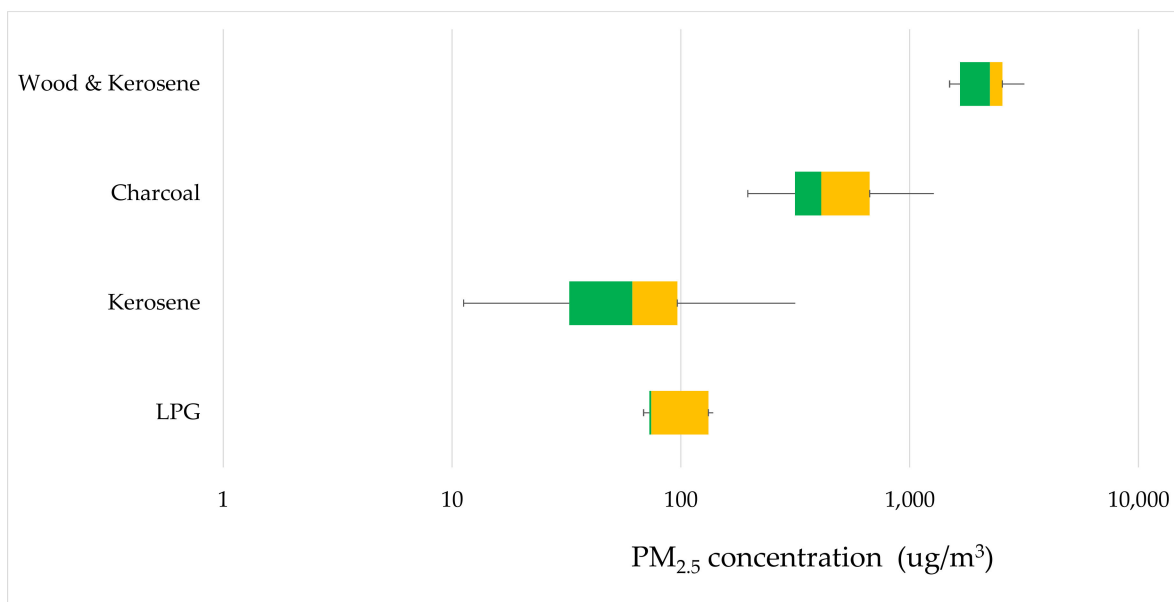

Figure 4. Distribution of indoor $PM_{2.5}$ mass concentrations with respect to the fuel used in the identified emission sources.

Table 2. Elemental mass concentration of $PM_{2.5}$ analyzed in the samples collected indoor (IN) and outdoor (OUT) in Ng'ando (U) and Leshau Pondo (R).

Location			Elements (ng/ m³)												
			K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Rb	Ba	Pb
U	IN	M_{in}	218	77	5	<	3	5	140	0	3	11	0	0	0	0
		M_{ax}	70,127	122,875	13,017	21	224	6847	152,523	33	90	1365	2	944	6367	677
		M_{ean}	16,642	11,373	1250	5	25	665	14,072	3	21	191	1	79	493	56
	OUT	M_{in}	193	19	1	0	0	1	36	0	1	1	0	0	0	0
		M_{ax}	65,488	28,122	4140	27	69	2133	46,230	12	92	548	3	167	1531	130
		M_{ean}	11,660	5339	744	5	15	402	8272	3	21	169	1	30	242	27
R	IN	M_{in}	3475	26	1	0	0	1	41	0	3	11	1	0	0	0
		M_{ax}	37,263	1099	174	2	11	276	9428	270	128	360	9	85	43	214
		M_{ean}	20,664	309	34	0	3	43	1202	30	29	97	2	31	5	26
	OUT	M_{in}	112	103	21	0	1	4	169	0	2	7	0	0	0	1
		M_{ax}	10,111	3943	492	5	7	365	4028	2	9	66	1	27	45	12
		M_{ean}	2476	1127	221	1	4	112	1959	0	6	27	0	6	19	5

The comparison of elemental relative percentage composition calculated over the seven major elements (K, Ca, Ti, Mn, Fe, Cu, Zn) is reported in Figure 5. Pie charts are built with the average elemental concentration calculated for Ng'ando and Leshau Pondo separately for indoor and outdoor samples. The percentage distribution is almost the same for the indoor and outdoor informal urbansettlements, and similar to the rural outdoor. In contrast, it is entirely different in rural indoor where more than 90% is K contribution.
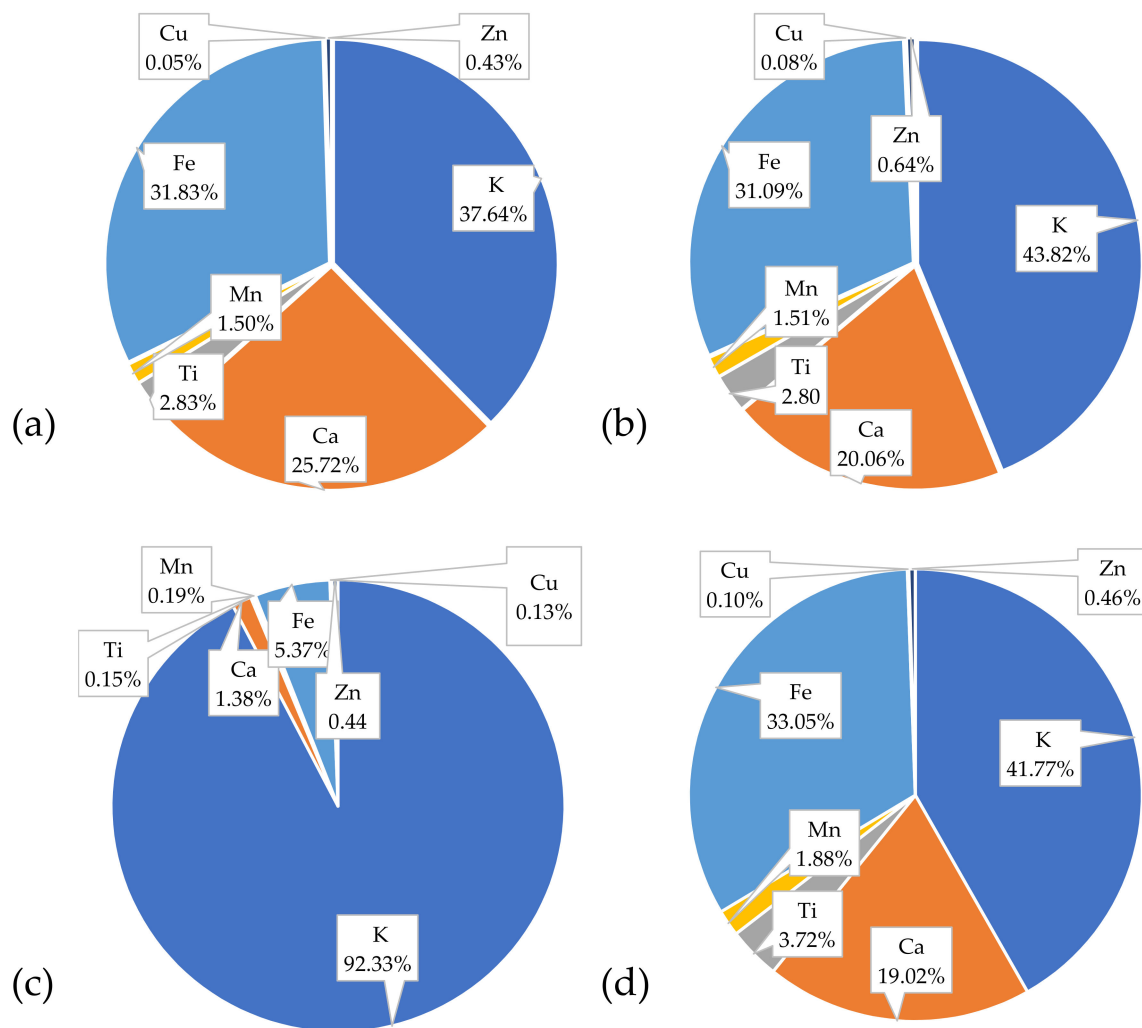
Figure 5. Relative percentage concentration of major elements in PM$_{2.5}$ collected in the samples of Ng'ando (**a**) indoor; (**b**) outdoor and Leshau Pondo (**c**) indoor; (**d**) outdoor.

3.3. Black Carbon Concentration

Figure 6 shows BBC and FBC concentrations extracted from the BC data, all available in Supplementary Materials (Table S2). In general, indoor BBC and FBC concentrations are higher in Leshau pondo compared to Ng'ando, except for sample R3 for FBC. The sample R1_OUT has abnormally high BC values due to its unlucky position outside the kitchen roof. The indoor BBC concentration ranges from 25.4 to 153.0 μg/m^3. The same samples also show a relatively high indoor FBC concentration, ranging from 13.7 to 146.2 μg/m^3. In Ng'ando, the higher BBC and FBC concentrations are observed indoor and outdoor of households U6, U7 and U12, corresponding to charcoal as fuel for cooking. Household U6 is also located near the Mama Wahu road, where waste burning and open-air cooking occur together with many motorcycles and vehicles passing all day.
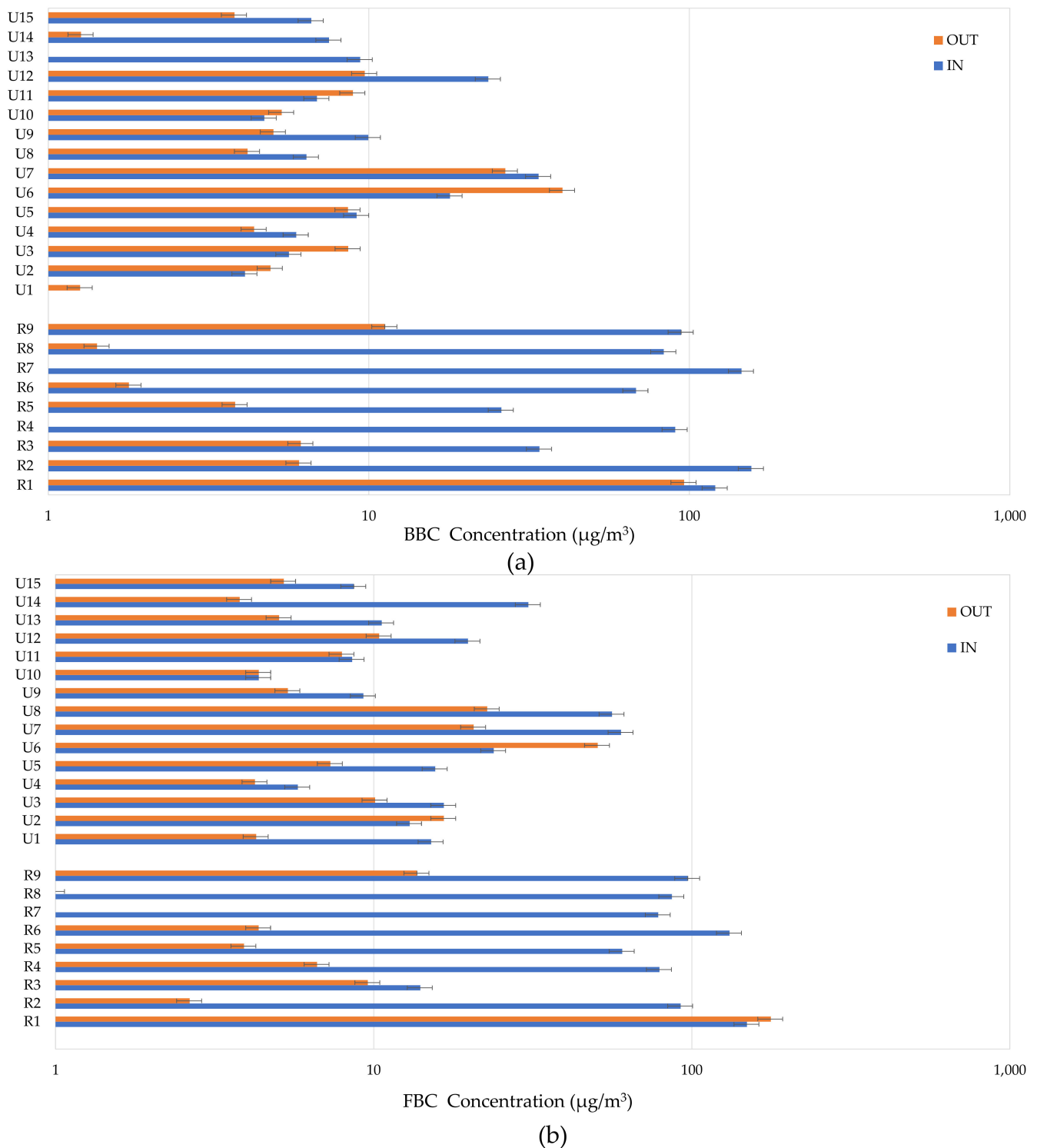
(a)

(b)

Figure 6. Comparison of (**a**) Biomass black carbon (BBC) and (**b**) Fossils black carbon concentration (FBC) for indoor and outdoor PM$_{2.5}$ in Leshau Pondo (R) and Ng'ando (U) households.

3.4. Statistical Analysis

Table 3 shows the linear correlation coefficients of PM$_{2.5}$, BBC and FBC data, indicating the good correlation of the three analytes in the rural settlements, with coefficients above 0.5. PCA is used to investigate the data structure and to find some pattern considering all the available results from PM$_{2.5}$, BBC, FBC and elemental composition. Figure 7 shows the

score plot of the first two components, PC1 and PC2 respectively, which together explain 74.4% of the total data variability. It can be noticed that samples collected indoor in the rural area form a type of clusterization (Figure 7a). They present negative scores values along the PC2. It is worth notice that also the "rural out samples" group themselves. Only the sample R1 represents an exception, for the already mentioned reasons. Urban samples do not separate into groups. Samples are colored according to the fuel used indoor in Figure 7b. The clusterization of the rural indoor samples (pink) corresponds to the use of wood and kerosene rural indoor samples (pink) correspond to the use of wood and kerosene. The corresponding loading plot (Supplementary Materials Figure S2) reveals that clusterization occurs with negative PC2 score values, mainly due to $PM_{2.5}$, FBC and BBC contributions. Clusterization is also observed by using the hierarchical cluster analysis, unlike other types of fuel, wood and kerosene samples from R1 to R9 shows further cluterization in indoor samples (Supplementary Materials Figure S3), this confirms PCA results.

Table 3. Linear correlation coefficients calculated for $PM_{2.5}$, BBC, and FBC for Ng'ando (U) and Leshau Pondo (R).

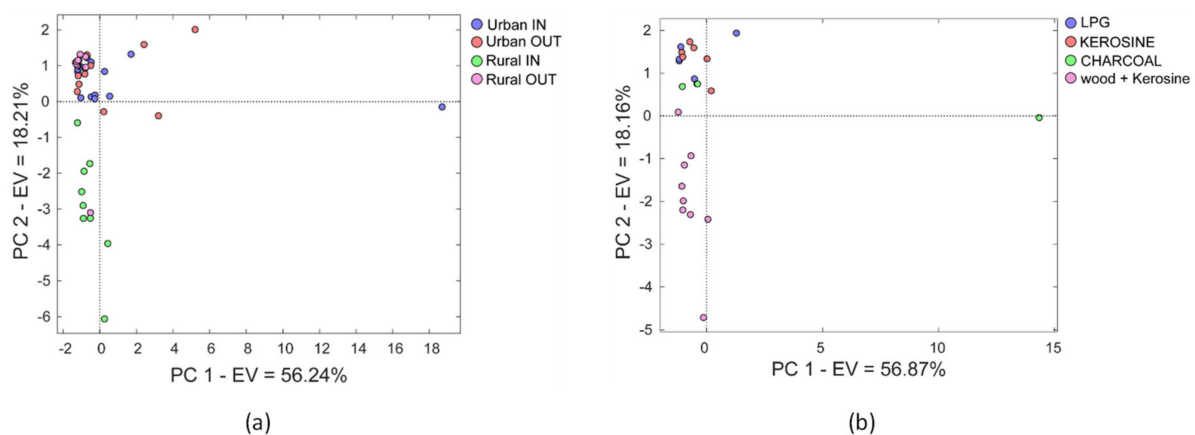|		$PM_{2.5}$	BBC	FBC
	PM2.5	1.0000	0.7066	0.6789
U	BBC	0.7066	1.0000	0.8000
	FBC	0.6789	0.8000	1.0000
	PM2.5	0.1000	0.3936	0.4652
R	BBC	0.3936	1.0000	0.6696
	FBC	0.4652	0.6696	1.0000

Figure 7. Score Plots of the first two components of PCA performed with all the available data. Samples are colored according to (**a**) indoor, outdoor, rural, and urban sampling position; (**b**) the fuel source used indoor.

4. Discussion

Several factors are to be blamed for the continuous deterioration of urban air quality in sub-Saharan Africa. The main contributions are industrialization, inadequate air pollution control policies and regulations, increased urban population due to rural-urban migration in search of better lives, and unregulated and poorly maintained vehicles [40,57,58]. Residents in Ng'ando like other urban informal settlements in Kenya have a low socioeconomic status associated with poor health [59]. The general living condition is characterized by poverty, poor infrastructure, insecurity, overcrowding, inadequate access to water and poor sanitation [59]. Each house is tiny, built with inferior materials and with low ventilation. One room serves as the kitchen, living and bedroom in all the informal settlements. Women cook food while the men and children seat in the same room. Thus, everyone in the household is exposed to emissions from cooking.

The availability of land in rural villages makes it possible to have adequate space in the homesteads. This allows a kitchen space to be built separately from the other rooms. Walls of the kitchen spaces are made of wood for seven of the households sampled, while two are made of mud. The type of cooking stove use is a simple three stones traditional cooking stove and a kerosene lantern lamp for lighting at night. Children under the age of five and their mothers spend time in the kitchen cooking, probably strapped on the mother's body. Men and boys are either working on the farm or a separate room from women and children. This study shows how rural women and children are far more affected by indoor pollution than others in society [60,61]. This is attributed to the traditional role of women in the kitchen, where they spent an average of three to seven hours daily. Children are worst affected due to smaller airwaves and their lungs and immune systems are yet to develop fully [11].

During the sampling campaign, the Kenyan government had banned logging of trees in public and community forests [62]. As a result, less wood and charcoal fuel were readily available for large or small scale use. Urban informal households were forced to use other alternative sources of fuels. From the 15 sampled household in Ng'ando, LPG, Kerosene, and charcoal were used in five, six and four households, respectively. In Leshau Pondo, having no alternative, all the households used wood for cooking and kerosene for lighting. They would fell their trees with permission from the area administration or buy wood from their neighbors. Report on the household fuels usage from the ministry of energy shows that; in urban households LPG, charcoal, kerosene, wood and crop residues is at 51%, 46%, 29%, 24% and 3%, while rural households depends on wood, charcoal, LPG, crop residues and kerosene at 86%, 42%, 15%, 11% and 7% respectively [63].

The $PM_{2.5}$ mass concentration observed reveals that most households in both sites live in highly polluted indoor and outdoor environments. Leshau pondo and Ng'ando Indoor and outdoor mean are above 160 $\mu g/m^3$ with higher indoor values due to cooking and lighting fuel emission. Both sites have exceeded the 24 h WHO recommended limits. However, in this study, the sampling was performed for 12 h during the day's busy time, which would lower the concentration values if sampling was performed for 24 h since there is less concentration of aerosols at night [64]. However, any exposure exceeding the WHO recommended limits for any duration would still have detrimental health effects. It is also an indication of how indoor pollutants, mainly from fuel sources affect the indoor air quality than outdoor [12].

Different exposure levels are observed according to the sample locations (urban and rural sampling sites), positions (indoor and outdoor), fuel used (wood, kerosene, LPG, charcoal) and emission sources (cooking and lighting). Weather conditions may affect the outdoor levels of $PM_{2.5}$ mass concentration [45,65–67]. The lowest outdoor $PM_{2.5}$ mass concentration values are recorded on rainy days or after a rainy night. Due to data unavailability, other weather aspects, such as temperature and wind direction, they are not considered in this study.

Indoor and outdoor $PM_{2.5}$ mass concentration mean in Ng'ando is 224 $\mu g/m^3$ and 164 $\mu g/m^3$ respectively. Studies performed in other Nairobi informal settlements (Viwandani, Korogocho, Mathare, Kibera, Mukuru kwa Reuben) already reveals critical values of $PM_{2.5}$ mass concentration. In Viwandani and Korogocho, an indoor mean of 59.3 $\mu g/m^3$ and 108.9 $\mu g/m^3$ [10] and an outdoor mean of 166 $\mu g/m^3$ and 67 $\mu g/m^3$ were recorded respectively [43]. However, a long term sampling performed in Kibera and Viwandani using low-cost optical particle counter reported lower $PM_{2.5}$ mean concentrations of 23 $\mu g/m^3$ and 21 $\mu g/m^3$ respectively [67]. These level were below WHO guidelines.

Pollution sources in Ng'ando are from vehicular emissions, construction activities, resuspension of dust from the unpaved roads, open-air burning of both organic and inorganic wastes and dumpsites, open-air kitchens along the access roads, and long-range transport of particles from the industrial area of Nairobi and the adjacent towns. Also, indoor activities, mainly cooking and sometimes lighting, contribute to the overall urban informal settlements' air quality. Vehicular emissions are probably the primary contributing

sources of $PM_{2.5}$ and the high Pb content in the outdoor samples collected in urban and rural areas [42,45,65]. Indeed, the highest concentration is recorded are from houses located near the major and busy access road. Indeed, most vehicles in Kenya are imported secondhand with 8 years old engines. Locally manufactured cars do not meet the international set standards and some are too old with the poorly maintained engine making it impossible to have clean emissions from the exhausts.

In Leshau Pondo dried maize stalks are used to start up the indoor fire because they are soft and can light up quickly, but the primary source of fuel is wood. The mixed-use of *Eucalyptus* and *Grevillea robusta* wood species does not allow a specific dependent emissions evaluation. The highest indoor $PM_{2.5}$ mass concentration in this study is 3174 $\mu g/m^3$ which compared to Gaza Bay Village, a rural area in Kenyan coast, where levels recorded were 400 times higher than the recommended WHO guideline [68] and wood (*Delonix regia* species) was the primary source of fuel.The highest indoor $PM_{2.5}$ and BC concentrations can be related to biomass fuel's low burning efficiency using the Kenyan traditional three-stone stove [69]. A literature comparison of nineteen different stoves revealed that simple wood and rocket stoves demonstrated the highest median BC emission factor while the lowest was in charcoal stoves [70]. In Leshau Pondo, kerosene lantern lamps are the only source of lighting at night. BC it has a residence time of 4 to 7 days [71], hence it canremain airborne inside the kitchen for a few days. High indoor FBC recorded in the rural sites compared to the informal urban settlement where there was an electricity connection.

The possible sources of air pollution in Leshau Pondo are agricultural activities, especially from land tillage and burning of crop wastes, unpaved roads and vehicular emissions from numerous cars and motorcycles which are the main mode of transport in the area. The K content contribution to $PM_{2.5}$ total elemental composition is 92%. Presence of K is a good indicator of biomass burning [72], which is the primary cooking energy source in rural kitchens. Ca, K and Fe in outdoor samples, can be attributed to the crustal dust and soil resuspension [73] due to agricultural activities and the burning of agricultural wastes.

High indoor FBC and BBC concentration were recorded from households mostly using wood and kerosene in Leshau Pondo and charcoal in Ngando. These values exceeded the daily $PM_{2.5}$ WHO recommended limits. Inhalation of such a high concentration of BC can significantly impact the health of women and children who spend most of their cooking time in the kitchen. Emitted BC is as a result of of incomplete combustion of fuels however, particle sizes produced during a combustion process vary significantly depending on the phase of combustion and temperature [66].

Statistical analysis helps to understand the cause-effect relation between the detected pollutants and fuel sources. The low correlation of BBC and FBC with $PM_{2.5}$ in Ng'ando is explained by the high number and variety of the emission sources mentioned above. The absence of many emission sources in rural areas makes it easy to consider indoor household emissions, as most of the outdoor activities on the farm are done manually. Only wood and kerosine are used in the rural settlements. This is reflected in the good correlation observed (Table 3). However, we cannot rule out the possibility of long-range transport of particles from the nearby town of Nyahururu. PCA clearly shows the clusterization of rural indoor samples corresponding to wood and kerosine fuels according to $PM_{2.5}$, FBC and BBC (Figure 7 and Figure S2), confirmed by the hierarchical cluster analysis (Figure S3). This may relate to the difference in composition of wood with respect to the other fuels.

5. Conclusions/Recommendations

This study is representative of the harmful impact of fuel usage affecting indoor and outdoor air quality in Kenya. Majority of the households located in urban informal settlements and rural villages had high $PM_{2.5}$ levels exceeding the WHO limit of 25 $\mu g/m^3$, with high concentration of black carbon and toxic elements. Air quality in Ng'ando are similar to other informal settlements in Nairobi, with a population of more than 3.1 million [74]. In addition, more than 75% of Kenyan population living in rural areas depends exclusively on wood for cooking [10], as the households represented in the rural

site of Leshau Pondo. This may significantly contribute to harmful effects on health of the most vulnerable population. This situation calls for public health and policymakers' actions to improve such living conditions, to reduce the number of illnesses and avoidable deaths due to household air pollution.

The findings of this study shows how low income households are affected by emissions from different fuels. There is need for enhanced sensitization on effects of air pollution on health in relation to types of household fuels, cooking stoves and house designs by the public health department in the ministry of health. The government should consider cheaper and cost-effective remedial measures suitable and applicable to this economic class. It is also important for policy makers to put into consideration the various available indoor pollution mitigation measures and figure out how they can be implemented successfully in a sustainable and financially viable manner.

Future works will be dedicated to deepen the source apportionment of the indoor aerosol particles. This will be done by analyzing real-time patterns of particle sizes and toxic gases emitted during the execution of different indoor activities, to evaluate the potential exposure and health related effects.

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