Association Between Specific Indoor Air Pollutants and Pneumonia Episodes in Children Under Five in Abuja, Nigeria: A Case-control Study

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Research

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Abstract

Background: Pneumonia causes most death in children under five globally. Indoor air pollution has been reported to increase the risk of children to pneumonia.

Objective

To investigate the association between specific indoor air pollutants and pneumonia episodes in children under five.

Methods

Using a case-control study design, we compared exposure of cases and controls to specific pollutants ($PM_{2.5}$, CO, BC and PM_1), using battery operated aerosol monitors. Data was analysed using Wilcoxon signed-rank test.

Results

The mean $PM_{2.5}$ was higher in controls compared to cases. $PM_{2.5}$ highest mean recorded for controls was 177 µg/m^3. There was a significant difference between cases and controls for 10 hours (*p*-value 0.0147), 15 hours (*p*-value 0.0111) and 20-24 hours (*p*-value 0.0296) for $PM_{2.5}$.

No significant difference in CO concentration between cases and controls, the highest CO mean concentration recorded being 2930 µg/m^3. Similarly, PM_1 was consistently higher in controls compared to cases. However, this difference was not significant from exposure to PM_1 between cases and controls (*P*-value>0.05), with the highest PM_1 mean concentration recorded being 91 µg/m3.

There was a significant difference (*p*-value 0.0260) in exposure to Black Carbon between cases and controls. BC was higher in households of cases compared to controls, with the mean average of BC for cases 4350 µg/m3 and controls 4126 µg/m3. In this study, BC is positively associated with a pneumonia episode. We also report the importance of unmodifiable and behaviourally modifiable factors on pneumonia episode in children.

Discussion: In conclusion, we show that children present during cooking, number of available windows and MUAC increased the likelihood of a pneumonia episode. We recommend household level behaviour changes and targeted IMCI including early effective detection and treatment of childhood pneumonia particularly in high pollution areas in Nigeria.

Introduction

Pneumonia is an inflammatory lung disease characterised by the build-up of fluid in the alveolus leading to obstructed breathing [1, 2]. It is caused predominantly, but not solely by bacteria, viruses and fungi and is one of the most serious forms of acute lower respiratory infection (ALRI). [1, 2]. Pneumonia is the leading cause of preventable paediatric deaths (especially in children under five) and associated morbidity globally [1, 3, 4]. In children, bacterial pneumonia is mostly caused by Streptococcus pneumoniae followed by Haemophilus influenzae type b (Hib) globally [1, 2]. More than 800,000 children under the age of five die every year from pneumonia [5]. In Nigeria 19% of child deaths were due to pneumonia in 2018, and it was a major killer of children under-five in 2017 [6, 7]. A UNICEF report has shown that one in six children would develop pneumonia at least once before the age of ten particularly in the poorest parts of low and middle-income countries [4]. Developing countries are also characterised by reduced access to quality health care, nutrition, and basic environmental hygiene which contributes to aggravating the disease incidence [4].

Indoor air pollution has been linked with increased risk of pneumonia particularly in children [8–10]. Pollutants compromise the host's immune response against evading pathogens in the respiratory tract. The epithelial cells lining the alveolar are specialised in secreting cytokines and radicals in response to foreign evading bodies [8, 11]. These mediate the recruitment of inflammatory cells such as macrophages and phagocytes to the site of evasion, which then engulfs and digests these foreign organisms. However, high levels of air pollution can lead to a compromise in this sterilisation and filtration mechanism of the respiratory tract, therefore, altering the risk of ALRIs [8]. Furthermore, the mucociliary apparatus and cellular immune defences have also been shown to be significantly reduced by nitrogen dioxide [8]. In addition to an increased oxygen requirement, which is relative to their size, children have narrower airways compared to adults. Thus, whilst a pollutant may cause a mild irritation in the adult airways, it can potentially result in a more significant obstruction in the airways of a young child [9].

Most characterised types of pollutants belong to a broad class called particulate matter (PM) [8]. PM has been previously reported as the key mediator of inflammation and compromised immune defences that is linked to the development of ALRIs [8]. Particulate matter refers to a mixture of solid and liquid particles suspended in air which can be visible or invisible [7]. PM exists in different sizes usually denoted in µm, from PM_{10} to PM_1 [7, 12]. Accumulating evidence shows that $PM_{2.5}$ is dangerous to human health as it is able to penetrate nostril cilia and travel to the lungs where it can cause damage [13]. Particulate matter do not only differ in size but it also differs in composition depending on season and location [7, 12, 14].

Limited studies assess the composition and effect of $PM_{2.5}$ in Nigeria on pneumonia in children. More generally, whilst the effect of $PM_{2.5}$ on health outcomes is usually been well researched globally, there is limited research on PM_1 [13]. PM_1 is the smallest detectable fraction of PM is possibly the most dangerous in children as it can easily by-pass air filtration systems and travel through nostrils, into lungs and blood vessels blood streams and by-pass air-filtration systems [13]. Exposure to PM_1, mostly outdoors have been linked to health outcome ranging from metabolic disorders, cancers, respiratory health disorders across health groups [13, 15, 16]. The link of PM_1 to childhood pneumonia remains largely unexplored.

More recently, black carbon (BC), which is a component of PM has been described as the main mediator of the effects of pollutants [8]. BC has been reported to significantly affect the behaviour of *S. pneumoniae* by altering the structure and proteolytic degradation of the biofilm, therefore promoting its tolerance to multiple antibiotics. Furthermore, in the human body BC promotes the spread of bacteria to the lungs and consequently exacerbates the disease occurrence [11, 17]. Although, these studies have looked at the relationship between the PM, BC and respiratory diseases in-vivo, the consensus on respiratory disease incidence remains contested.

Children are at risk because of their increased resting metabolic rate and a higher rate of oxygen consumption per unit body weight compared to adults [18, 19]. Children are continuously undergoing organ development; this coupled with an elevated surface area per unit body weight increases the oxygen demand and respiratory rates [20].

Most of the research carried out in low and middle-income countries has focused mainly on the risk factors associated with childhood pneumonia [21, 22]. These studies might be limited because they depend on self-reported questionnaires on exposures, hence subject to several biases. The use of a specific instrument to quantify indoor air quality has enabled researchers to identify pollutants involved in causing diseases in rural and urban areas in France [21] and low and middle-income countries such as Eastern Indonesia [23].

Several reviews have been published looking at the effect of indoor air pollution on pneumonia in children. However, there was no standard assessment for exposure across studies [8, 9, 24–29]. Also, the combination of varying study designs, sample sizes, follow up period and dose response renders the conclusions less useful and hard to interpret [8, 9, 24–29]. Finally, there was no consensus on what variables should be adjusted for across all reviews [8, 9, 24–29]. Indoor concentrations of carbon monoxide (CO), particulate matter (PM), or more recently volatile organic compounds (VOC) and black carbon (BC) concentrations have been associated with respiratory infections in children [23, 30–32]. Unfortunately, the current understanding of the association of indoor air pollution on pneumonia in children under five is inconclusive and only partially understood.

Air pollution research and guidelines have exclusively focused on $PM_{2.5}$ [17, 23], including those proposed by the World Health Organisation rather than the sources or components [31–33]. Emerging research shows that BC has a higher health-related impact compared to $PM_{2.5}$ [17]. Previous studies have separate assessments of these pollutants, none assessing these simultaneously.

This study therefore, expands and measures additional pollutants such as carbon monoxide (CO) and black carbon (BC). This is the first study investigating based on primary field observation the association between specific indoor air pollutants ($PM_{1,}$ $PM_{2.5,}$ CO and Black Carbon) and a pneumonia episode in children under five in Abuja, Nigeria.

Methods

Study Design And Participant Recruitment

This case-control study recruited cases from eleven general hospitals and seven primary healthcare centres (PHC) in Abuja. All PHCs had primary health workers (PHWs) that provided basic health services both precautionary and curative care for common illnesses such as diarrhoea, malaria and pneumonia.

- **Diagnosis of pneumonia and recruitment of cases.**

Cases were identified either following presumptive diagnosis by healthcare workers or where possible, radiographic confirmation of pneumonia. Cases were referred to our study by medical professionals in the different facilities. And at the end of the month total numbers of cases was collated manually from ward registers.

Diagnosis of pneumonia

We included clinically suspected (using IMCI Guidelines) and radiologically confirmed cases of Pneumonia.

Cases recruited from general hospitals were diagnosed using chest radiographs (gold standard). Clinically suspected cases were identified as per Integrated Management of Childhood Illness (IMCI) Guidelines. Non-severe pneumonia was defined as the presence of cough or difficulty breathing and fast breathing (60, 50, or 40 breaths per min or higher in those aged < 2 months, 2–12 months, and 1–5 years, respectively) [34]. Severe IMCI pneumonia was defined additionally by chest in-drawing, stridor, or any general danger sign (inability to drink or breastfeed, vomiting, convulsions, lethargy, or unconsciousness) [34]. Cases identified from primary health care centres were diagnosed using IMCI guidelines.

The following sampling approach was employed to collect data from a sample representative of the entire population. Applying judgement sampling approach [35, 36], Abuja was selected as the study location. A random sampling approach [37], was used to identify 20 urban and 20 rural enumeration areas within the different council areas. Hospitals and primary healthcare centres from these areas were approached and pneumonia cases recruited into the study. Adopting systemic sampling [37] the addresses of cases recruited from the hospitals were used as the starting point and control houses were identified by knocking every 4th household within the same street where cases lived. If study criteria were not met the process was repeated until a household that met all study eligibility criteria was located. All households with children aged 0–5 were selected and parents were invited to participate.

Control households with children having cough or difficulty breathing, age-specific tachypnea, and auscultatory evidence of crepitation were not included and referred to the hospital for pneumonia tests. For inclusion, they must have lived in Abuja for the last five years and parents must have not moved houses in the last five years. Also, a control must be living in the same areas as a case.

Parents of all children were asked for their informed consent for recruitment into the study. Caregivers for cases, were contacted within one week of identification at participating hospitals and measurements were made within two weeks of identification based on participant availability and consent. Control participants were contacted immediately after consent was obtained from matching cases and measurements were made within two weeks of identification.

Air Quality Measurements

We measured concentrations of carbon monoxide (CO), fine particles ($PM_{2.5}$ and PM_1), and black carbon (BC). Black carbon was measured and monitored using a cell phone based system developed by NEXLEAF ANALYTICS [38–45]. This involves an optical technique where a photograph of the filter is captured with a cell-phone or a camera and transmitted to a server where an algorithm compares the image (the colour of the filter) with a calibrated scale [38–45]. The BC load is estimated by measuring its reflectance in the red wavelength, based on the “blackness” of the photograph. PM_1 concentrations were measured using a battery-operated SidePak Personal Aerosol Monitor AM510 (TSI Inc, MN, USA) fitted with a PM_1 impactor and set to a calibration factor of 0.30. In accordance with manufacturer’s instructions, SidePak devices were cleaned, the impactor re-greased, zero calibrated and the flow rate set at 1.7 l/min before each use. PM_1 measurements were logged at one-minute intervals, with each one-minute data point being an average of 60 seconds of sample measurements. $PM_{2.5}$ and CO was monitored and measured using PATS + which is a small, portable datalogging device that measures real-time particle concentrations. Its specifications include lower particulate matter detection limit of 10 to 20 $\mu g/m^3$ upper particulate matter detection limit is 30,000 to 50,0000 $\mu g/m^3$. These techniques have been validated in laboratory and household-level applications [38–43] (Fig. 1). Air quality measurements were made in the cooking environment.

Each set of sampling data was downloaded from their monitors using their manufacturer’s software (i.e. Trakpro and Pica software’s and NEXLEAF Analytics Black Carbon portal) and transferred to STATA 16 (alongside the unique household ID). Each of the data was measured in a minute-by-minute format, except for PATs + where the pollutants had measurements second by second, but were then aggregated to minute by minute to compute measures.

Data was matched for control and cases to ensure the same hours were been considered when making comparisons between both groups. For matching, each case was matched to its own control (obtained in the same geographical area). At the stated time points (3 to 24 h), both the case and control needed to possess 3 h, 15 h or 24 h measurements to be included in the corresponding analysis at the time point. Data with no matched sample time were discarded, reducing the amount of sampling minutes to compare from 150 cases and 140 controls in total to 112 cases and 112 controls having 3 hours, 112 cases and 112 controls having 10 hours, 112 cases and 112 controls having 15 h and 112 cases and 112 controls having 24 h measurements. For paired analyses, the percentage change of pollutant (PM_1, $PM_{2.5}$ and CO) concentrations was determined by comparing the mean and median levels overall and in each case and control household. Although data distributions were skewed towards zero, we present arithmetic mean figures throughout since these are used by the WHO to define their upper guidance limits. To compare differences in exposure to our measures of indoor pollution between cases and controls we used the Wilcoxon signed-rank test. This test has been used in similar studies of air quality measurements [46, 47].

Household Questionnaires

Information on demographics, socioeconomic status, environmental, structural characteristics of the house and health information of participants was collected using a structured questionnaire. Information on the health status of the child requested from parents on history and issues relating to pneumonia and malnutrition were as defined by the WHO [4, 19, 48]. Finally, mid-upper arm circumference (MUAC) measuring tapes were used to map the prevalence of undernutrition within the study population [48].

Data Management And Analyses

First, we compared cases and controls based on: age, sex, socioeconomic status, income, immunization, and MUAC, and used chi-square to assess statistical difference. Using chi-square to assess statistical difference, we compared cases and controls in terms of structural characteristics of the house (e.g. number of windows, type of building materials used and type of roofing material used etc.) and lifestyle factors affecting exposure to pollutants(e.g. time children spent in the cooking environment, fuel type) .

We compared cases and controls in terms of mean, range, median, IQR and the proportion of time the $PM_{2.5}$, PM_1 and CO concentration exceeded WHO 24-hour mean $PM_{2.5}$ upper limit of 25 $\mu g/ m^3$ [49], based on continuous indoor monitoring of 3, 15 and 24 hours each of the specific air pollutant. Finally, to illustrate the sampled $PM_{2.5}$ and BC distribution between pneumonia cases and controls we graphically constructed box plots. All analyses were performed in STATA version 16™ and the confidence level was set to 95% with *p*-values < 0.05 considered to be significant.

Given the influence of seasonality on the burden of pneumonia, data were collected throughout a year (January 2018 – January 2019). [50]. Rainy season was designated from April to October 2018, whilst dry season from January to March 2018 and November 2018 to January 2019. As seasonality is important in changing both the composition and concentration of pollutants, we carried out a sub group analysis by season.

Ethics And Ethical Considerations For Study

Prior to data collection, the protocol for the study was reviewed and approved by the University of Nottingham Medical School Ethics Committee (Reference number: 134–1710) and the National Health Research Ethics Committee of Nigeria (Reference number: NHREC/01/01/2007). All procedures performed in this study were in accordance with the ethical standards of institutional research committees and with the 1964 Helsinki declaration and its amendments [51].

Results

The study population comprised of 290 children. 150 cases (aged 1–59 months) presenting to the study hospitals and PHCs and 140 controls who met all eligibility criteria. Of the 60 households that had measurements less than 3 h or more than 24 h, six households had equipment tampering and were discarded for its matched household. The remaining 112 cases and 112 controls had measures on pollutants that ranged between 3 hours and 24 hours and were included in the analyses. Hence, cases and controls were matched based on time of the day and total time of data observed in order to compute comparable means and medians per household consisting of the same times of the day and same total number of minutes.

Table 1 (below) summarises the number of children IMCI or radiographically diagnosed with pneumonia.

Table 1
Sociodemographic characteristics of the study population, Abuja, Nigeria (Cases = 150, Controls = 140) Chi square.

Characteristics	Cases (150)	Controls (140)	*p*-value
Age, Months			
0–6 (%)	17 (11.33)	20 (14.29)	
7–12 (%)	40 (26.67)	19 (13.57)	
13–24 (%)	41 (27.33)	31 (22.14)	
25–59 (%)	51 (34)	64 (45.71)	
			0.079
Sex			
Male (%)	56 (37.33)	87 (62.14)	
Female (%)	94 (62.67)	53 (37.86)	**0.000**
Socio-economic status			
Low	76 (50.67)	54 (38.57)	
Middle	57 (38)	70 (50)	
High	17 (11.33)	16 (11.43)	0.090
Household Income per month (₦)			
0–20,000	4 (2.67)	10 (7.14)	
20,001-100,000	86 (57.33)	105 (75)	
100,001-500,000	53 (35.33)	19 (13.57	
500,001–1,000,000	3 (2)	4 (2.86)	
> 1,000,000	0 (0)	1 (0.71)	
Missing	4 (2.67)	1 (0.71)	**0.000**
Immunization			
Yes	141 (94)	138 (98.57)	
No	6 (4)	1 (0.71)	
Missing	3 (2)	1 (0.71)	0.115
MUAC			
Green	88 (58.67)	108 (77.14)	
Red	62 (41.33)	32 (22.86)	**0.001**

Nearly 50% of the population of cases and controls aged between 25–59 months, there was no significant difference of age between cases and controls with a *p*-value > 0.05, sex was uneven amongst cases and control, with more girls approximately 63% in the case population, compared with 53% of girls making up the control population (Table 1).

Socio economic status was defined as the ownership of certain physical assets as described in study questionnaire. 50% of cases where within the lowest social group, whilst it was roughly 39% of the control group within the lowest social category. However, for the middle group 50% was from the control households and 38% were cases. There was no difference observed within the highest socio-economic group with roughly 11% for both cases and controls.

There was a significant difference in undernutrition (MUAC) between cases and controls. Around, 62 (41%) of case population were malnourished, compared to 32 (23%) of the control population (Table 1).

Table 2
Lifestyle factors affecting exposure to pollutants. (Cases = 150, Controls = 140) Chi square.

Characteristics	**Cases (150)**	**Controls (140)**	***P*-value**
Child present during cooking			
Yes	113 (75.33)	52 (37.14)	
No	28 (18.66)	83 (59.29)	**0.000**
Sometimes	3 (2)	0 (0)	
Main cooking fuel			
Woods	10 (6.71)	13 (9.35)	
Charcoal	8 (5.37)	3 (2.16)	
Kerosene	18 (12.08)	28 (20.14)	
Electricity	7 (4.70)	4 (2.88)	
Liquid petroleum gas (LPG)	43 (28.86)	31 (22.30)	
Bio-gas	21 (14.09)	24 (17.27)	
Fuel combinations	41 (27.52)	36 (25.90)	
No reply	1 (0.67)	0 (0)	0.268
Roof Materials			
Local sources	1 (0.67)	0 (0)	
Tiles, slate, shingle	17 (11.33)	16 (11.43)	
Zinc, Iron or other metal sheets	126 (84)	121 (86.43)	
Asbestos cement sheets	2 (1.33)	0 (0)	
Other material	0 (0)	2 (1.43)	
Don't know	3 (2)	0 (0)	0.168
Floor Material			
Mud/dirt	2 (1.33)	2 (1.43)	
Brick, stone & lime	2(1.33)	0 (0)	
Cement	75 (50)	74 (52.86)	
Mosaic/tiles	64 (42.67)	61 (43.57)	
Other materials	2 (1.33)	0 (0)	
Combination	3 (2)	2 (1.43)	
No reply	1 (0.67)	0 (0)	0.552
Wall materials			
Mud/dirt	28 (18.67)	30 (21.43)	
Unburnt bricks	4 (2.67)	8 (5.71)	
Stone	3 (2)	1 (0.71)	
Cement concrete	109 (72.67)	98 (70)	
Combination	1 (0.67)	2 (1.43)	
No reply	3 (2)	0 (0)	0.302
Number of windows and major openings in house			
0–2	69 (46)	50 (35.71)	
3–5	64 (42.67)	64 (45.71)	
6–8	11 (7.33)	15 (10.71)	
9–13	3 (2)	6 (4.29)	0.246
Number of windows in Kitchen			

Characteristics	Cases (150)	Controls (140)	*P*-value
0	50 (35.46)	9 (7.63)	
1	82 (58.16)	88 (74.58)	
2	5 (3.55)	14 (11.86)	
3	0 (0)	2 (1.69)	
5	0 (0)	1 (0.85)	
No reply	1 (0.71)	4 (3.39)	
Don't know	2 (1.42)	0 (0)	**0.000**
Not applicable	1 (0.71)	0 (0)	

More cases 113 (75%) were present in the cooking environment with their mothers during cooking, compared to 52 (37%) being present in the control population. This difference was significant with a *P*-value < 0.05 (Table 2).

Within the households of cases approximately 43 (29%) used liquid petroleum gas (LPG) compared to 31 (22%) of controls. Similarly, 18 (12%) of cases used kerosene compared to 28 (20%) controls. However, it was clear that both cases 41 (28%) and controls 36 (26%) used a mixture of fuels for their daily needs.

In cases with lack of electricity, rechargeable electric lamps were the most common alternative source of lighting among study household with 52% cases and 61% controls. The second most common source of alternative lighting was generators with 29 (20%) cases and 14 (10%) controls using them (Table 2).

Over, 105 controls had windows in their kitchens compared to 87 in cases with over 50 (36%) cases reporting no windows in their kitchen (Table 2).

Table 3
Estimated burden of pneumonia in children under five within study setting (January 2018 – January 2019)

	January	February	March	April	May	June	July	August	September	October	November	December	January
General Hospitals													
1	0	0	0	0	3	4	0	0	2	7	4	0	0
2	1	0	0	0	0	0	2	0	1	8	0	0	0
3	0	1	1	0	0	0	1	1	1	0	1	7	1
4	0	0	0	0	7	0	7	0	0	9	0	1	2
5	0	0	0	0	0	0	0	0	0	0	0	0	1
6	0	0	7	0	0	5	2	0	5	4	5	5	0
7	2	0	0	1	2	0	1	2	2	0	0	2	0
8	0	0	0	0	1	1	2	2	2	3	3	4	1
9	0	0	0	7	0	1	0	3	4	3	0	0	0
10	0	0	0	0	0	0	5	0	7	5	7	1	2
11	0	0	1	1	5	2	3	5	6	7	10	4	0
Public Health Centres (PHC)													
1	0	7	1	0	0	0	2	2	2	6	4	1	0
2	0	0	0	1	1	2	1	6	0	2	7	1	5
3	0	0	0	5	2	7	2	5	6	0	0	3	0
4	0	0	0	0	0	1	0	2	0	1	0	3	1
5	0	5	3	2	2	1	3	7	4	2	3	1	1
6	0	2	3	3	0	2	5	5	3	2	5	4	0
7	7	1	2	3	2	1	0	0	2	0	0	2	0
Total	10	16	18	23	25	27	36	40	47	59	49	39	14
												Total	403

Estimated Burden Of Pneumonia Across Medical Facilities

Table 3 summarises the estimated burden of pneumonia in children under- five who presented to the Hospitals and PHCs assessed over the 12-month study period. The overall highest and lowest estimated burden of pneumonia during the 12-month study period was 14.6% in October and 2.5% in January according to combined IMCI and radiographic diagnosis.

The estimated burden of pneumonia varied significantly across the study location and their respective hospital and PHCs. All healthcare facilities contributed at least one case during the study period.

Table 4
Summary data showing the comparison of the $PM_{2.5}$, CO, PM_1 and BC in matched (N) cases and control at particular time points.

Variables	**3 hours (10am – 5 pm)**			**10 hours (3am – 2 pm)**			**15 hours (3am – 5 pm)**			**20–24 hours**		
	Case mean (n)	Control mean (n)	P Value	Case mean (n)	Control mean (n)	P Value	Case mean (n)	Control mean (n)	P Value	Case mean (n)	Control mean (n)	P Value
$PM_{2.5}$ (μg/m3)	51.87 (110)	105.06 (112)	0.0533	129.3 (111)	176.97 (112)	**0.0147**	100.2 (112)	162.3 (112)	**0.0111**	117.4 (112)	174.4 (111)	**0.0296**
CO (μg/m3)	2700 (110)	1730 (112)	0.3527	2270 (111)	2930 (112)	0.3251	2340 (112)	2700 (112)	0.3269	1950 (112)	2810 (111)	0.0729
PM_1 (μg/m3)	50.04 (112)	123.9 (112)	0.0653	62.13 (112)	91.06 (112)	0.3545	65.19 (112)	85.95 (112)	0.6163	61.26 (112)	94.39 (111)	0.1819
BC (μg/m3)										4350.5 (132)	4126.3 (123)	**0.0260**

Note that BC was a single measurement showing the average for a 24 h period. **Bold figures show where there was a statistically significant difference between cases and controls.** (Rank sum test, *P* value < 0.05).

PM

Across the board, mean $PM_{2.5}$ was higher in controls compared to cases (Table 4). The highest mean recorded for controls was 177 μg/m^3. However, there was a statistically significant difference in mean between cases (129.3 μg/m^3) and controls (176.97 μg/m^3) for 10 hour measures (*P*-value 0.0147), cases (100.2 μg/m^3) and controls (162.3 μg/m^3) for 15 hour measures (*P*-value 0.0111) and cases (117.4 μg/m^3) and controls (174.4 μg/m^3) for 20–24 hour measures (*P*-value 0.0296) (Table 4).

$PM_{2.5}$ was higher in rainy season than dry season by 11.7% at 3 h, 52.7% higher at 10 h, 44.4% higher at 15 h and 48.7% higher at 20–24 h for controls. In cases, $PM_{2.5}$ was higher in rainy season than dry season by 11.9% at 3 h, 57% higher at 10 h, 45.9% higher at 15 h and 52.5% higher at 20–24 h. Overall, $PM_{2.5}$ was higher in cases during the rainy season than controls by 0.15% at 3 h, 5% higher at 10 h, 2% higher at 15 h and 4% higher/lower at 20–24 h (Table 5).

PM_1 was higher in dry season than rainy season by 10.5% at 3 h, 16.5% higher at 10 h, 16.5% higher at 15 h and 12.5% higher at 20–24 h for controls. In cases, PM_1 was higher in dry season than rainy season by 5.4% at 3 h, but PM_1 was higher in rainy season than dry season by 4.9% higher at 10 h, 6.8% higher at 15 h and 9.4% higher at 20–24 h. Overall, PM_1 was higher in cases during the rainy season than controls by 4% at 3 h, 21.6% higher at 10 h, 24.4% higher at 15 h and 21.3% higher/lower at 20–24 h (Table 5). There was no significant difference in exposure to PM_1 between cases and controls with PM_1 consistently higher in controls compared to cases. With the highest PM_1 mean concentration recorded being 124 μg/m^3 (Table 5)

Table 5
Summary data showing the comparison of the $PM_{2.5}$, CO, PM_1 and BC in cases and control divided by season and mode of diagnosis.

Variables	**3 hours**							**10 hours**						
	Case mean (n)				Control mean (n)		P Value	Case mean (n)				Control mean (n)		P Value
	Dry Season		Rainy Season		Dry Season	Rainy Season		Dry Season		Rainy Season		Dry Season	Rainy Season	
Diagnosis	IMCI	RC	IMCI	RC				IMCI	RC	IMCI	RC			
$PM_{2.5}$ (μg/m3)	43.18	52.03	83.65	37.25	91.01	114.85	0.0533	43.57	47.77	42.26	289.62	85.82	240.50	**0.0147**
CO (μg/m3)	1420	1250	5950	3090	1740	1730	0.3527	1990	1000	2260	3920	2140	3480	0.3251
PM_1 (μg/m3)	23.32	64.81	33.41	45.70	144.61	109.48	0.0653	24.18	71.20	30.31	74.80	135.30	60.22	0.3545
BC (μg/m3)														

IMCI – IMCI diagnosed clinically suspected pneumonia RC – Radiologically Confirmed pneumonia. Rainy season was from April to October 2018, whilst dry season was from January to March 2018 and November 2018 to January 2019 [93]. **Bold figures show where there was a statistically significant difference between cases and controls.** (Rank sum test, *p*-value < 0.05).

Variables	**15 hours**							**20–24 hours**						
	Case mean (n)				Control mean (n)		P Value	Case mean (n)				Control mean (n)		P Val
	Dry Season		Rainy Season		Dry Season	Rainy Season		Dry Season		Rainy Season		Dry Season	Rainy Season	
Diagnosis	IP	CP	IP	CP				IP	CP	IP	CP			
$PM_{2.5}$ (μg/m3)	43.13	50.36	56.50	195.72	86.478	215.22	**0.0111**	46.60 (8)	49.25 (47)	64.49 (19)	243.13 (38)	90.12 (45)	231.88 (66)	**0.0**
CO (μg/m3)	1760	1090	3570	3410	1960	3230	0.3269	1350 (8)	720 (47)	2220 (19)	3460 (38)	1590 (45)	3650 (66)	0.0
PM_1 (μg/m3)	25.77	73.00	33.46	79.68	131.96	53.89	0.6163	19.37 (8)	66.87 (47)	20.49 (19)	83.54 (38)	133.39 (46)	66.79 (65)	0.1
BC (μg/m3)								4274.67 (9)	3481.02 (53)	4376.71 (19)	5257.65 (51)	3217.41 (45)	4650.61 (78)	**0.0**

IP – IMCI Pneumonia CP – Confirmed Pneumonia. Rainy season was from April to October 2018, whilst dry season was from January to March 2018 and November 2018 to January 2019 [93]. **Bold figures show where there was a statistically significant difference between cases and controls.** (Rank sum test, *p*-value < 0.05).

BC

There was a significant difference (*p*-value 0.0260) in exposure to Black Carbon between cases and controls. With the average mean for cases 4350 μg/m^3 and controls 4126 μg/m^3.

In all the cases identified in the study, 24.11% of measurements were from IMCI diagnosed Pneumonia and 75.89% were from pneumonia confirmed by chest radiographs in hospital. BC was higher in rainy season than dry season by 13% at 20–24 h. In cases, BC was higher in rainy season than dry season by 10.80% at 20–24 h (Table 5).

CO

For controls CO was higher in rainy season than dry season by 41.9% at 3 h, 30.6% higher at 10 h, 36% higher at 15 h and 43.7% higher at 20–24 h. In cases, CO was higher in rainy season than dry season by 54.4% at 3 h, 34.8% higher at 10 h, 42% higher at 15 h and 46.6% higher at 20–24 h. Overall, CO was higher in cases during the rainy season than controls by 27% at 3 h, 5.5% higher at 10 h, 9% higher at 15 h and 4% higher/lower at 20–24 h (Table 5). There was no significant difference in CO concentration between cases and controls. With the highest CO mean concentration recorded being 2930 μg/m^3.

Over all, concentrations of pollutants were higher during the rainy season compared to dry season. The highest reported mean concentration (289.62 μg/m3) was observed when cases and controls where compared after a 10-hour period. Overall concentrations of PM_1 were higher in most cases during the dry season.

Distribution of $PM_{2.5}$ and BC concentrations was measured between houses of cases and controls. When outside (Fig. 2) values were excluded $PM_{2.5}$ was higher in controls during the dry season compared to cases, with the highest mean value over 150 μg/m^3. However, in contrast BC was higher in cases compared to controls both during the rainy and dry season, the highest mean of over 11,000 μg/m^3.

Discussion

Effect Of Indoor Air Pollutants And Pneumonia Incidence

This is the first study to measure and compare the association between indoor air quality in terms of specific component pollutants ($PM_{2.5}$, PM_1, CO and BC) and pneumonia episodes in children under five in Abuja, Nigeria. Previous studies have measured single pollutants or used proxies measurements in the absence of observed primary data [9, 23–26, 28, 29, 52–62]. We have previously reported that when directly measuring pollutants, there was no association with pneumonia incidence, but when using biomass fuel as a proxy, there was [63]. This highlights the need for targeted approaches for measuring indoor pollutant levels. Studies directly measuring BC levels in association with pneumonia incidence are scarce. Herein, we also report the importance of behaviourally modifiable and unmodifiable factors during the study period on pneumonia incidence in children. Unmodifiable factors include increasing the number of windows and doors in the kitchen and the entire house whilst behaviourally modifiable factors, such as behavioural changes that might arise from consultation with healthcare professionals like, cooking with cleaner fuels, keeping children away from the cooking environment and opening windows more to allow the flow of fresh air.

In this study, we found that most participants were exposed to levels of pollution that overwhelmingly exceed WHO guidelines. Whilst it might be expected to find higher levels of household air pollution in households where there had been a reported case of childhood pneumonia, we found that both cases and controls were exposed to extreme levels of household air pollution. In some cases the levels were 10 times higher than the WHO guidelines, which confirms published reports from the WHO reporting extreme levels of exposure [64, 65]. For individual pollutants, we found that the mean $PM_{2.5}$ was higher in controls compared to cases (Table 4). There was no significant difference in CO concentration between cases and controls. There was no significant difference in PM_1 between cases and controls (*P*-value > 0.05). Furthermore, there was a significant difference (*P*-value 0.0260) in exposure to Black Carbon between cases and controls. BC was higher in households of cases compared to controls.

The finding that $PM_{2.5}$ was higher in controls than cases was initially perplexing, however, it is important to note that the study design was such that measurements were made following a lag time from when cases presented to hospital and consent was given to take measurements. The presence of a sick child and visit to health care centres presents the possibilities of behavioural changes following medical advice [66]. Education on pollution levels and practical actions to reducing indoor pollution such as opening of windows is part of the care given to parents and caregivers when treatment is sought [67]. This can potentially lead to modifications in habits that could have led to reduction in $PM_{2.5}$ levels prior to our measurements among cases. Future studies should adopt a study design that follows a representative sample within a prolonged timeframe where periodic indoor air quality measurements are observed and respiratory symptoms are continuously monitored by a healthcare professional to give a wholistic view of exposure to pollutants and pneumonia association. We return to the effect of unmodifiable factors later in this discussion.

Nonetheless, there was higher BC measures in houses with a pneumonia episode. Furthermore, within matched time frames, the average BC load was higher in cases compared to controls (Fig. 2). This result is in line with results from in vitro studies conducted by Hussey *et al* [11] that reported BC has been reported to significantly affect the behaviour of *S. pneumoniae* by altering the structure and proteolytic degradation of the biofilm, therefore promoting its tolerance to multiple antibiotics. Furthermore, BC promotes the spread of bacteria to the lungs and consequently exacerbates the disease occurrence [11, 17].

In recent times, there has been increased interest into the role of black carbon in climate change, air quality and health [68]. Epidemiological studies have shown that BC is a better indicator for short-term health effects compared to undifferentiated PM mass [69]. Furthermore, pneumococcal bacteria which causes pneumonia has been shown to be more associated with BC than with $PM_{2.5}$ [70], suggesting that BC is a better indicator of harmful particulate substances from combustion sources than undifferentiated PM mass. Whilst $PM_{2.5}$ has been widely used in the literature as an indicator of indoor air pollution [13, 71], new research is showing that it in itself contains PM_1 and BC in different proportions depending on the source [13, 71]. This finding highlights the importance to measure each pollutant and not depend on proxies or surrogate markers of the pollutants. This is therefore the first case-control study to investigate and report an association between BC and childhood pneumonia at the household level in Abuja, Nigeria. Furthermore, this is the first population-based study to report this association; previous studies investigating the influence of BC have been done mostly in controlled settings.

There was an association of seasonality on pollutant levels. We found that households were exposed to higher concentration of $PM_{2.5}$, CO and BC during rainy season compared to dry season, this could be due to increased cooking activities indoors during the rainy season. This reinforces previous findings where higher exposure during the rainy season compared to the dry season has been observed in other studies [12, 14, 72]. However, PM_1 was higher during the dry (i.e. November to March) season compared to rainy season (i.e. April to October). This could be due to increased exposure to outdoor air whilst cooking outside during dry seasons [73].

Seasonality is important in changing both the composition and concentration of pollutants. For example, in a study conducted in Italy, $PM_{2.5}$ analysed in the winter months was made up of organic species and products of combustion such as from heating however, in the spring and summer months, the same $PM_{2.5}$ was characterised by soil-related organic components and secondary inorganic components [74]. As lifestyle is significantly affected by season it is not inconceivable that the compositions of PM between seasons in Nigeria is likely to also vary and requires careful evaluation. However, it is important to note that a longer study of at least two years is required to fully understand the effect of seasonality on pollutants and disease incidence.

Malnutrition And Pneumonia Incidence

Furthermore, our results indicate that cases were more likely to be undernourished (p-value < 0.05). This result agrees with existing research; most healthy children can fight the infection with their natural defences, children whose immune systems are compromised are at higher risk of developing pneumonia, although it is difficult to ascertain if malnutrition in this case, was present before pneumonia episode or was a consequence of the disease. A child's immune system may be weakened by malnutrition especially in infants who are not exclusively breastfed [75, 76]. Childhood undernutrition, especially wasting (children who have a weight too low for their height) is a risk factor for pneumonia in children [77]. It contributed to 53% of pneumonia deaths in 2017 in children under five in Nigeria. Without sufficient energy intake the body cannot cope with increased energy demands required to fight off the infection. A literature review of pneumonia in malnourished children by Chisti and colleagues found that undernourished children are between two and four times more likely to be admitted to hospital due to pneumonia and up to 15 times more likely to die from it in developing countries [78].

Effect of behaviourally modifiable and unmodifiable factors.

As previously mentioned, behaviourally modifiable factors may have affected our observations and interpretation of the pneumonia episodes. The problem is that results could have been different if behaviour has been affected after the hospital/health care advice.

Alongside pollution levels, a higher proportion of cases were within the lowest socioeconomic group compared to controls. Poverty is known to affect early treatment seeking behavior by care givers predominantly due to barriers to financial access [79]. Treatment seeking behavior is associated with high disease incidence usually in low-income countries [79].

In general, we found that more cases (75%) were present in the cooking environment accompanying their mothers during cooking, compared to 37% of the control group. A study assessing cooking fuel choice in Lagos, Nigeria, reports the choice of cooking fuels was predominantly kerosene, followed by charcoal and liquified petroleum gas was the least used [80]. Dirty cooking fuels such as kerosene and firewood are known to increase household pollution levels increasing the risk of health damaging effects [80]. In this study, 12% of cases used kerosene compared to 20% of controls. Furthermore, 12% of cases used biomass fuel while 11.5% of control. Overall, a high percentage of the study population used a combination of these fuel choices. This therefore suggests, time children spent with their mothers during cooking is an important factor to consider in reducing pollution-induced pneumonia incidence. Time spent in cooking-environment is a behaviourally modifiable factor, which following education to care-givers can have beneficial effects on pneumonia incidence.

Interestingly, we noted that, of the cases present with mothers during cooking, 63% of them were females compared to 37% males. This gender difference was also significant with a p-value < 0.05. This is consistent with the literature that women and children, especially female children are often with their parents during cooking [81–84]. This gender bias means that women and female children are more frequently exposed to the dangers of indoor air pollution [81–84]. This can be due to the observation that culturally women are responsible for cooking, cleaning and childcare which could contribute to this observation. Although sex is a unmodifiable construct in this setting, both genders could respond differently to the exposure to pollutants hence the observed differences [84]. Therefore, more research is required to fully understand why this observation occurs.

Bruce *et al.* found that windows did not have an independent association with indoor air pollution exposure of children. Contrary to Bruce *et al.*'s [85] findings, we found that cases had lower number of windows in the kitchen which suggests that there can be an association between less ventilation, BC levels and a pneumonia episode. Our finding that number of windows and ventilation holes have a positive association with the likelihood of a recent pneumonia episode in children under five may not only be due to differences in size of these structures, location, and frequency of keeping windows open as observed by Jing Chang *et al* [86]. It is likely that in some households, though there is an active chimney, owing to poor house construction (lack of concrete material), smoke removed from the chimney may be circulating back into the house owing to porous walls. Echoing Langbien's [87] finding which suggests the need to study pollutant exposure and its impact on human health under various ventilation conditions and cooking locations.

In summary, our observations showed that unmodifiable factors such as reduced number of windows showed a statistically significant difference between those who had a pneumonia episode and those who didn't, whereas behaviorally modifiable factors such as opening of windows could potentially have a positive effect on reducing pollution levels but not enough to reach WHO "safe" levels.

Strengths And Limitations Of The Current Study

We employed a case control study design to compare exposures to different indoor pollutants between cases and controls with the assumption that they would have similar exposures. However, a limitation to this approach was that cases where recruited from hospitals, which might influence the post diagnosed exposure of the child.

Measurements were taken over 24 hours. In 60 households equipment was tampered with (e.g. by blocking the air inlet or batteries running out due to electricity issues) or experienced interruption in device power supply leading to a break in the continuous measurements over the 24 h period. Second, we also had measures for less than 24 hours while WHO guidelines are based on 24 hour measures.

We cannot rule out selection bias within the cases population as only a certain group of people choose to go and can afford to go to the hospital.

A major strength of this study is that it measures for the first time the association of multiple component exposures of household air pollution (PM_1 $PM_{2.5}$, CO and BC) and pneumonia in Abuja, Nigeria. This works strengthens available primary data evidence on the effects of indoor air pollution on pneumonia episodes in children under five.

Recommendations From Our Findings

The reduction of pneumonia incidence in children under five in Nigeria is urgently needed and this requires a multifaceted approach from the government, caregivers and other stakeholders. Educational and health promotion campaigns to prevent exposure of children under five to pollutants from cooking fuel is essential because the understanding the health consequences of indoor pollution amongst the studied population varies considerably. Certain people think it's the presence of smoke from burning biomass, making a kerosene stove cleaner, whilst others believe that any source of fuel other than electricity and LPG is polluting the indoor environment [88–90]. Also, in Nigeria there is a lack of knowledge that links pollution to pneumonia amongst caregivers. When asked, most responders did not think smoke was a risk factor that could be linked with childhood pneumonia and accordingly did not think that avoiding smoke in their homes could prevent pneumonia in their children [90]. Public health education of the public at large with routine reminders on the dangers of using solid fuels for cooking and potential health implications would be beneficial.

Furthermore, we propose active prevention actions such as cleaner fuel choices, household behavioural modifications such as reducing child presence in the cooking environment and encouraging the opening of windows for optimal ventilation [86]. Firstly, it can thus be summarised that the lack of stable electricity, lack of access to affordable clean fuels and a lack of clear health benefits of using clean fuels have acted as primary obstacles to energy transition [91]. The development of infrastructure to facilitate access to clean fuels and promotion of safety consciousness should be considered. Second, children should be kept away from cooking areas to help reduce their exposure to pollutants emitted during cooking. This is crucial because children in homes that uses good quality chimney stoves and exclusive use of gas cookers, still show high exposure levels [91]. This information needs to be reiterated in schools, hospitals and through the media for parents to be well informed.

We also propose early and effective treatment seeking as beneficial to reducing pneumonia incidence. Early treatment is not common in Nigeria, most homes are at the lower socio economic class with little purchasing power. For these families, the first point of call are often pharmacies, which indirectly encourages home treatment and self-mediation [92]. We recommend any ongoing public health interventions aimed at mitigating the burden of pneumonia episodes in children under five nationally, should focus on improving the access to early detection and treatment, IMCI community training of healthcare workers at the local level and improvement of the standard of healthcare centres, as priority outcomes.

Finally, a more targeted research approach and effective monitoring of the implementation of current and new policies is needed particularly in high population areas. One aspect of the problem so far is the lack of household air quality monitoring in Nigeria. This study provides a representation of the household air quality factors associated with pneumonia episodes in children under five in Nigeria. Therefore, results reported in this study can help guide the government and public health practitioners in developing appropriate household and treatment seeking behaviour interventions and a review of the policy around air quality and childhood respiratory illnesses in Nigeria.

Conclusion

In conclusion, we report, a statistically significant differences between BC levels and a pneumonia episode in a case-control study. We confirm that time spent in cooking environment was associated with a pneumonia episode. The number of windows in the house was positively associated with a pneumonia episode in children under five. We propose a multifaceted approach that combines educational and health promotion campaigns to prevent childhood pneumonia. This includes, promoting healthy housing and behaviour changes that support exposure reduction and adequate ventilation, early treatment seeking behaviour and targeted implementation of the Integrated Management of Childhood Illness particularly in high pollution areas is an important step in reducing the pneumonia burden in children under five in Nigeria.

Declarations

Ethics approval and consent to participate

Prior to data collection, the protocol for this study was reviewed and approved by the University of Nottingham Medical School Ethics Committee (Reference number: 134–1710) and the National Health research Ethics Committee of Nigeria (Reference number: NHREC/01/01/2007). And consent was sort from all study participants.

Consent for publication

Consent was sort from participants.

Availability of data and materials

The datasets during and/or analysed during the current study available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

EEA, JG, MC and RP conceptualized the study. EEA and MB analysed and interpreted the data regarding air quality measurements. All authors contributed for preparation of manuscript and all authors read and approved the final manuscript.

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Figures

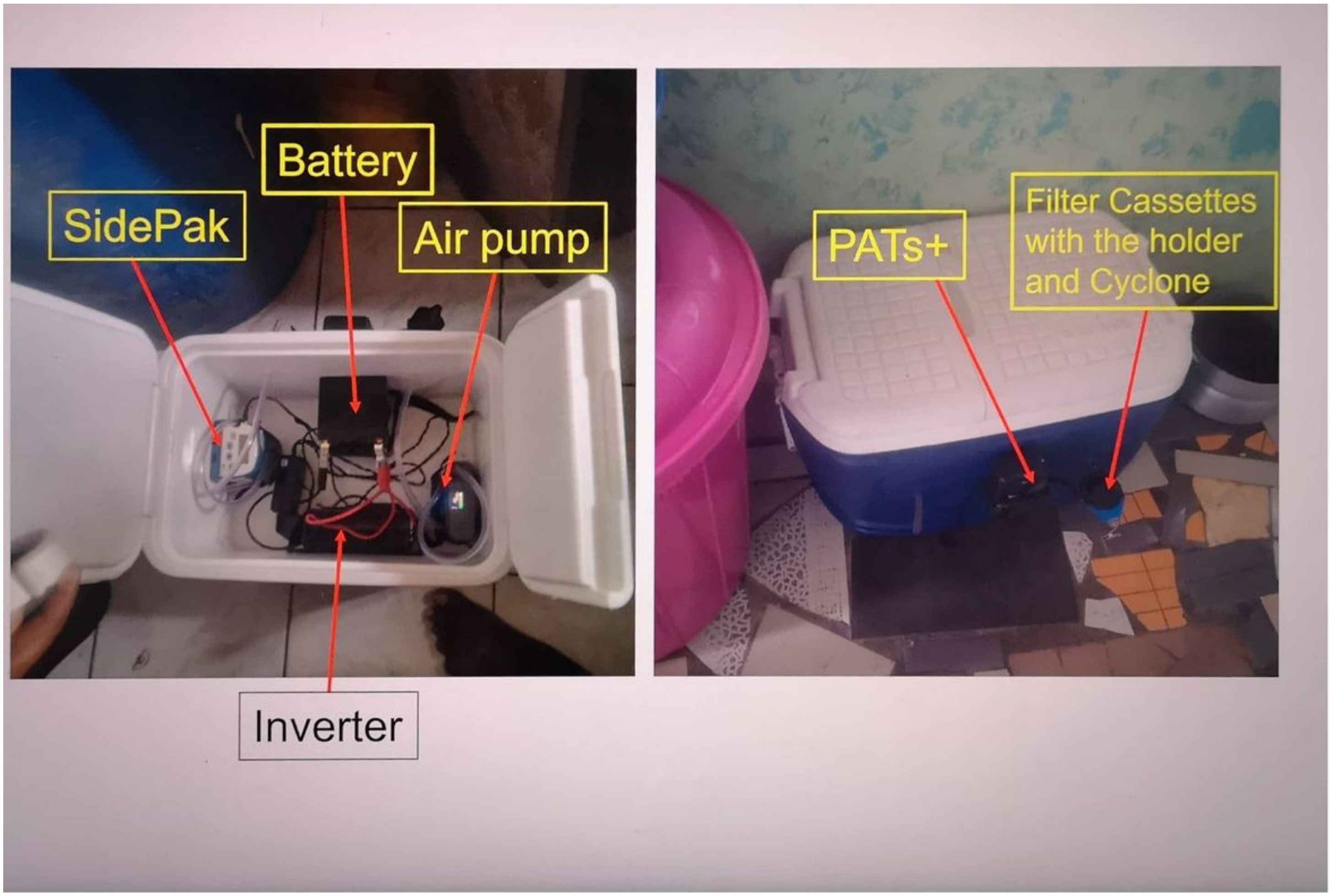

Figure 1

Equipment setup for indoor air measurements (Picture Credit: Author).

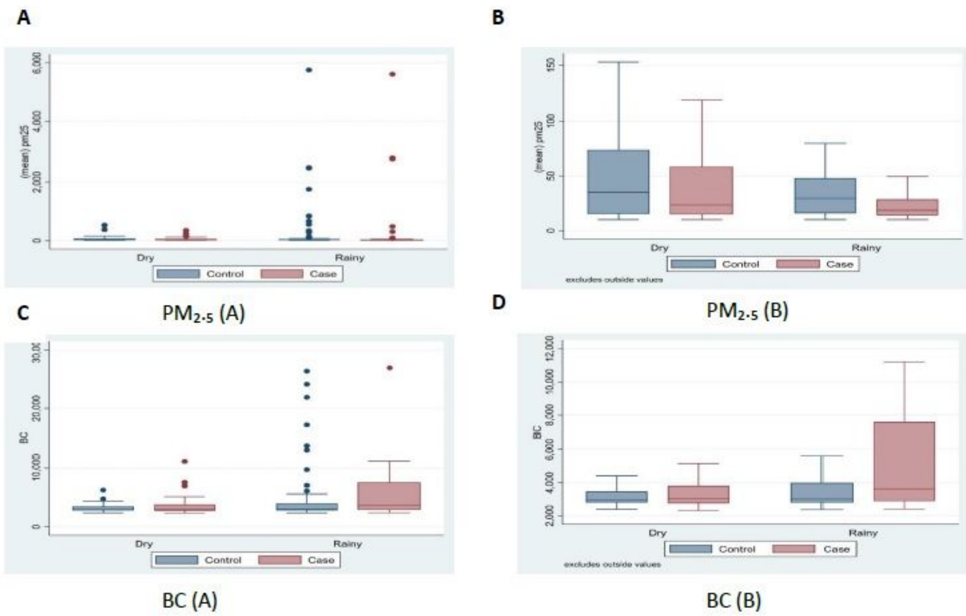

Figure 2

Box plots of PM2.5 and Black carbon (BC) distributions over 20 to 24 hours. The horizontal line in each box represents the median value and the top and bottom of the box represent the 25th and 75th percentile, with the lines extending from the top and bottom of the boxes widening to the 5th and 95th percentile of the distribution. For ease of representation, (B) and (D) does not show outside values. PM