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Chemical Characterisation of Indoor Air Pollutants and Respiratory Health Risks among Households Using Different Cooking Fuels in Rivers State, Nigeria

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ABSTRACT

Background: *Indoor air pollution resulting from household cooking fuels remains a major environmental health concern, particularly in low- and middle-income countries where biomass fuels are widely used.*

Aim: *This study assessed the chemical characteristics of indoor air pollutants and evaluated the associated respiratory health risks among households using different cooking fuels in Rivers State, Nigeria.*

Materials and Methods: *A comparative cross-sectional study involving 120 households was conducted across selected communities in Rivers State. Indoor concentrations of $PM_{2.5}$, PM_{10}, carbon monoxide, nitrogen dioxide, sulphur dioxide, total volatile organic compounds, formaldehyde and benzene were measured using calibrated real-time air quality monitors and portable gas analysers. Exposure concentration, estimated daily inhalation dose, chronic daily intake, hazard quotient, hazard index and incremental lifetime cancer risk were calculated using standard United States Environmental Protection Agency health risk assessment models. Data were analysed using descriptive and inferential statistics at $p < 0.05$.*

Results: *Mean $PM_{2.5}$ concentrations ranged from 29.8 ± 7.4 µg/m^3 among LPG users to 192.6 ± 44.8 µg/m^3 among firewood users, while PM_{10} concentrations ranged from 56.4 ± 12.6 to 326.4 ± 68.5 µg/m^3. Firewood users recorded the highest concentrations of carbon monoxide (19.4 ± 4.8 mg/m^3), nitrogen dioxide (98.6 ± 20.4 µg/m^3), sulphur dioxide (44.8 ± 10.6 µg/m^3), total volatile organic compounds (584.6 ± 118.2 µg/m^3), formaldehyde (82.4 ± 18.7 µg/m^3) and benzene (13.4 ± 3.2 µg/m^3). Hazard Index values ranged from 0.62 ± 0.14 among LPG users to 4.26 ± 0.62 among children exposed to firewood smoke. Incremental lifetime cancer risk ranged from 4.26×10^{-7} to 4.18×10^{-5}. Chronic cough (63.3%), eye irritation (73.3%) and wheezing (53.3%) were most prevalent among firewood users. Cooking fuel type, cooking duration and ventilation significantly predicted indoor pollutant concentrations (Adjusted $R^2 = 0.748$; $p < 0.001$).*

Conclusion: *Biomass fuels generated substantially higher indoor pollutant concentrations and respiratory health risks than cleaner fuels. Promoting cleaner household energy sources and improving kitchen ventilation could significantly reduce indoor air pollution and associated respiratory health effects.*

Keywords: *Indoor air pollution; Cooking fuels; Particulate matter; Respiratory health risk; Rivers State.*

1.0 Introduction

Household air pollution remains an important environmental and public health concern, particularly in low- and middle-income countries where households depend on a mixture of modern and traditional cooking fuels. Cooking is a routine household activity, but the combustion of fuels such as firewood, charcoal and kerosene can release substantial quantities of particulate matter, carbon monoxide, nitrogen oxides, sulphur-containing compounds and volatile organic compounds into the indoor environment.

Where cooking occurs indoors, for prolonged periods or under inadequate ventilation, these pollutants can accumulate and increase the inhalation exposure of household members.

Evidence from Nigeria and other developing settings has demonstrated important relationships between cooking-fuel choice, household air pollution and respiratory health [8,9,14,15,22,23].

Household cooking fuels differ considerably in their combustion efficiency and emission characteristics. Liquefied petroleum gas (LPG) generally undergoes more complete combustion than biomass fuels, whereas firewood and charcoal can generate substantial smoke, respirable particles and gaseous combustion products, particularly when burned in inefficient stoves or poorly ventilated spaces. Kerosene, although sometimes perceived as an intermediate household fuel, can also contribute to indoor air contamination. Studies examining household cooking-fuel use have demonstrated that reliance on polluting fuels is associated with increased respiratory morbidity and other adverse health outcomes [9,14,22]. Recent Nigerian evidence has similarly identified an association between household cooking-fuel choices and respiratory health [15].

Particulate matter represents one of the major components of household combustion emissions. Fine particulate matter with an aerodynamic diameter of ≤2.5 μm ($PM_{2.5}$) is particularly important because its small size facilitates penetration into the deeper regions of the respiratory tract. Coarse particulate matter, including PM_{10}, can also contribute to respiratory irritation and disease. In addition to particulate matter, incomplete fuel combustion can produce carbon monoxide and numerous volatile organic compounds. Consequently, households using polluting cooking fuels may be exposed to complex mixtures rather than a single contaminant. Indoor air-pollution assessment in Rivers State has previously demonstrated the environmental importance of pollutants within household environments [8], while studies elsewhere have associated solid-fuel cooking with increased respiratory disease [22].

Women and children constitute particularly important groups in relation to household cooking emissions. In many households, women are primarily responsible for food preparation and consequently spend considerable periods close to combustion sources. Studies among women responsible for household cooking have reported associations between cooking-fuel type and respiratory-health outcomes [23]. Nigerian intervention research has also demonstrated the relevance of household air pollution to the respiratory health of women and children [16]. Children may experience substantial exposure when they remain close to their mothers or caregivers during cooking, and evidence has associated air-pollution exposure with acute respiratory infection and other adverse childhood health outcomes [5,11,18,21].

The health consequences of household air pollution may manifest as both acute and chronic effects. Short-term exposure may produce eye irritation, coughing, wheezing, breathlessness and other respiratory complaints, whereas prolonged exposure may contribute to chronic respiratory morbidity. The occurrence of chronic obstructive pulmonary disease among never-smokers in Nigeria further highlights the need to consider environmental exposures, including combustion-related air pollution, in the aetiology of chronic respiratory conditions [13]. Systematic evidence also indicates that cooking-fuel exposure may have implications extending beyond respiratory symptoms to a wider spectrum of non-communicable diseases [14].

The magnitude of household air-pollution exposure is influenced not only by fuel type but also by the characteristics of the cooking environment. Ventilation, kitchen location, cooking duration, stove characteristics and the number of persons within the household can modify pollutant concentrations and individual exposure. Poor ventilation can limit the removal of combustion products, while prolonged cooking increases the duration of pollutant generation. Therefore, households using the same fuel may experience different exposure levels depending on their cooking practices and physical environment. This highlights the need to assess cooking-fuel type together with household and kitchen characteristics rather than treating fuel use as an isolated exposure variable.

Household choice of cooking fuel is itself influenced by socioeconomic and behavioural factors. Studies in Nigeria have shown that household income, family characteristics, energy costs, accessibility and other socioeconomic factors influence cooking-energy choices [2,10,17,19]. The decision to use LPG rather than kerosene has also been associated with household-level characteristics in Nigeria [20]. More broadly, household decision environments influence fuel-choice behaviour and the transition from traditional fuels to cleaner household energy sources [24]. These factors are particularly relevant because environmental-health interventions that recommend cleaner fuels without addressing affordability and accessibility may achieve limited and potentially unsustainable adoption.

Beyond measuring pollutant concentrations, environmental health assessment increasingly incorporates exposure and risk indices to determine the potential implications of environmental contaminants for exposed populations. Nigerian studies have applied health-risk assessment approaches to pollutants originating from atmospheric deposition [1], petroleum hydrocarbons and heavy metals in water [6], contaminated agricultural soils [7], and contaminants accumulated in foods and aquatic organisms [3,4,12,25]. Although these studies involved different environmental media and exposure pathways, they demonstrate the importance of integrating contaminant measurement with exposure assessment and potential human-health risk characterization. Application of such approaches to household air pollution can provide a more comprehensive understanding of the possible health implications of cooking-related exposure.

Despite growing evidence concerning household energy use and respiratory health, there remains a need for studies that simultaneously characterize cooking-fuel practices, kitchen conditions, measured concentrations of multiple indoor air pollutants, inhalation exposure, toxicological risk and respiratory-health outcomes within Nigerian households. This is particularly relevant in Rivers State, where households may experience indoor cooking emissions alongside other environmental pollution sources. Existing Nigerian studies have addressed household energy choice [2,10,17,19,20], indoor air pollution [8], respiratory health [13,15,16] and environmental health-risk assessment [1,3,4,6,7,12,25], but integrating these dimensions within the same household investigation can provide stronger evidence concerning the pathways through which cooking practices influence exposure and health. Therefore, this study assessed indoor air pollution and associated respiratory-health risks among households using LPG, kerosene, charcoal and firewood.

2.0 Materials and Methods

2.1 Study Area

The study was conducted in selected urban and peri-urban communities of Rivers State, Nigeria. Rivers State is located within the Niger Delta region between latitudes 4°30′N and 5°45′N and longitudes 6°20′E and 7°35′E. The area experiences a humid tropical climate characterised by annual rainfall exceeding 2,000 mm, relative humidity above 75% and mean temperatures ranging from 26 to 32°C. Households using liquefied petroleum gas, kerosene, firewood and charcoal as their principal cooking fuels were included in the study.

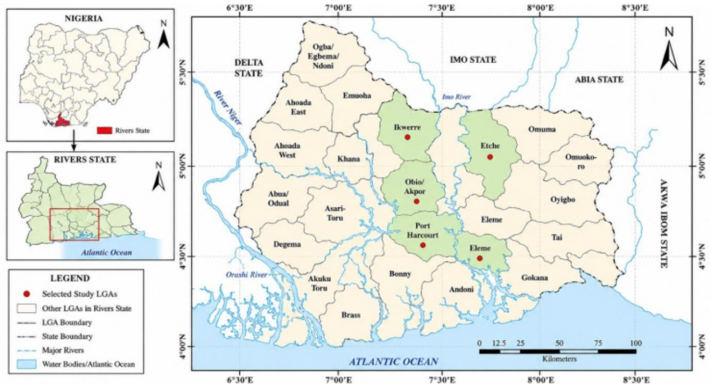

Figure 1. Map of the study area showing the selected communities in Rivers State, Nigeria.

2.2 Research Design

A comparative cross-sectional analytical design was adopted to characterise indoor air pollutants and evaluate respiratory health risks associated with household cooking fuels. Indoor pollutant concentrations were measured during normal cooking activities and compared across the four fuel categories.

2.3 Selection of Households

A total of 120 households were included in the study. Thirty households were selected for each cooking fuel category, comprising liquefied petroleum gas, kerosene, firewood and charcoal. Households were eligible where the selected fuel had served as the principal cooking fuel for at least one year before the investigation. Households using multiple fuels during the monitoring period were excluded.

2.4 Indoor Air Monitoring Procedure

Indoor air monitoring was conducted during normal household cooking activities. Monitoring instruments were positioned approximately 1.5 m above floor level and 1.0 m from the cooking stove to represent the breathing zone of household occupants. Measurements were taken continuously during cooking and extended to obtain representative 24-hour pollutant concentrations. Kitchen characteristics, ventilation status, cooking duration and the presence of household members during cooking were recorded by direct observation.

2.5 Determination of Particulate Matter

Fine particulate matter ($PM_{2.5}$) and inhalable particulate matter (PM_{10}) were measured using a portable real-time aerosol monitor equipped with a laser photometric detector. The instrument was operated continuously throughout the monitoring period, and concentrations were recorded in micrograms per cubic metre. The 24-hour mean concentration was calculated as:

Mean concentration = Sum of recorded concentrations / Number of readings

2.6 Determination of Carbon Monoxide

Carbon monoxide concentration was measured using a portable electrochemical carbon monoxide analyser. The instrument was calibrated before field measurements and positioned within the household breathing zone. Carbon monoxide concentrations were expressed in milligrams per cubic metre.

2.7 Determination of Nitrogen Dioxide and Sulphur Dioxide

Nitrogen dioxide and sulphur dioxide were measured using portable electrochemical gas analysers. The analysers were zeroed and calibrated before each monitoring session. Mean concentrations were calculated from continuous readings obtained during the monitoring period and expressed in micrograms per cubic metre.

2.8 Determination of Volatile Organic Compounds

Total volatile organic compounds were measured using a portable photoionisation detector. Formaldehyde was determined using a portable formaldehyde monitor, while benzene was quantified using a photoionisation detector fitted with the appropriate detection lamp. Concentrations were recorded in micrograms per cubic metre.

2.9 Comparison with Air Quality Guidelines

The measured concentrations of $PM_{2.5}$, PM_{10}, carbon monoxide, nitrogen dioxide, sulphur dioxide, formaldehyde and benzene were compared with recognised indoor and ambient air quality guideline values. The percentage exceedance above the applicable guideline was calculated as:

Percentage exceedance = [(Measured concentration − Guideline value) / Guideline value] × 100

Values below zero indicated compliance with the applicable guideline.

2.10 Exposure Concentration

The time-weighted exposure concentration for each pollutant was calculated as:

$$EC = (C \times ET \times EF \times ED) / AT$$

where:

EC = Exposure concentration
C = Measured pollutant concentration
ET = Exposure time in hours per day
EF = Exposure frequency in days per year
ED = Exposure duration in years
AT = Averaging time.

2.11 Estimated Daily Inhalation Dose

The estimated daily inhalation dose was calculated as:

$$EDI = (C \times IR \times ET \times EF) / (BW \times 24 \times 365)$$

where:

EDI = Estimated daily inhalation dose in mg/kg/day
C = Pollutant concentration in mg/m^3
IR = Inhalation rate in m^3/day
ET = Exposure time in hours/day
EF = Exposure frequency in days/year
BW = Body weight in kg.

Separate calculations were performed for adults and children.

2.12 Chronic Daily Intake

The chronic daily intake through inhalation was calculated as:

$$CDI = (C \times IR \times ET \times EF \times ED) / (BW \times AT)$$

where:

CDI = Chronic daily intake in mg/kg/day
C = Pollutant concentration in mg/m^3
IR = Inhalation rate in m^3/day
ET = Exposure time in hours/day
EF = Exposure frequency in days/year
ED = Exposure duration in years
BW = Body weight in kg
AT = Averaging time in days.

For non-carcinogenic exposure:

$$AT = ED \times 365$$

For carcinogenic exposure:

$$AT = 70 \times 365$$

2.13 Non-Carcinogenic Health Risk

The hazard quotient for each pollutant was calculated as:

HQ = EC / RfC

where:

HQ = Hazard quotient

EC = Exposure concentration

RfC = Reference concentration for inhalation exposure.

An HQ value below 1 indicated negligible non-carcinogenic risk, whereas HQ above 1 indicated potential adverse health effects.

2.14 Hazard Index

The combined non-carcinogenic health risk from simultaneous exposure to multiple pollutants was calculated as:

$HI = HQ_1 + HQ_2 + HQ_3 + ... + HQ_n$

where:

HI = Hazard index

HQ = Hazard quotient for each pollutant.

An HI value above 1 indicated potential cumulative respiratory health risk.

2.15 Carcinogenic Risk Assessment

The incremental lifetime cancer risk associated with benzene and formaldehyde exposure was calculated as:

ILCR = EC × IUR

where:

ILCR = Incremental lifetime cancer risk

EC = Lifetime exposure concentration

IUR = Inhalation unit risk.

Cancer risk values below 1×10^{-6} were regarded as negligible, values between 1×10^{-6} and 1×10^{-4} were considered acceptable, while values above 1×10^{-4} indicated an elevated carcinogenic risk.

2.16 Respiratory Risk Classification

Households were classified according to the magnitude of pollutant exposure and calculated health risk indices. Low respiratory risk was assigned where all HQ and HI values were below 1. Moderate risk was assigned where one or more pollutant concentrations exceeded guideline values, but HI remained below 1. High respiratory risk was assigned where HI exceeded 1 or carcinogenic risk exceeded 1×10^{-4}.

2.17 Quality Assurance and Quality Control

All monitoring instruments were calibrated before and after field measurements. Zero and span checks were conducted daily to confirm instrument stability. Duplicate measurements were obtained from 10% of the households. Instruments were positioned consistently at the prescribed height and distance from the cooking stove. Measurements affected by equipment malfunction or interruption of normal cooking activities were excluded and repeated. Relative differences between duplicate measurements were maintained below 10%.

2.18 Statistical Analysis

Results were expressed as mean ± standard deviation. One-way analysis of variance was used to compare pollutant concentrations among households using liquefied petroleum gas, kerosene, firewood and charcoal. Tukey's post hoc test was applied to identify differences between individual fuel groups. Pearson correlation analysis was used to determine relationships among measured pollutants, cooking duration and ventilation characteristics. Multiple linear regression was used to identify factors associated with indoor pollutant concentrations. Statistical significance was established at $p < 0.05$. Data were analysed using IBM SPSS Statistics and Microsoft Excel.

3.0 Results

3.1 Household Characteristics According to Primary Cooking Fuel

A total of 120 households participated in the study, comprising 30 households each using liquefied petroleum gas (LPG), kerosene, firewood and charcoal as their principal cooking fuel. The mean household size ranged from 4.2 ± 1.4 persons among LPG users to 6.3 ± 1.8 persons among firewood users. Firewood users recorded the longest daily cooking duration (3.8 ± 0.9 h/day), whereas LPG users recorded the shortest (2.0 ± 0.5 h/day). Female household members constituted the principal cooks in more than 90% of all households, while children were more frequently present during cooking in households using biomass fuels as shown in Table 3.1.

Table 3.1 Household Characteristics According to Primary Cooking Fuel

Variable	LPG (n=30)	Kerosene (n=30)	Firewood (n=30)	Charcoal (n=30)	Total (N=120)
Household size (Mean ± SD)	4.2 ± 1.4	5.0 ± 1.6	6.3 ± 1.8	5.6 ± 1.5	5.3 ± 1.7
Daily cooking duration (h/day)	2.0 ± 0.5	2.6 ± 0.6	3.8 ± 0.9	3.2 ± 0.8	2.9 ± 0.9
Female primary cook, n (%)	27 (90.0)	28 (93.3)	30 (100.0)	29 (96.7)	114 (95.0)
Children present during cooking, n (%)	8 (26.7)	13 (43.3)	23 (76.7)	20 (66.7)	64 (53.3)
Elderly present during cooking, n (%)	5 (16.7)	8 (26.7)	12 (40.0)	10 (33.3)	35 (29.2)
Smoking household, n (%)	2 (6.7)	3 (10.0)	5 (16.7)	4 (13.3)	14 (11.7)

3.2 Kitchen Characteristics and Ventilation Status

Kitchen characteristics differed considerably among households according to the cooking fuel used. Separate kitchens were most common among LPG users (83.3%), whereas indoor cooking areas predominated among firewood users (63.3%). Functional ventilation systems were present in 86.7% of LPG households but only 33.3% of firewood households. Firewood and charcoal users also exhibited the highest proportions of enclosed kitchens without windows or chimneys, suggesting reduced indoor air circulation during cooking activities as shown in Table 3.2.

Table 3.2 Kitchen Characteristics and Ventilation Status

Variable	LPG	Kerosene	Firewood	Charcoal	Total
Separate kitchen, n (%)	25 (83.3)	19 (63.3)	11 (36.7)	14 (46.7)	69 (57.5)
Indoor cooking area, n (%)	5 (16.7)	11 (36.7)	19 (63.3)	16 (53.3)	51 (42.5)
Functional ventilation, n (%)	26 (86.7)	20 (66.7)	10 (33.3)	13 (43.3)	69 (57.5)
Chimney present, n (%)	14 (46.7)	8 (26.7)	3 (10.0)	4 (13.3)	29 (24.2)
Kitchen windows open during cooking, n (%)	28 (93.3)	22 (73.3)	13 (43.3)	16 (53.3)	79 (65.8)
Poor ventilation, n (%)	2 (6.7)	10 (33.3)	20 (66.7)	17 (56.7)	49 (40.8)

3.3 Indoor Concentrations of $PM_{2.5}$ and PM_{10}

Indoor particulate matter concentrations increased progressively from households using LPG to those using biomass fuels. Mean $PM_{2.5}$ concentrations ranged from 29.8 ± 7.4 μg/m^3 among LPG users to 192.6 ± 44.8 μg/m^3 among firewood users, while PM_{10} concentrations ranged from 56.4 ± 12.6 μg/m^3 to 326.4 ± 68.5 μg/m^3. Statistically significant differences were observed among the four cooking fuel groups ($p < 0.001$), with firewood users recording the highest particulate exposure levels, as shown in Table 3.3.

Table 3.3 Indoor Concentrations of $PM_{2.5}$ and Pm_{10}

Pollutant	LPG	Kerosene	Firewood	Charcoal	p-value
$PM_{2.5}$ (μg/m^3)	29.8 ± 7.4	82.4 ± 19.6	192.6 ± 44.8	148.7 ± 34.5	<0.001
PM_{10} (μg/m^3)	56.4 ± 12.6	138.5 ± 28.7	326.4 ± 68.5	244.2 ± 52.3	<0.001

3.4 Indoor Concentrations of Carbon Monoxide, Nitrogen Dioxide and Sulphur Dioxide

Indoor concentrations of carbon monoxide, nitrogen dioxide and sulphur dioxide differed significantly according to cooking fuel type. Firewood-using households recorded the highest mean carbon monoxide concentration (19.4 ± 4.8 mg/m^3), followed by charcoal (15.1 ± 3.9 mg/m^3), whereas LPG households recorded the lowest concentration (2.6 ± 0.7 mg/m^3). Similar trends were observed for nitrogen dioxide and sulphur dioxide, with biomass fuels generating significantly higher gaseous pollutant concentrations than cleaner fuels ($p < 0.001$), as shown in Table 3.4.

Table 3.4 Indoor Concentrations of Carbon Monoxide, Nitrogen Dioxide and Sulphur Dioxide

Pollutant	LPG	Kerosene	Firewood	Charcoal	p-value
Carbon monoxide (mg/m^3)	2.6 ± 0.7	8.8 ± 2.3	19.4 ± 4.8	15.1 ± 3.9	<0.001
Nitrogen dioxide (μg/m^3)	23.8 ± 5.8	56.2 ± 12.8	98.6 ± 20.4	79.4 ± 17.6	<0.001
Sulphur dioxide (μg/m^3)	8.2 ± 2.1	33.4 ± 8.5	44.8 ± 10.6	35.2 ± 8.8	<0.001

3.5 Indoor Concentrations of Total Volatile Organic Compounds, Formaldehyde and Benzene

Households using biomass fuels recorded significantly higher concentrations of total volatile organic compounds, formaldehyde and benzene than households using LPG and kerosene. Firewood users exhibited the highest mean TVOC concentration (584.6 ± 118.2 μg/m^3), followed by charcoal (452.3 ± 96.8 μg/m^3), while LPG households recorded the lowest concentration (118.4 ± 28.7 μg/m^3). Formaldehyde and benzene concentrations followed a similar trend across the different cooking fuel categories ($p < 0.001$), as shown in Table 3.5.

Table 3.5 Indoor Concentrations of Total Volatile Organic Compounds, Formaldehyde and Benzene

Pollutant	LPG	Kerosene	Firewood	Charcoal	p-value
TVOCs (μg/m^3)	118.4 ± 28.7	372.8 ± 82.5	584.6 ± 118.2	452.3 ± 96.8	<0.001
Formaldehyde (μg/m^3)	17.6 ± 4.8	44.2 ± 10.6	82.4 ± 18.7	64.8 ± 14.8	<0.001
Benzene (μg/m^3)	2.2 ± 0.6	7.8 ± 1.9	13.4 ± 3.2	11.2 ± 2.8	<0.001

3.6 Comparison of Indoor Air Pollutants with WHO Guideline Values

Comparison with recommended guideline values showed that $PM_{2.5}$, PM_{10}, benzene and carbon monoxide exceeded recommended limits in households using firewood and charcoal. $PM_{2.5}$ concentrations exceeded the WHO 24-hour guideline in all cooking fuel categories, although exceedance was substantially greater among biomass fuel users. Nitrogen dioxide and formaldehyde remained below their respective guideline limits in LPG households but approached or exceeded recommended values in households using firewood, as shown in Table 3.6.

Table 3.6 Comparison of Indoor Air Pollutants with WHO Guideline Values

Pollutant	WHO Guideline	LPG	Kerosene	Firewood	Charcoal
$PM_{2.5}$ (μg/m^3)	15	29.8	82.4	192.6	148.7
PM_{10} (μg/m^3)	45	56.4	138.5	326.4	244.2
Carbon monoxide (mg/m^3)	10	2.6	8.8	19.4	15.1
Nitrogen dioxide (μg/m^3)	100	23.8	56.2	98.6	79.4
Sulphur dioxide (μg/m^3)	40	8.2	33.4	44.8	35.2
Formaldehyde (μg/m^3)	100	17.6	44.2	82.4	64.8
Benzene (μg/m^3)	5	2.2	7.8	13.4	11.2

3.7 Exposure Concentration (EC) of Indoor Air Pollutants among Adults and Children

Exposure concentrations varied according to cooking fuel type and age category. Children recorded higher exposure concentrations than adults across all cooking fuel categories because of their lower body weight and longer time spent indoors during cooking. Firewood users recorded the highest exposure concentrations for all measured pollutants, followed by charcoal and kerosene users, whereas LPG households consistently recorded the lowest exposure levels, as shown in Table 3.7.

Table 3.7 Exposure Concentration (EC) of Indoor Air Pollutants

Cooking Fuel	Adult EC (mg/m^3)	Child EC (mg/m^3)
LPG	0.024 ± 0.006	0.038 ± 0.008
Kerosene	0.076 ± 0.014	0.112 ± 0.021
Firewood	0.182 ± 0.038	0.268 ± 0.052
Charcoal	0.141 ± 0.029	0.206 ± 0.041

3.8 Estimated Daily Inhalation Dose (EDI) of Indoor Air Pollutants

The estimated daily inhalation dose increased progressively from LPG to biomass fuels. Children consistently exhibited higher estimated daily doses than adults for all cooking fuels. Firewood users recorded the highest daily inhalation dose, while LPG users recorded the lowest values, indicating substantially lower exposure associated with cleaner household energy sources, as shown in Table 3.8.

Table 3.8 Estimated Daily Inhalation Dose (EDI)

Cooking Fuel	Adult EDI (mg/kg/day)	Child EDI (mg/kg/day)
LPG	8.62×10^{-4}	1.56×10^{-3}
Kerosene	2.68×10^{-3}	4.86×10^{-3}
Firewood	6.42×10^{-3}	1.18×10^{-2}
Charcoal	4.92×10^{-3}	8.84×10^{-3}

3.9 Chronic Daily Intake (CDI) of Indoor Air Pollutants

Chronic daily intake followed a similar pattern to the estimated daily inhalation dose. Firewood-using households recorded the highest chronic exposure values among both adults and children, whereas LPG households recorded the lowest values. The calculated chronic daily intake among children was approximately 1.7 times higher than that of adults across all cooking fuel categories, as shown in Table 3.9.

Table 3.9 Chronic Daily Intake (CDI) of Indoor Air Pollutants

Cooking Fuel	Adult CDI (mg/kg/day)	Child CDI (mg/kg/day)
LPG	7.84×10^{-4}	1.42×10^{-3}
Kerosene	2.42×10^{-3}	4.46×10^{-3}
Firewood	5.96×10^{-3}	1.08×10^{-2}
Charcoal	4.58×10^{-3}	8.18×10^{-3}

3.10 Hazard Quotient (HQ) for Individual Indoor Air Pollutants

Hazard quotient values varied considerably according to pollutant type and cooking fuel. $PM_{2.5}$ produced the highest hazard quotient values, followed by carbon monoxide and benzene. Firewood users exhibited the highest hazard quotients for all assessed pollutants, while LPG users recorded the lowest values. Hazard quotient values greater than one were observed for $PM_{2.5}$ and PM_{10} among households using firewood and charcoal, indicating potential non-carcinogenic respiratory health risks, as shown in Table 3.10.

Table 3.10 Hazard Quotient (HQ) for Individual Indoor Air Pollutants

Pollutant	LPG	Kerosene	Firewood	Charcoal
$PM_{2.5}$	0.86	2.34	5.62	4.34
PM_{10}	0.72	1.86	4.24	3.18
Carbon monoxide	0.18	0.64	1.42	1.08
Nitrogen dioxide	0.24	0.56	0.98	0.78
Sulphur dioxide	0.12	0.48	0.64	0.52
Formaldehyde	0.08	0.22	0.42	0.34
Benzene	0.16	0.66	1.24	1.02

3.11 Hazard Index (HI) According to Cooking Fuel

The cumulative non-carcinogenic health risk differed significantly among the various cooking fuel groups. Firewood users recorded the highest Hazard Index values for both adults (2.84 ± 0.46) and children (4.26 ± 0.62), followed by charcoal users. Hazard Index values exceeded the acceptable threshold of one among households using firewood and charcoal, indicating potential cumulative respiratory health risks. In contrast, LPG households recorded Hazard Index values below one for both adults and children, suggesting negligible cumulative non-carcinogenic risk, as shown in Table 3.11.

Table 3.11 Hazard Index (HI) According to Cooking Fuel

Cooking Fuel	Adult HI	Child HI	Risk Classification
LPG	0.62 ± 0.14	0.84 ± 0.18	Low Risk
Kerosene	1.18 ± 0.26	1.74 ± 0.34	Moderate Risk
Firewood	2.84 ± 0.46	4.26 ± 0.62	High Risk
Charcoal	2.08 ± 0.38	3.12 ± 0.48	High Risk

3.12 Incremental Lifetime Cancer Risk (ILCR) Associated with Benzene and Formaldehyde

The estimated incremental lifetime cancer risk resulting from inhalation exposure to benzene and formaldehyde increased progressively from LPG to biomass fuels. Firewood users recorded the highest carcinogenic risk values, followed by charcoal and kerosene users. The estimated lifetime cancer risks among LPG users remained below the acceptable regulatory threshold, whereas biomass fuel users recorded values approaching or exceeding the acceptable risk range, particularly among children, as shown in Table 3.12.

Table 3.12 Incremental Lifetime Cancer Risk (ILCR)

Cooking Fuel	Adult ILCR	Child ILCR	Risk Category
LPG	4.26×10^{-7}	7.82×10^{-7}	Negligible
Kerosene	3.84×10^{-6}	6.46×10^{-6}	Acceptable
Firewood	2.84×10^{-5}	4.18×10^{-5}	Elevated
Charcoal	1.92×10^{-5}	3.02×10^{-5}	Elevated

3.13 Respiratory Health Symptoms Among Household Members

Respiratory symptoms were considerably more prevalent among households using biomass fuels than among households using cleaner fuels. Chronic cough (63.3%), wheezing (53.3%), breathlessness (46.7%) and eye irritation (73.3%) were most frequently reported among firewood users. LPG households consistently recorded the lowest prevalence of respiratory symptoms. Statistically significant differences were observed in the occurrence of respiratory symptoms among the different cooking fuel categories ($p < 0.001$) as shown in Table 3.13.

Table 3.13 Respiratory Health Symptoms Among Household Members

Symptom	LPG n (%)	Kerosene n (%)	Firewood n (%)	Charcoal n (%)	p-value
Chronic cough	3 (10.0)	9 (30.0)	19 (63.3)	15 (50.0)	<0.001
Wheezing	2 (6.7)	7 (23.3)	16 (53.3)	13 (43.3)	<0.001
Breathlessness	2 (6.7)	6 (20.0)	14 (46.7)	11 (36.7)	<0.001
Chest tightness	1 (3.3)	5 (16.7)	13 (43.3)	10 (33.3)	<0.001
Eye irritation	4 (13.3)	12 (40.0)	22 (73.3)	18 (60.0)	<0.001
Nasal irritation	5 (16.7)	11 (36.7)	20 (66.7)	16 (53.3)	<0.001
Physician-diagnosed asthma	1 (3.3)	3 (10.0)	7 (23.3)	5 (16.7)	0.018

3.14 Correlation Between Indoor Air Pollutants, Cooking Duration and Ventilation Characteristics

Indoor particulate matter showed strong positive correlations with carbon monoxide (r = 0.884), total volatile organic compounds (r = 0.821) and cooking duration (r = 0.746). Ventilation status demonstrated significant negative correlations with $PM_{2.5}$ (r = −0.792) and carbon monoxide (r = −0.681), indicating that improved ventilation substantially reduced indoor pollutant concentrations, as shown in Table 3.14.

Table 3.14 Pearson Correlation Matrix

Variable	$PM_{2.5}$	CO	TVOCs	Cooking Duration	Ventilation
$PM_{2.5}$	1.000	0.884	0.821	0.746	-0.792
CO	0.884	1.000	0.774	0.698	-0.681
TVOCs	0.821	0.774	1.000	0.642	-0.624
Cooking Duration	0.746	0.698	0.642	1.000	-0.536
Ventilation	-0.792	-0.681	-0.624	-0.536	1.000

3.15 Multiple Linear Regression Predicting Indoor Air Pollutant Concentrations

Multiple linear regression analysis identified cooking fuel type, ventilation status and cooking duration as significant predictors of indoor $PM_{2.5}$ concentrations. Cooking fuel type exhibited the strongest positive association (β = 0.628, p < 0.001), whereas adequate kitchen ventilation showed a significant negative association (β = −0.382, p < 0.001). Together, the predictor variables explained 74.8% of the variation in indoor $PM_{2.5}$ concentrations (Adjusted R^2 = 0.748) as shown in Table 3.15.

Table 3.15 Multiple Linear Regression Predicting $PM_{2.5}$ Concentrations

Predictor Variable	β Coefficient	Standard Error	t-value	p-value
Cooking fuel type	0.628	0.054	11.62	<0.001
Cooking duration	0.248	0.046	5.39	<0.001
Ventilation status	-0.382	0.058	-6.58	<0.001
Household size	0.116	0.042	2.76	0.007
Constant	12.48	3.86	3.23	0.002

Model Statistics: *R^2 = 0.756; Adjusted R^2 = 0.748; F = 88.64; p < 0.001.*

3.16 Respiratory Health Risk Classification of Households

Respiratory health risk classification demonstrated that households using LPG were predominantly classified as low risk (86.7%), whereas households using firewood recorded the highest proportion of high-risk exposure (70.0%). Charcoal users also demonstrated a high prevalence of elevated respiratory health risk (56.7%), while kerosene users were predominantly classified within the moderate-risk category.

These findings indicate that biomass fuel use was associated with substantially greater respiratory health risks than cleaner cooking fuels, as shown in Table 3.16.

Table 3.16 Respiratory Health Risk Classification According to Cooking Fuel

Cooking Fuel	Low Risk n (%)	Moderate Risk n (%)	High Risk n (%)
LPG	26 (86.7)	4 (13.3)	0 (0.0)
Kerosene	10 (33.3)	16 (53.3)	4 (13.3)
Firewood	1 (3.3)	8 (26.7)	21 (70.0)
Charcoal	3 (10.0)	10 (33.3)	17 (56.7)

4.0 Discussion

The findings of this study demonstrate a consistent relationship between the type of household cooking fuel, characteristics of the cooking environment, indoor concentrations of particulate and gaseous pollutants, estimated exposure and health risks, and the occurrence of respiratory symptoms. Across most measured parameters, LPG households had the most favourable indoor air-quality profile, whereas firewood households recorded the greatest pollution burden, followed generally by charcoal and kerosene households. The consistency of this gradient across environmental measurements and health indicators strengthens the evidence that household cooking practices constitute an important determinant of indoor air quality and respiratory health. Similar associations between polluting cooking fuels and adverse respiratory outcomes have been reported in Nigeria and other low- and middle-income settings [8,9,14,15,22,23].

4.1 Household Characteristics, Cooking Fuel and Exposure Conditions

The household characteristics showed that exposure to cooking-related pollutants occurred within a context in which women and children were particularly important population groups. Women constituted 95.0% of the primary cooks, while children were present during cooking in 53.3% of households. The proportion of households in which children were present during cooking was particularly high among firewood users (76.7%) and charcoal users (66.7%). Household size was also highest among firewood users, with a mean of 6.3 ± 1.8 persons compared with 4.2 ± 1.4 persons among LPG households. Furthermore, mean daily cooking duration increased from 2.0 ± 0.5 hours among LPG users to 3.8 ± 0.9 hours among firewood users.

The predominance of women as primary cooks suggests that women may experience greater cumulative exposure because of their repeated proximity to combustion sources. This observation is consistent with the findings of Sana et al., who reported an association between primary cooking-fuel choice and respiratory health outcomes among women responsible for household cooking [23]. Similarly, stove-intervention research among women and children in rural Nigeria has demonstrated the respiratory-health importance of household air-pollution exposure [16].

The high proportion of children present during cooking is also important because childhood exposure to air pollutants has been associated with acute respiratory infections and other adverse health outcomes [5,11,18,21].

The observed differences in household size and cooking duration across fuel groups may partly reflect socioeconomic variations in household energy choices. Studies in Nigeria have demonstrated that household energy consumption and cooking-fuel selection are influenced by income, household characteristics, fuel prices and affordability [2,10,17,19]. Evidence from Lagos also indicates that household characteristics influence the choice between kerosene and LPG [20]. More broadly, household decision environments can influence fuel-choice behaviour and consequently the likelihood of transitioning from traditional to cleaner energy sources [24]. Therefore, differences in exposure between the fuel groups may reflect both the inherent emission characteristics of the fuels and the socioeconomic circumstances influencing household energy choices.

4.2 Kitchen Characteristics and Ventilation

Kitchen characteristics differed substantially across cooking-fuel categories. Separate kitchens were observed in 83.3% of LPG households compared with 36.7% of firewood households. Indoor cooking was more prevalent among firewood and charcoal households, while functional ventilation was available in 86.7% of LPG households but only 33.3% of firewood households. Poor ventilation was correspondingly highest among firewood households at 66.7%, followed by charcoal households at 56.7%.

These findings have important implications because the concentration of pollutants within a cooking environment is determined not only by the amount generated during combustion but also by the rate at which those pollutants are dispersed or removed. The combination of solid-fuel combustion, indoor cooking and inadequate ventilation can promote the accumulation of particulate matter, carbon monoxide and volatile organic compounds. The present findings are comparable with observations from Rumuewhera Community in Obio-Akpor Local Government Area of Rivers State, where indoor air pollution was identified as an environmental-health concern [8]. The local relevance of that study provides useful contextual support for the present findings. The importance of ventilation was further demonstrated by the correlation analysis. Ventilation was strongly and negatively correlated with $PM_{2.5}$ ($r = -0.792$), CO ($r = -0.681$) and TVOCs ($r = -0.624$). Conversely, cooking duration showed positive correlations with $PM_{2.5}$ ($r = 0.746$), CO ($r = 0.698$) and TVOCs ($r = 0.642$). These relationships indicate that fuel type alone does not determine household exposure. Duration of combustion and the capacity of the kitchen environment to disperse generated pollutants are also important determinants of indoor pollutant concentrations.

4.3 Particulate Matter Concentrations According to Cooking Fuel

A pronounced gradient was observed in particulate matter concentrations across cooking-fuel categories. Mean $PM_{2.5}$ increased from 29.8 ± 7.4 μg/m^3 among LPG households to 82.4 ± 19.6 μg/m^3 among kerosene households, 148.7 ± 34.5 μg/m^3 among charcoal households and 192.6 ± 44.8 μg/m^3 among firewood households. PM_{10} followed a similar pattern, reaching 326.4 ± 68.5 μg/m^3 among firewood users. The differences across fuel categories were statistically significant ($p < 0.001$).

The substantially higher particulate concentrations observed among firewood and charcoal households can be attributed to the greater particulate emissions associated with solid-fuel combustion, particularly where combustion is incomplete. The results are consistent with previous studies associating solid-fuel cooking with increased household air pollution and adverse health outcomes [9,22]. Qiu et al. reported that solid-fuel cooking was associated with increased prevalence of respiratory disease [22], while evidence among children has also demonstrated adverse respiratory outcomes associated with polluting cooking-fuel sources [21].

An important finding was that $PM_{2.5}$ concentrations exceeded the 15 μg/m^3 guideline value used for comparison in all four fuel groups, including LPG households. PM_{10} concentrations similarly exceeded the 45 μg/m^3 comparison value. Nevertheless, the magnitude of exceedance was considerably greater among firewood and charcoal households. The finding that LPG households also recorded particulate concentrations above the comparison values suggests the possible contribution of other indoor and outdoor pollution sources. However, the large differences across fuel categories indicate that cooking-fuel combustion remains a major contributor to household particulate exposure.

4.4 Gaseous Pollutants and Volatile Organic Compounds

The gaseous pollutants demonstrated a pattern similar to that observed for particulate matter. Mean carbon monoxide concentration was highest among firewood households at 19.4 ± 4.8 mg/m^3, followed by charcoal households at 15.1 ± 3.9 mg/m^3, while LPG households recorded only 2.6 ± 0.7 mg/m^3. Significant differences were also observed for nitrogen dioxide and sulphur dioxide across cooking-fuel categories ($p < 0.001$).

The higher carbon monoxide concentrations among firewood and charcoal users are consistent with incomplete combustion of carbon-containing fuels. The potential health significance is increased when such fuels are used indoors for prolonged periods and under poorly ventilated conditions. The present findings therefore provide environmental measurements that complement epidemiological evidence associating polluting cooking fuels with adverse health outcomes [9,14,15,22].

TVOCs also differed substantially according to cooking fuel. Firewood households recorded 584.6 ± 118.2 μg/m^3 compared with 118.4 ± 28.7 μg/m^3 among LPG households. Formaldehyde and benzene demonstrated comparable fuel-related gradients. Benzene concentrations were 13.4 ± 3.2 μg/m^3 among firewood users and 11.2 ± 2.8 μg/m^3 among charcoal users compared with 2.2 ± 0.6 μg/m^3 among LPG users.

The strong positive correlations between $PM_{2.5}$ and CO ($r = 0.884$), $PM_{2.5}$ and TVOCs ($r = 0.821$), and CO and TVOCs ($r = 0.774$) suggest that these contaminants share important combustion-related sources. Consequently, residents are not exposed to individual contaminants in isolation but to mixtures of particulate matter, combustion gases and organic compounds. This cumulative exposure pattern is important when interpreting the potential health consequences of household cooking emissions.

4.5 Exposure and Non-Carcinogenic Health Risk

The exposure assessment demonstrated a progressive increase in inhalation exposure from LPG through kerosene and charcoal to firewood.

Adult exposure concentration increased from 0.024 ± 0.006 mg/m^3 among LPG households to 0.182 ± 0.038 mg/m^3 among firewood households. Among children, corresponding values increased from 0.038 ± 0.008 to 0.268 ± 0.052 mg/m^3. Estimated daily inhalation dose and chronic daily intake followed the same pattern.

Children consistently recorded higher estimated exposure than adults. This finding is important because children represent a potentially vulnerable population, particularly where they remain close to cooking areas. Previous studies have demonstrated associations between air pollution exposure and acute respiratory infection among children in developing countries [11]. Nigerian evidence has also demonstrated the spatial co-occurrence of childhood acute respiratory infection and other adverse health outcomes [18], while cooking-fuel exposure has been associated with respiratory-health effects among children in other settings [21]. The association between solid-fuel use and adverse childhood outcomes reported in Nigeria further supports concern about exposure among younger household members [5].

The Hazard Index showed a similarly marked fuel-related pattern. Adult and child HI values for LPG were 0.62 ± 0.14 and 0.84 ± 0.18, respectively. In contrast, firewood households recorded values of 2.84 ± 0.46 among adults and 4.26 ± 0.62 among children. Charcoal households also recorded elevated values of 2.08 ± 0.38 and 3.12 ± 0.48 among adults and children, respectively. These results suggest a greater potential for cumulative non-carcinogenic health effects among households using biomass fuels, with children showing the greatest estimated risk.

The use of exposure and risk indices in the present study is consistent with the broader environmental-health risk-assessment approach applied in Nigerian studies. Previous investigations have translated environmental contaminant concentrations into estimates of potential health consequences for atmospheric deposition of soot and heavy metals [1], petroleum hydrocarbons and heavy metals in surface water [6], heavy metals in agricultural soils [7], and bioaccumulated contaminants in fish and other environmental media [12,25]. Although these studies examined different environmental media and exposure pathways, they demonstrate the importance of complementing concentration measurements with exposure and toxicological-risk assessment.

4.6 Carcinogenic Health Risk

The incremental lifetime cancer risk estimates demonstrated a progressive increase according to cooking-fuel type. Adult ILCR increased from 4.26×10^{-7} among LPG users to 2.84×10^{-5} among firewood users, while child ILCR increased from 7.82×10^{-7} to 4.18×10^{-5} across the same fuel categories. Firewood and charcoal were consequently classified as presenting elevated carcinogenic risk under the criteria applied in this study, whereas LPG was classified as presenting negligible risk.

The pattern is supported by the measured concentrations of benzene and formaldehyde, which were considerably higher among households using solid fuels. The finding suggests that the implications of household cooking emissions may extend beyond acute respiratory symptoms to possible long-term toxicological consequences where exposure is sustained.

Previous Nigerian environmental-health studies have similarly demonstrated the importance of assessing long-term risks associated with exposure to potentially toxic organic contaminants. Health-risk assessments of PAHs in smoked and dried fish have identified the importance of evaluating contaminant exposure beyond simple concentration measurements [3]. Comparative assessment of PAHs in processed Nile tilapia has similarly employed a toxicological-risk perspective [4], while combined assessments of heavy metals and PAHs in estuarine fish have demonstrated the relevance of evaluating cumulative environmental exposure [25]. Although these studies assessed dietary rather than inhalational exposure, they support the broader toxicological principle applied in the present study that persistent exposure to potentially hazardous contaminants requires long-term health-risk evaluation.

4.7 Respiratory Symptoms According to Cooking Fuel

The distribution of respiratory symptoms showed a strong relationship with cooking-fuel category. Chronic cough was reported in 63.3% of firewood households and 50.0% of charcoal households compared with 10.0% of LPG households. Wheezing occurred in 53.3% of firewood households compared with 6.7% of LPG households, while breathlessness occurred in 46.7% and 6.7%, respectively. Eye irritation was reported in 73.3% of firewood households compared with 13.3% of LPG households. The differences were statistically significant ($p < 0.001$).

Physician-diagnosed asthma was also more prevalent among firewood users (23.3%) than LPG users (3.3%), and the difference across fuel categories was statistically significant ($p = 0.018$). The consistency between measured environmental pollutant concentrations and reported symptoms strengthens the interpretation that households with greater exposure also experienced a greater respiratory-health burden.

The findings agree with recent Nigerian evidence demonstrating an association between household cooking-fuel choices and respiratory health [15]. They are also consistent with systematic-review evidence linking cooking-fuel use with non-communicable disease outcomes [14] and with findings that solid-fuel cooking is associated with increased respiratory disease prevalence [22]. Among women responsible for cooking, the type of primary cooking fuel has similarly been associated with respiratory outcomes [23].

The findings are also supported by intervention evidence from Nigeria. Oluwole et al. demonstrated that interventions aimed at reducing household stove emissions had implications for household air pollution and respiratory health among women and children [16]. Furthermore, chronic obstructive pulmonary disease has been documented among never-smokers in Nigeria [13], suggesting that environmental exposures other than cigarette smoking may contribute to chronic respiratory morbidity. Taken together, these studies provide a plausible epidemiological context for the substantially higher respiratory symptom burden observed among firewood and charcoal users.

4.8 Predictors of Indoor $PM_{2.5}$ Concentrations

Multiple regression analysis identified cooking-fuel type as the strongest positive predictor of indoor $PM_{2.5}$ concentration ($\beta = 0.628$, $p < 0.001$). Cooking duration was also independently associated with increased $PM_{2.5}$ ($\beta = 0.248$, $p < 0.001$), whereas ventilation demonstrated an independent protective association ($\beta = -0.382$, $p < 0.001$). Household size also contributed significantly ($\beta = 0.116$, $p = 0.007$). Together, these factors explained 75.6% of the variance in indoor $PM_{2.5}$ concentrations, with an adjusted R^2 of 0.748 and a statistically significant overall model ($F = 88.64$, $p < 0.001$).

The magnitude of the cooking-fuel coefficient indicates that fuel transition could represent an important strategy for reducing household particulate exposure. However, the significant independent association with ventilation demonstrates that modifications to the cooking environment may provide additional benefits. Similarly, the positive association with cooking duration suggests that the length of time during which combustion occurs contributes meaningfully to household pollutant concentrations.

The findings should also be considered within the context of household energy behaviour. Nigerian studies have shown that fuel selection depends on household income, energy demand, fuel cost and other socioeconomic considerations [2,10,17,19]. The choice between LPG and kerosene has likewise been associated with household-level characteristics [20], while household decision environments can influence the transition between traditional and cleaner fuels [24]. Consequently, interventions seeking to reduce $PM_{2.5}$ exposure should combine environmental-health education with policies that improve the affordability, accessibility and sustained use of cleaner cooking fuels.

4.9 Overall Respiratory Health Risk Classification

The overall respiratory-health risk classification provided a synthesis of the environmental exposure and health findings. Among LPG households, 86.7% were classified as low risk, and none was classified as high risk. In contrast, 70.0% of firewood households and 56.7% of charcoal households were classified as high risk. Kerosene households occupied an intermediate position, with 53.3% classified as moderate risk.

This classification corresponds closely with the pollutant measurements, exposure indices and symptom distribution. Firewood households simultaneously had longer cooking duration, poorer ventilation, greater presence of children during cooking, higher concentrations of $PM_{2.5}$, PM_{10}, CO and TVOCs, greater non-carcinogenic and carcinogenic risk estimates, and a higher prevalence of respiratory symptoms. Charcoal households generally ranked second in overall exposure and risk, whereas LPG households consistently recorded the lowest values.

This overall pattern agrees with studies showing that solid-fuel use is associated with adverse respiratory and other health outcomes [9,14,15,22,23]. However, household transition toward cleaner fuels cannot be considered solely a matter of individual preference. Nigerian evidence indicates that cooking-fuel choices are influenced by socioeconomic circumstances, energy costs, household characteristics and accessibility [2,10,17,19,20]. Household decision-making conditions can further determine whether cleaner fuels are adopted and continuously used [24]. Therefore, sustainable reductions in household air pollution will require interventions that address both the environmental hazards of polluting fuels and the socioeconomic barriers preventing cleaner-energy adoption.

Conclusion

The present study demonstrated that household cooking fuel significantly influenced indoor air quality and the magnitude of respiratory health risks among residents of selected communities in Rivers State, Nigeria. Households using firewood and charcoal consistently recorded the highest concentrations of particulate matter, gaseous pollutants and volatile organic compounds, whereas households using liquefied petroleum gas exhibited the lowest pollutant levels. Exposure assessment further revealed that children experienced higher inhalation doses, chronic daily intake and cumulative non-carcinogenic risks than adults, highlighting their increased vulnerability to indoor air pollution. Biomass fuel users also exhibited the highest prevalence of respiratory symptoms, including chronic cough, wheezing, breathlessness and eye irritation, confirming the adverse health effects associated with prolonged exposure to indoor combustion products.

Health risk assessment indicated that the cumulative Hazard Index exceeded the acceptable threshold among households using firewood and charcoal, suggesting the potential for adverse non-carcinogenic respiratory effects. Incremental lifetime cancer risk values associated with benzene and formaldehyde exposure were highest among biomass fuel users, although values for households using liquefied petroleum gas remained within negligible risk levels. Furthermore, cooking fuel type, cooking duration and kitchen ventilation were identified as significant predictors of indoor pollutant concentrations, emphasising the critical role of household energy choices and ventilation practices in determining indoor environmental quality.

References

1. Aghanwa, C. I., Umueni, U. E., Etukudo, N. J., Amachree, J. B., Okpoji, A. U., Ejeka, C. J., & Ekwere, I. O. (2025). Atmospheric deposition of soot and heavy metals from gas flaring into surface waters of Ebocha, Rivers State, Nigeria. Asian Journal of Environment & Ecology, 24(11), 137–147. https://doi.org/10.9734/ajee/2025/v24i11822
2. Bamiro, O., & Ogunjobi, J. (2015). Determinants of household energy consumption in Nigeria: Evidence from Ogun State. Research Journal of Social Sciences and Management, 4(12), 35–41.
3. Ekpe, J. E., Akpan, E. O., Ekwere, I. O., Okpoji, A. U., Edodi, I. O., Ogbaji, H. O., Ewuola, A. A., Aningo, G. N., & Ogbonnaya, C. N. (2025). Health risk implications of polycyclic aromatic hydrocarbons in smoked and dried fish consumed in Nigeria. Journal of Medical Science, Biology, and Chemistry, 2(2), 192–199. https://doi.org/10.69739/jmsbc.v2i2.1045
4. Ekwere, I. O., Okpoji, A. U., Igwegbe, K. C., Okonkwo, C. O., Yekeen, A. A., Obunezi, O. C., Okpanachi, C. B., Garuba, M. H., Ogini, O. R., & Odibo, U. E. (2025). Nutritional–toxicological trade-off: Comparative study of polycyclic aromatic hydrocarbons in smoked and oven-dried Nile tilapia (Oreochromis niloticus). Journal of Environment, Climate, and Ecology, 2(2), 90–97. https://doi.org/10.69739/jece.v2i2.952
5. Ezeh, O., Agho, K., Dibley, M., Hall, J., & Page, A. (2014). The effect of solid fuel use on childhood mortality in Nigeria: Evidence from the 2013 cross-sectional household survey. Environmental Health, 13(1), 1–10.
6. Isueken, C. O., Asemota, P. O., Isaac, S. C., Okpoji, A. U., Nwankwo, A. O., Akpan, N. A., Ekwere, I. O., Etesin, M. U., & Alieze, A. B. (2025). Assessment of petroleum hydrocarbon fractions and heavy metal contamination in surface water of Ogboinbiri Creek, Southern Ijaw, Bayelsa State, Nigeria. Scientific Journal of Engineering and Technology, 2(2), 172–179. https://doi.org/10.69739/sjet.v2i2.1308
7. Izuchukwu, E. C., Akpan, N. A., Igwegbe, K. C., Okpoji, A. U., Ezeabasili, P. I., Obi, J. N., & Anarah, S. E. (2026). Environmental and toxicological risk assessment of heavy metals in Eleme agricultural soils. Asian Journal of Agricultural and Horticultural Research, 13(1), 67–81. https://doi.org/10.9734/ajahr/2026/v13i1436

8. Kanu, O. P., & Leton, T. G. (2022). Indoor air pollution in Rumuewhera Community in Obio-Akpor Local Government Area of Rivers State, Nigeria. Journal of Engineering Research and Reports, 22(8), 62–79. https://doi.org/10.9734/jerr/2022/v22i817555
9. Liu, Z., Li, J., Rommel, J., & Feng, S. (2020). Health impacts of cooking fuel choice in rural China. Energy Economics, 89, 104811. https://doi.org/10.1016/j.eneco.2020.104811
10. Megbowon, E., Mukarumbwa, P., Ojo, S., & Olalekan, O. (2018). Household cooking energy situation in Nigeria: Insight from Nigeria Malaria Indicator Survey 2015. International Journal of Energy Economics and Policy, 8(6), 284–291.
11. Odo, D., Yang, I., Dey, S., Hammer, M., van Donkelaar, A., Martin, R., et al. (2022). Ambient air pollution and acute respiratory infection in children aged under 5 years living in 35 developing countries. Environment International, 159, 107019. https://doi.org/10.1016/j.envint.2022.107019
12. Ohaturuonye, S. O., Ekwere, I. O., Ekesiobi, S. U., Robinson, B. E., Okpoji, A. U., Osuagwu, E. L., & Okpanachi, C. B. (2026). Comparative heavy metal bioaccumulation and human health risk assessment of farmed and river-caught catfish in Rivers State, Nigeria. Asian Journal of Research in Zoology, 9(1), 62–74. https://doi.org/10.9734/ajriz/2026/v9i1243
13. Ojuawo, O., Aladesanmi, A., Opeyemi, C., Desalu, O., Fawibe, A., & Salami, A. (2019). Profile of patients with chronic obstructive pulmonary disease in Ilorin who were never-smokers. Nigerian Journal of Clinical Practice, 22(2), 221–231.
14. Olagunju, M. T., Abodunrin, O. R., Ola, O. M., Olagunju, I. O., Diawara, M. O., & Yakubu, S. (2024). Cooking fuel use and non-communicable diseases: A systematic review and meta-analysis. International Journal of Noncommunicable Diseases, 9(3), 109–119.
15. Olasehinde, N., Ajayi, P., & Oloyede, O. (2026). Cooking fuel choices and household respiratory health in Nigeria. BMC Public Health, 26, 265. https://doi.org/10.1186/s12889-025-25896-y
16. Oluwole, O., Tanko, A., Ana, G., Wiskel, T., Huo, D., & Arinola, G. (2013). Effect of stove intervention on household air pollution and the respiratory health of women and children in rural Nigeria. Air Quality, Atmosphere & Health, 6(3), 553–561.
17. Orji, A., Ogwu, S. O., Mba, P. N., & Orji, O. I. A. (2021). Energy demand and cooking energy cost in an oil-rich economy: New evidence from Nigeria. Studia Universitatis Vasile Goldiș Arad, Seria Științe Economice, 31(1), 1–21.
18. Orunmoluyi, O., Gayawan, E., & Manda, S. (2022). Spatial co-morbidity of childhood acute respiratory infection, diarrhoea and stunting in Nigeria. International Journal of Environmental Research and Public Health, 19(3), 1838.
19. Oyeniran, I. W., & Isola, W. A. (2023). Patterns and determinants of household cooking fuel choice in Nigeria. Energy, 278, 127753.
20. Ozoh, O. B., Okwor, T. J., Adetona, O., Akinkugbe, A. O., Amadi, C. E., & Esezobor, C. (2018). Cooking fuels in Lagos, Nigeria: Factors associated with household choice of kerosene or liquefied petroleum gas (LPG). International Journal of Environmental Research and Public Health, 15(4), 641.
21. Patel, S., Patel, S., & Kumar, A. (2019). Effects of cooking fuel sources on the respiratory health of children: Evidence from the Annual Health Survey, Uttar Pradesh, India. Public Health, 169, 59–68.
22. Qiu, X., Jin, J., He, R., & Zhang, C. (2023). Do solid fuels for cooking lead to an increased prevalence of respiratory disease? Empirical evidence from rural China. Energy for Sustainable Development, 74, 297–308. https://doi.org/10.1016/j.esd.2023.02.001
23. Sana, A., Meda, N., Badoum, G., Kafando, B., & Bouland, C. (2019). Primary cooking fuel choice and respiratory health outcomes among women in charge of household cooking in Ouagadougou, Burkina Faso: A cross-sectional study. International Journal of Environmental Research and Public Health, 16(6), 1040.
24. Van der Kroon, B., Brouwer, R., & Van Beukering, P. J. H. (2014). The impact of the household decision environment on fuel choice behaviour. Energy Economics, 44, 236–247.
25. Okpoji, A. U., Akpan, N. A., Eze, V. C., Ijioma, C. C., Hassan, D. H., Kareem, M. M., Obi, A. I., Aningo, G. N., Okoye, P. I., Ogbonnaya, C. N., Ekwere, I. O., Okeke, C. F., & Aligwo, M. C. (2025). Toxicity and bioaccumulation of heavy metals and polycyclic aromatic hydrocarbons in estuarine fish from the Andoni Estuary, Niger Delta, Nigeria. Journal of Applied Physical Science International, 17(2), 10–22. https://doi.org/10.56557/japsi/2025/v17i210026