Research article

Urban kitchens under siege: The silent toll of charcoal and firewood on indoor air in Tanzania

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Abstract

This study evaluated indoor air pollution in urban Tanzanian kitchens reliant on solid biomass fuels (SBF), focusing on pollutant concentrations and structural determinants. Using a cross-sectional design in Morogoro Municipality (n=153 kitchens), real-time measurements of suspended particulate matter ($PM_{2.5}$, PM_{10}), carbon monoxide (CO), relative humidity, and temperature were conducted alongside assessments of kitchen size, wall material, ventilation, and location during the end of the rainy season (April–May 2024) to minimize temporal variability and isolate pollutants from cooking activities.

During cooking periods, $PM_{2.5}$ 24-h TWA concentrations had a median of 30.9 µg/m^3 (8.8–121.9 µg/m^3), with 63% of kitchens exceeding the WHO guideline, PM_{10} were below WHO and TBS limits but exceeded guideline values in 12% of kitchens. 30% of kitchens had relative humidity ≥60%, 75% exceeded thermal comfort limits, and CO concentration in all kitchens surpassed WHO/TBS 1-h guidelines (60 ppm > 2-fold higher vs. 26 ppm 1-h; all $p<0.001$), with some kitchens recording levels up to ten-fold higher, indicating a substantial risk of acute exposure. Kitchens situated within dwelling houses had higher $PM_{2.5}$ (251 vs. 235 µg/m^3) and PM_{10} (269 vs 237µg/m^3) than detached ($p<0.05$); block-brick walls were hotter (35±4 °C) and drier (33±10%) than mud walls ($p<0.05$). $PM_{2.5}$ and PM_{10} correlated strongly ($r=0.921$, $p<0.001$), signaling combustion co-exposure.

These findings reveal hazardous pollution levels elevating respiratory/cardiovascular risks, especially for women/children, driven by SBF and poor kitchen design. Interventions should promote cleaner fuels, efficient stoves, and ventilation per Tanzania's Clean Cooking Strategy (2024-2034). Longitudinal seasonal studies are needed to refine exposure estimates and inform sustainable policy intervention strategies.

Keywords

Clean energy, health risks, indoor pollutants, traditional kitchens, traditional cooking fuels

Introduction

The use of solid biomass fuels (SBF) for cooking has been a longstanding practice, serving as the primary energy source in many households in developing countries. Despite urbanization and the availability of alternative cooking fuels like liquefied petroleum gas (LPG), electric cookers, and solar cookers, a substantial number of developing countries continue to rely heavily on SBF (Landrigan et al., 2018). Approximately 3 billion people globally depend on solid biomass, including wood, charcoal, crop residues, dung cakes, and coal, for cooking and household heating (WHO, 2018). Indoor air pollution is particularly prevalent in rural areas where SBF is widely used due to its accessibility and affordability (Begum et al., 2009). National survey data indicate that firewood continues to dominate as the primary cooking fuel in rural Tanzania (~ 88%), while urban households rely more on charcoal (~ 69%) and have modest uptake of liquefied petroleum gas (LPG) ~ 46% and electricity (~3%) (NBS, 2023; Clean Cooking Alliance, 2024). Despite national policies promoting clean cooking, fewer than 10% of Tanzanian households currently use clean cooking fuels and technologies, with stark rural–urban disparities (Ndifwa et al., 2025; Clean Cooking Alliance, 2024). These patterns help explain why indoor air pollution exposures remain high across both rural and urban households, particularly affecting women and children who spend prolonged periods near cooking areas.

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The combustion of SBF in kitchens poses significant environmental and public health challenges worldwide. The burning process releases pollutants including carbon monoxide (CO), particulate matter (PM), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs) (Wernecke et al., 2015; Majdan et al., 2015; Agbo et al., 2021). These pollutants are mainly emitted due to incomplete combustion of dirty fuels and the use of inefficient technologies commonly found in many African kitchens (Masondo et al., 2016; Nkosi et al., 2018; San Jose et al., 2021; Pauw et al., 2022), where households often cannot afford improved stoves or proper ventilation and air purification systems (Uribe et al., 2023; URT., 2024).

Exposure to these pollutants is linked to various adverse health outcomes, including respiratory and cardiovascular diseases, allergic reactions, cancers, stillbirths, and premature mortality (Fullerton et al., 2009; De Juniac et al 2012; Kurt et al., 2016). In poorly ventilated homes, indoor airborne particle levels can be hundreds of times higher than those found outdoors (Fullerton et al., 2008). The global reliance on SBF is estimated to cause over 3.5 million premature deaths annually, with approximately 1 million fatalities linked to acute respiratory infections in young children (Lim et al., 2012; Murray et al., 2022). These deaths predominantly occur in low-resource settings where pollutant exposure is compounded by elevated environmental pathogens and limited healthcare access (Polsky et al., 2012). Pollutant accumulation during routine household activities such as cooking and cleaning continues to pose significant health risks, particularly for women and children, who spend prolonged periods near cooking areas (Kuye et al., 2023; WHO, 2024a). Recent estimates from Bennitt et al., (2025) indicate that household air pollution contributes approximately 250,000 disability-adjusted life years (DALYs) annually in Tanzania, with the burden disproportionately affecting women and young children Epidemiological evidence from South Africa has consistently linked exposure to household air pollution with adverse respiratory outcomes, including chronic respiratory symptoms and impaired lung function among women and children (Röllin, 2017; Shezi et al., 2018). Similar associations have been reported across sub-Saharan Africa, with studies from Kenya, Ethiopia, and Nigeria documenting increased risks of acute respiratory infections, chronic cough, asthma-like symptoms, and reduced lung function among women and children exposed to biomass fuel smoke during cooking (Bickton et al., 2020; Joseph et al., 2026; WHO, 2024a).

Building characteristics play a critical role in determining the levels of indoor air pollutants, particularly in kitchens where solid biomass fuels are used. Architectural features such as ventilation, building materials, kitchen location, and the presence of openings like windows and doors significantly influence the entrainment and infiltration of pollutants (Baeza-Romero et al., 2022; Nibagwire et al., 2025). Poor ventilation and airtight construction can trap pollutants indoors, leading to elevated exposures, whereas adequate natural ventilation promotes pollutant dispersion and lowers concentrations (Baeza-Romero et al., 2022; Bhagat et al., 2024). Additionally, kitchen designs, such as detached kitchens or improved airflow layouts, reduce pollutant migration into living spaces, mitigating health risks associated with chronic exposure (Nibagwire et al., 2025). These factors highlight the importance of integrating building design interventions alongside cleaner cooking technologies to effectively improve indoor air quality and health outcomes in vulnerable populations.

This study employs a mixed-methods design to evaluate kitchen air pollution exposure and its determinants. Real-time measurements of indoor air pollutants during cooking are used to reveal concentration patterns and variability across kitchens. Detailed assessments of kitchen structure and building features identify factors influencing pollutant levels, while statistical analyses quantify the relationships between these structural characteristics and air quality, comparing observed concentrations with established health standards. The findings provide valuable insights for policies and regulations promoting clean energy use to safeguard both the environment and public health in Tanzania and other low-income countries.

Materials and methods

Study area

This study was conducted in Morogoro Municipality, situated 195 kilometers west of Dar es Salaam in eastern Tanzania. The municipality lies between 5° and 7° south latitude and 37° and 38° east longitude. Administratively, it is divided into 29 wards, among which Mafisa and Mafiga wards were purposively selected for this study (Figure 1).

Morogoro experiences a tropical climate characterized by warm temperatures and distinct wet and dry seasons. Average monthly temperatures range from approximately 22 °C in cooler months (July and August) to about 26 °C in the warmest months (January and February) (Climate-Data.org, 2021). Rainfall peaks from March through April, with March typically seeing the highest precipitation, around 220 mm, while the dry season spans from June to August with significantly reduced rainfall (TMA., 2024). The climatic conditions have implications for indoor air quality, as the end of the rainy season generally coincides with reduced ambient particulate levels (Emekwuru et al., 2023), allowing for clearer assessment of pollutants directly linked to biomass fuel combustion indoors.

According to the Tanzania Population and Housing Census report of 2022, the dwelling patterns in the surveyed wards reflect a mix of traditional and modern housing types, comprising both planned residential zones and informal neighborhood pockets (squatters) (URT., 2022). Predominantly, households live in single-story buildings constructed with local materials such as block bricks, mud, and concrete. Roofing materials include corrugated iron sheets or thatch in less formal settlements (URT., 2022). These mixed settlement patterns, characterized by varying building density, ventilation, and infrastructure quality,

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influence local air dispersion and pollutant accumulation. The wards were therefore purposively selected to represent the diversity of urban housing conditions and their implications for indoor air quality in Tanzania.

As of 2022, the Morogoro Municipal Council reported a population of approximately 471,409, a notable increase from 315,866 in 2012, reflecting an annual urban growth rate of 4.21% (URT., 2022). The community relies on both formal and informal activities for their livelihoods, engaging in various economic pursuits such as administrative work, casual labor, industrial jobs, cloth and food vending, and agricultural production, all contributing to income generation.

Kitchen surveys and air quality data

A total of 180 households were approached for participation in this study, with 153 households, primarily relying on charcoal and firewood as their main fuel sources, agreeing to take part. The kitchens were selected using convenience sampling, which was biased towards accessible and diverse SBF users while purposive ward-level diversity mitigated selection effects. Data collection was consistently conducted between April and May 2024, at the end of the rainy season, to reduce temporal variability. This timing is significant, as particulate matter levels are generally lower at the end of the rainy season compared to the dry season, enhancing the accuracy of capturing air pollution levels associated with the fuels used in kitchens and not the general ambient sources. Efforts were made to include both private and communal kitchens used by the population during the study period. Pre-determined kitchen characteristics were systematically observed using a structured checklist designed to capture key physical and environmental characteristics relevant to indoor air quality. Direct visual inspections of each kitchen were done while recording parameters such as kitchen size, construction materials (walls, roof, floor), ventilation features (presence and status of windows and doors during cooking), and the use of SBF. Observations were standardized across households following a pre-established protocol to ensure consistency and accuracy. The features included those typically dependent on SBF, enclosed walls and roof, in-house kitchens, and one without secondary ventilation systems for air circulation in the kitchen. The study employed portable, low-cost air quality monitors, which are widely used in household air pollution studies in low- and middle-income settings.

Kitchen air temperature (°C), relative humidity (in %), and suspended particulate matter ($PM_{2.5}$ and PM_{10}) in µg/m^3, were measured using a portable handheld Air Quality Detector (VSON WP6930S) monitor, an integrated air quality monitor capable of simultaneously measuring $PM_{2.5}$ / PM_{10} ±15%, 1 µg/m^3 LOD, (range 1–999 µg/m^3), temperature (1-50°C), and relative humidity (20-90% RH). Thus, it is the same device used to

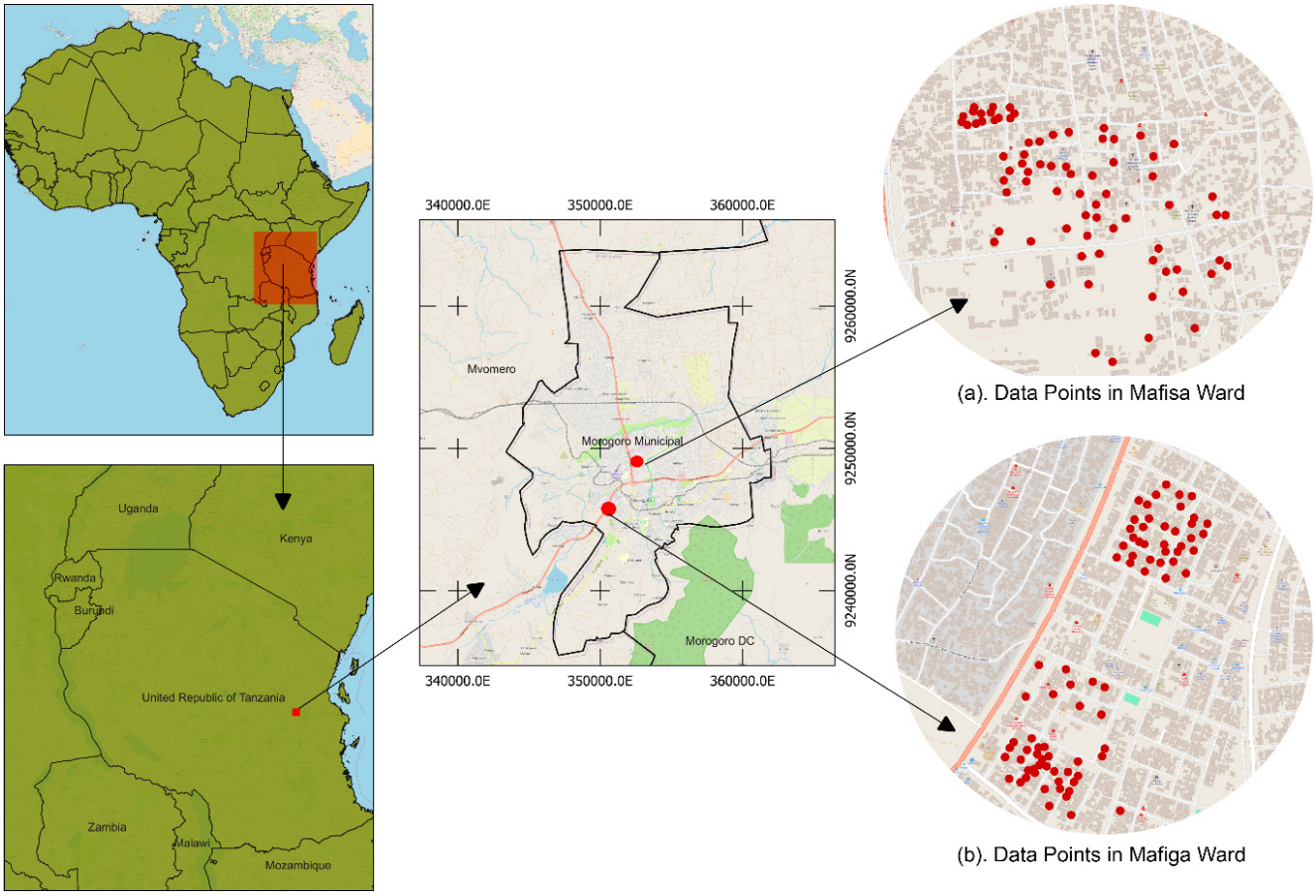


Figure 1: *A map of Morogoro Municipality, Tanzania, showing the sampling points*

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monitor PM, temperature, and humidity concurrently during the kitchen sampling. For kitchens with elevated temperatures (> 50 °C), a portable handheld Multi Gas Detector (Gas Sensing BH-4S model, with an operating (working) temperature range of −20°C to + 50°C and detection ranges of CO up to 1000 ppm (± 5 ppm), and O_2 up to 30% vol, was utilized to measure such elevated temperatures and concentrations of carbon monoxide and carbon dioxide during active cooking periods. Although these instruments do not provide the same precision as reference-grade monitors, previous manufacturer's validation studies have demonstrated acceptable performance for assessing relative exposure levels in indoor environments.

Measuring protocols

Data were collected with the kitchen owners present, who provided verbal consent for measurements to be taken. Both instruments were pre-calibrated by the manufacturers before deployment to ensure measurement accuracy. For each kitchen, triplicate readings were taken at standardized locations within the kitchen area to ensure uniformity. Sampling points were selected approximately 1.2 to 1.5 meters above the floor, representing a typical breathing zone adapted dynamically to the kitchen user's position and size of the kitchen, avoiding direct emission sources such as stoves and ventilation openings to ensure representative measurement of inhalation exposure. This protocol was consistently applied across all kitchens to facilitate comparability. All measurements followed the respective device pre-calibrated protocols and manufacturer use guidelines for reliable data collection. To ensure a representative assessment of kitchen air quality, each household was visited once. For each kitchen, triplicate readings were recorded at three defined stages of cooking: the start of burning (within 5-10 minutes after ignition), the middle (around 50% of total cooking time, during active simmering/boiling), and the end of cooking cessation (5-10 minutes when fire smolders and vessels are removed), resulting in 459 readings of the five measured parameters ($PM_{2.5}$, PM_{10}, CO, temperature, and relative humidity) taken in each of the 153 kitchens during the beginning, middle, and end of cooking. All measurements followed standardized indoor air monitoring protocols consistent with the Tanzanian Bureau of Standards (Tanzania Bureau of Standards., 2005) and the World Health Organization (WHO., 2021) guidelines. The triplicate readings were averaged to provide an overall on site exposure to kitchen users. Over two-thirds of the readings were obtained during peak kitchen activities using SBF, defined as active cooking periods typically occurring between 1100 hours to1400 hours and 1700 hours to 1900 hours, consistent with local meal preparation practices. All kitchen measurements were conducted during the same study period at the end of the rainy season (from early April to mid-May 2024) spanning for approximately 40 days. Data collection was conducted by a trained field team consisting of 4 personnel, each responsible for operating the monitoring equipment and recording observational data under a standardized protocol to ensure consistency across households. The gathered data were subsequently imported into Microsoft Excel for cleaning and tabulation. Data cleaning involved importing the raw readings into Microsoft Excel, where outliers and inconsistent entries were reviewed and corrected before analysis.

Statistical analysis

Measured indoor air-quality parameters ($PM_{2.5}$, PM_{10}, carbon monoxide, temperature, and humidity) from 153 households were entered into Excel and subsequently cleaned to remove entry errors and ensure consistency in units. Descriptive statistical analyses were conducted to summarize the distribution of each parameter. Because the data were not normally distributed, distribution-robust summary statistics were used. These included the median, range (minimum–maximum), 25th percentile (Q1), 75th percentile (Q3), and interquartile range (IQR = Q3 − Q1). Measures of central tendency (mean) and variability (standard deviation) were also generated but were not used for primary interpretation due to skewed distributions. The measured concentrations were then benchmarked against international and national guideline values. The WHO Air Quality Guidelines (2021) were used for particulate matter and carbon monoxide, while the Tanzania Ambient Air Quality Standards (GN 237:2007) and TBS 2005 provided additional threshold values for PM and CO. Since no indoor household standards exist in Tanzania, WHO guidelines were considered the primary reference point. Carbon monoxide concentrations were compared to the WHO and TBS short-term exposure limit of 26 ppm (1-hour averaging time) because household cooking typically occurs over short time intervals. Particulate matter concentrations were compared to the WHO 24-hour time-weighted average (TWA), as these are the closest applicable standards for indoor exposure. A compliance assessment was not conducted; instead, a threshold-based remarks approach was applied, indicating whether concentrations were within or above the guideline values.

To evaluate the relationship between kitchen characteristics such as kitchen type, construction materials, and space configuration, and indoor air quality parameters when using SBF, a non-parametric Mann–Whitney U test was used. Indoor air parameters ($PM_{2.5}$, PM_{10}, relative humidity, temperature and CO) levels across multiple kitchen characteristic categories (e.g., kitchen size, location, walling materials, and ventilation) were compared using the non-parametric Kruskal–Wallis test, followed by Dunn's multiple comparison test for pairwise differences, because the data were not normally distributed. Pearson correlation analysis was conducted to assess linear relationships between averaged continuous indoor measured air quality parameter levels ($PM_{2.5}$, PM_{10}, CO, temperature, and relative humidity), measured in each kitchen during three standardized cooking phases (start, middle, and end) over the monitoring period. Kitchen characteristics assessed included continuous variables (size) and categorical variables (location, walling materials, and ventilation status), which were coded as binary variables where applicable. Assumptions of normality and linearity were tested prior to analysis. All statistical analyses and graphical representations were performed using the GraphPad Prism 5 statistical software package (GraphPad Software, San Diego, CA, USA), with significance set at $p < 0.05$.

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Results

Kitchen characteristics

Table 1 shows that the majority of households (81%, n = 124) primarily used charcoal as their solid biomass fuel, while 19% (n = 29) relied on a combination of charcoal and firewood for cooking. None of the surveyed households used other biomass sources, such as crop residues or animal dung, for kitchen activities. Most kitchens (88%, n = 135) were constructed with block brick walls, while a small number (12%, n = 18) were made from mud. None of the kitchens were built using stones, bamboo, or thatch as construction materials. In terms of size, over half of the surveyed households (52%, n = 80) had relatively large kitchens measuring approximately over 12 square meters, while 42% (n = 65) had small to medium -sized kitchens measuring between 4 to 12 square meters. Regarding kitchen location, 53% (n = 81) of the kitchens were situated inside the main house, while 47% (n = 72) were detached from the main house (Table 1). This study found that flooring varied among the kitchens, with 53% (n = 81) having concrete cement floors and 47% (n = 72) having mud floors. No kitchens had stone or wooden floors. In terms of ventilation, over 72% (n = 110) of the kitchens had windows open during cooking, while 24% (n = 36) did not utilize windows for ventilation. Regarding door usage, 82% (n = 126) of the kitchens had their doors open during cooking sessions, whereas 18% (n = 27) kept their doors closed during the cooking period (Table 1).

Table 1: *Kitchen characteristics of the surveyed households (n = 153)*

Variables	Percentage (Frequency)
Solid biomass fuel used	
Charcoal	81% (n = 124)
Charcoal and firewood	19% (n = 29)
Walling materials of the kitchen	
Block	88.24% (n=135)
Mud	11.76% (n= 18)
Stone	0% (n= 0)
Bamboo	0% (n= 0)
Thatch	0% (n= 0)
Kitchen size (in sqm)	
Small (4 to 8)	52.28 % (n= 80)
Medium (8 to 12)	42.48% (n= 65)
Large (over 12)	5.22% (n= 8)
Location of the kitchen	
Detached from the main house (Outside)	47.05% (n= 72)
Part of the main house (Inside)	52.95% (n= 81)
Kitchen floor	
Mud	47.05% (n= 72)
Stone	0% (n= 0)
Cement	52.95% (n= 81)
Wooden	0% (n= 0)
Open windows during cooking	
Open window	71.90% (n=110)
Closed window	23.53% (n=36)
Not present	4.57% (n=7)
Status of the doors during cooking	
Open door	82.35% (n=126)
Closed door	17.64% (n=27)

The trends of the measured kitchen air quality parameters

Based on the averaged triplicate readings from 153 households assessed, Table 2 presents the summary of the measured concentrations of $PM_{2.5}$, PM_{10}, humidity, temperature, and carbon monoxide, along with their distributional statistics and applicable guideline thresholds.

Although NO_x, SO_2, and VOCs are relevant indoor pollutants, they were not detected by the instrument used in this study. Therefore, the study focused only on the detected pollutants across the kitchens, which are well-established indicators of biomass-related indoor air pollution with significant health relevance to ensure reliable and actionable results.

Indoor air quality across kitchen structural designs, locations and ventilation

Suspended particulate matter

Figure 2 shows slightly higher median $PM_{2.5}$ and PM_{10} in mud-walled kitchens (n=18) than block-walled (n=135), but extensive IQR overlap and no significant differences (Mann-Whitney U: $PM_{2.5}$, p=0.344; PM_{10}, p=0.827). Both wall types exhibited widespread exceedances: 97% of kitchens (85 block, 12 mud) surpassed WHO 24-h $PM_{2.5}$ limit (15 µg/m^3; up to 4-fold higher (Table 2). Although the median 24-hr TWA for PM_{10} concentration was below both WHO and TBS guideline limits, upper percentile values approached or exceeded the WHO threshold, and 18% of 153 surveyed kitchens (block = 14, mud = 4) recorded cooking-period PM_{10} concentrations up to two-fold above TBS guideline values.

$PM_{2.5}$ and PM_{10} concentrations did not differ significantly by kitchen location (inside-within dwelling house n=81 vs. detached n = 72), as determined using non-parametric tests appropriate for skewed data (Kruskal-Wallis p = 0.807; Dunn's post hoc comparisons: all p > 0.05). Although kitchens located within dwelling houses showed slightly higher median concentrations ($PM_{2.5}$: 251 vs. 235 µg/m^3; PM_{10}: 269 vs. 237 µg/m^3) these differences were not statistically significant. Concentration distributions exhibited substantial overlap, with median values ranging from 334 to 353 µg/m^3 for $PM_{2.5}$ and from 338 to 372 µg/m^3 for PM_{10}, and overlapping interquartile ranges across kitchen locations (Figure 4). Accordingly, no meaningful difference in particulate matter levels by kitchen location was detected.

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Table 2: *Summary of the concentrations of surveyed kitchen air quality parameters with threshold exposure levels benchmarked against WHO & TBS Standards (n=153)*

Air quality Parameter	Median	Range	75% percentile	25% percentile	IQR	Applicable Limit (WHO/TBS) vs estimated 3-hr cooking period values	Remarks on thresholds
$PM_{2.5}$ (µg/m³)	247	70–975	454	174	280	WHO 24-hr limit: 15 µg/m³ Cooking period values per 24-hr TWA, Median = 30.9 µg/m³, Range:= 8.8–121.9 µg/m³)	63% (97 of surveyed kitchens of which 85 block and 12 mud walled) substantially higher than WHO guideline reference values concentrations up to four fold higher than recommended exposure limits during cooking periods.
PM_{10} (µg/m³)	247	75–975	470	185	285	WHO 24-hr: 45 µg/m³; TBS 24-hr: 60–90 µg/m³ Cooking period values per WHO-24-hr TWA-, Median = 30.9 µg/m³ Range= 9.4–121.9 µg/m³, 75th percentile= 58.8 µg/m³)	Median 24-hr TWA is below both WHO and TBS limits, but upper percentiles approach or exceed WHO levels. 12% (18) of surveyed kitchens (14 block and 4 mud walled) exhibited PM10 concentrations up to two-fold above TBS guideline values during cooking periods.
Humidity (%)	54	33–76	60	46	14	No WHO/TBS limit	30% (45) of the kitchens had moderately high relative humidity levels ≥ 60% (block= 41 kitchens mud=4); may influence particulate suspension, although no formal health threshold exists.
Temp. (°C)	32	24–54	34	30	4	No WHO/TBS limit, (comfort range ~18–30 °C)	75% (115) of surveyed kitchens (Block=106, Mud =9) recorded temperatures > 30°C, exceeding WHO thermal comfort recommendations; high temperatures may worsen indoor exposure conditions.
CO (ppm)	60	20–105	76	45	31	WHO 1-hr limit: 26 ppm; TBS 1-hr: 26 ppm	CO levels in all surveyed kitchens (n=153) significantly exceeded short-term WHO/TBS limits ranging from 2-10 fold for some kitchens (block 89%: Mud= 11%) indicating risk of acute CO exposure during cooking.

Note: $PM_{2.5}$ and PM_{10} concentrations were measured during active cooking periods and reflect approximately 3 hours of average daily cooking time, consistent with local household practices. These values therefore represent short-term cooking-period exposures and are compared with 24-hour WHO and TBS guideline values for contextual interpretation, recognizing that direct equivalence may underestimate cumulative daily exposure where background concentrations persist outside cooking hours.

Neither kitchen size (small n=80, medium n=65, large n=8; nor window configuration (small/large/open/non-opening) significantly affected PM levels (Figure 3 Kruskal-Wallis p=0.366). Medians spanned 236-332 µg/m³ ($PM_{2.5}$) and 319-417 µg/m³ (PM_{10}) with broad overlap; large/open windows trended slightly higher, indicating high emissions overwhelmed ventilation.

Relative humidity

Mud-walled kitchens (n=18) showed slightly higher median humidity than block-walled (n=135), with narrower IQR in block walls indicating greater stability (Figure 2), but no significant difference (Mann-Whitney U, p=0.482). Approximately 30% of kitchens (41 block, 4 mud-walled) exceeded 60% RH, potentially promoting particulate suspension though no WHO/TBS thresholds exist.

Humidity levels did not differ significantly by kitchen location (detached n=72 vs. inside-within dwelling house, n=81; Mann-Whitney U, p=0.416; Figure 4) or size categories (Kruskal-Wallis, p=0.807; all Dunn's p>0.05). Medians were comparable across groups (range: 46-60%), with overlapping IQRs.

Window ventilation (small n=110, large n=43, open n=127, non-opening n=26) also showed no effect (Kruskal-Wallis, p=0.657; Figure 5). Non-opening windows trended higher (median 57%, range 36-74%), but broad overlap across categories indicates microclimate factors dominated over structural ventilation.

Temperature

Median temperatures were similar between mud-walled (n=18) and block-walled kitchens (n=135), with overlapping distributions (Mann-Whitney U, p=0.282; Figure 2). Overall, 75% of kitchens (106 block, 9 mud) exceeded WHO thermal comfort range (>30°C), potentially exacerbating pollutant exposure.

Temperature varied significantly by kitchen size (Kruskal-Wallis H=13.29, p=0.001; Figure 3). Dunn's post-hoc tests showed large kitchens (>12 m², n=8) were significantly hotter than small (4-8 m², n=80; p=0.01) and medium (8-12 m², n=65; p=0.05), with narrower IQR indicating less fluctuation.

No significant differences occurred by kitchen location (detached n=72 median 33°C (mean 33.9± 4.2 °C) vs. kitchen-

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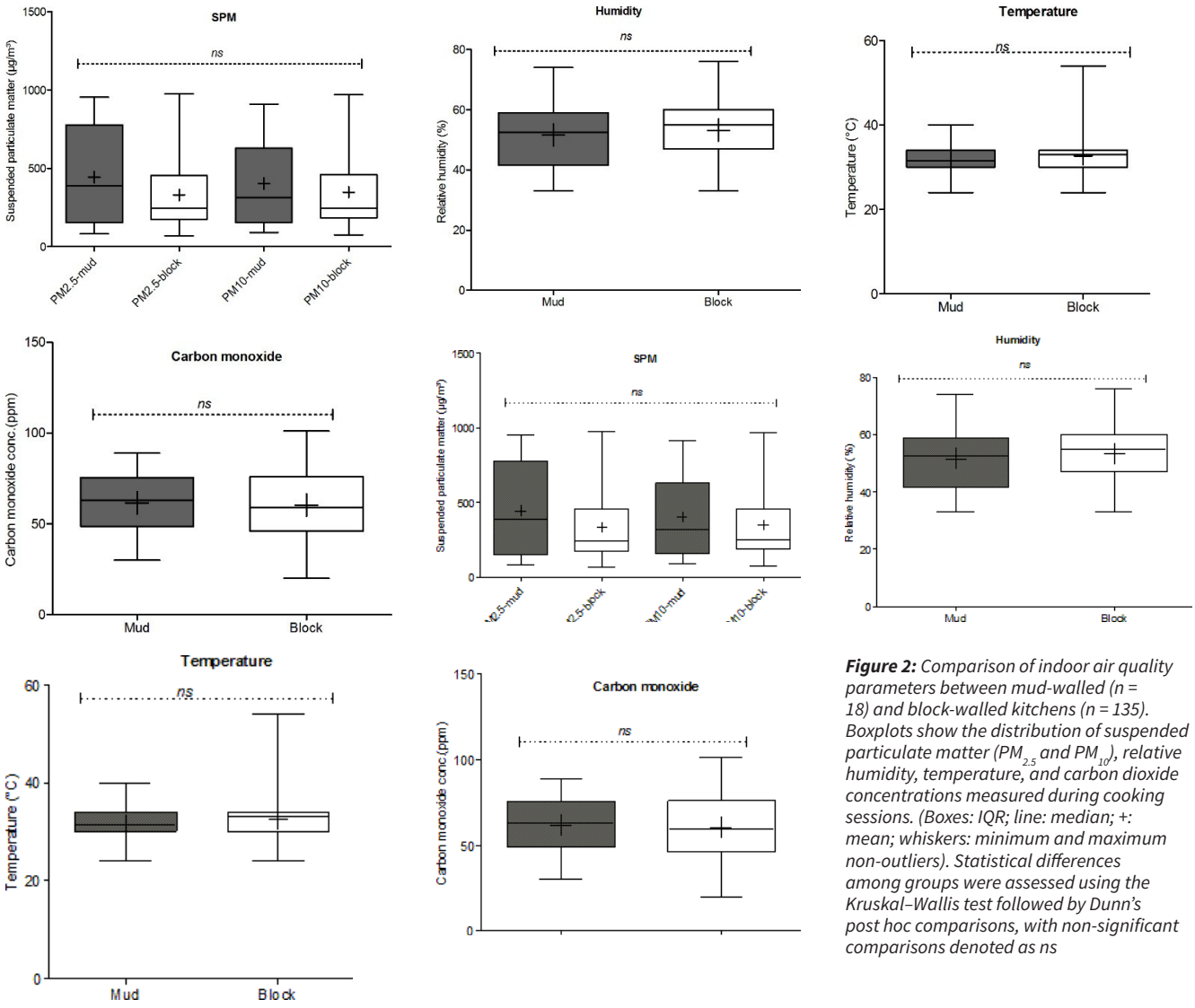


Figure 2: *Comparison of indoor air quality parameters between mud-walled (n = 18) and block-walled kitchens (n = 135). Boxplots show the distribution of suspended particulate matter ($PM_{2.5}$ and PM_{10}), relative humidity, temperature, and carbon dioxide concentrations measured during cooking sessions. (Boxes: IQR; line: median; +: mean; whiskers: minimum and maximum non-outliers). Statistical differences among groups were assessed using the Kruskal–Wallis test followed by Dunn's post hoc comparisons, with non-significant comparisons denoted as ns*

inside the dwelling house n=81 median 32°C (mean 32.2± 4.8 °C). (Mann-Whitney U, p=0.186; Figure 4) or window ventilation (small/large/open/non-opening; Kruskal-Wallis, p=0.848; Figure 5). Elevated temperatures across designs suggest combustion heat dominated structural factors.

Carbon monoxide

CO levels showed no significant differences between mud-walled (n=18) and block-walled kitchens (n=135; Mann-Whitney U, p=0.707; Figure 2), despite slightly higher medians in mud walls. Kitchen size categories exhibited comparable medians with overlapping IQRs (Kruskal-Wallis H=1.83, p=0.402; all Dunn's p>0.05; Figure 3). Location of the kitchen also showed no effect (detached n=72 vs. inside the dwelling house n=81; Mann-Whitney U, p=0.549; Figure 4).

Window ventilation categories displayed no differences (Kruskal-Wallis, p=0.864; all Dunn's p>0.05; Figure 5). All 153 kitchens exceeded WHO/TBS 1-h limit (26 ppm), with medians (60 ppm) 2-10 fold higher, indicating acute exposure risk during ~3-h cooking despite structural variations.

Associations between household characteristics and measured indoor air quality parameters

Table 3 presents correlations between air quality parameters and kitchen characteristics in the surveyed households (n = 153). Correlation analysis showed a very strong positive relationship between $PM_{2.5}$ and PM_{10} (r = 0.921), and weak or negligible correlations between particulate matter and other kitchen characteristics, including ventilation, size, and building materials. These findings indicate that, in this sample, PM levels were largely independent of kitchen location or structural features.

Building materials "block" and "mud" are perfectly negatively correlated (r = -1.000), indicating mutually exclusive use. Relative humidity and temperature show negligible correlations with air quality metrics. Carbon monoxide (CO) exhibits weak positive correlations with $PM_{2.5}$ and PM_{10} (r = 0.188 and 0.168), suggesting some association with particulate pollution but not strongly associated. The door states "open" and "closed" are perfectly negatively correlated (r = -1.000), consistent with binary coding.

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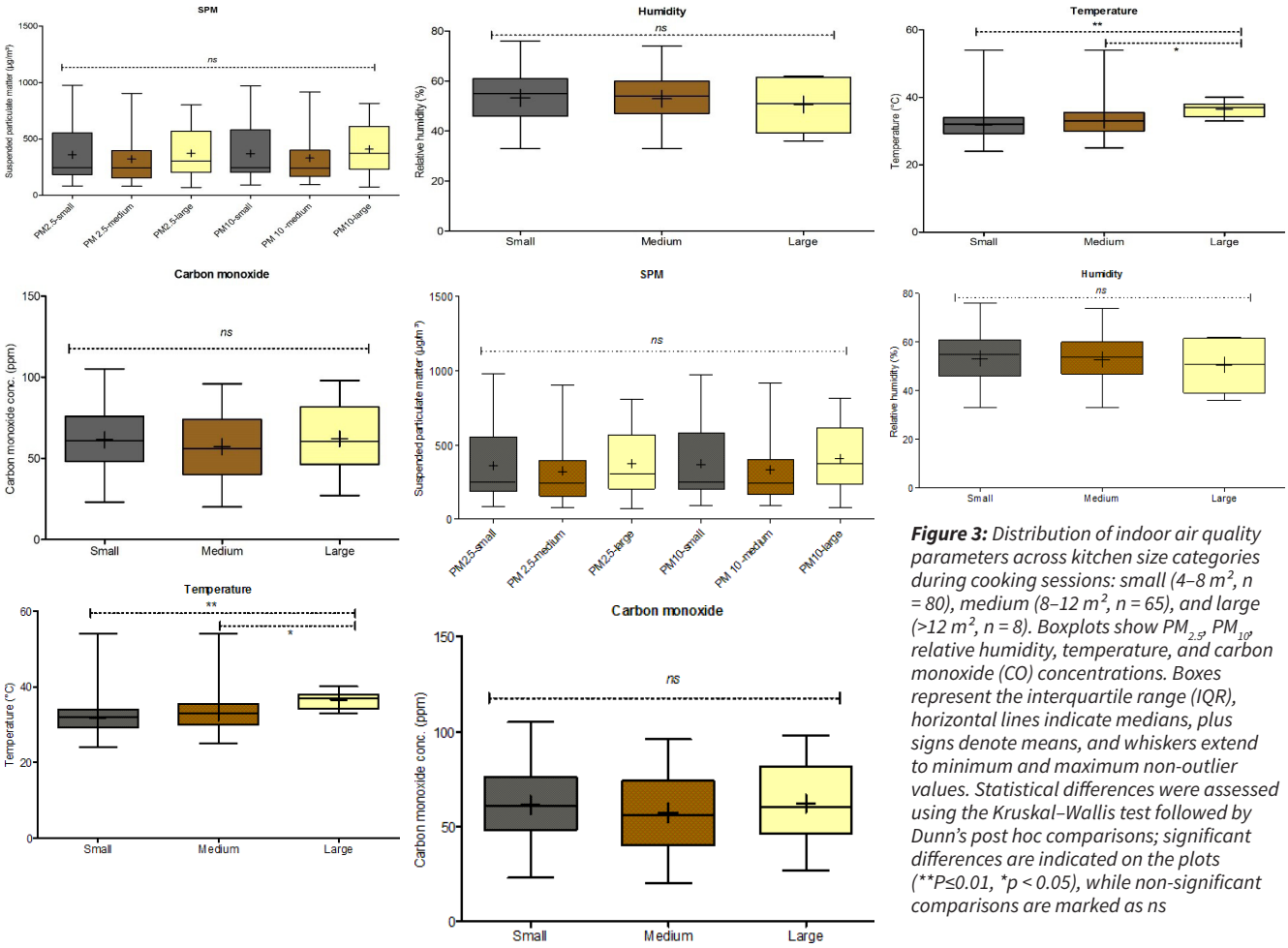


Figure 3: *Distribution of indoor air quality parameters across kitchen size categories during cooking sessions: small (4–8 m², n = 80), medium (8–12 m², n = 65), and large (>12 m², n = 8). Boxplots show $PM_{2.5}$, PM_{10}, relative humidity, temperature, and carbon monoxide (CO) concentrations. Boxes represent the interquartile range (IQR), horizontal lines indicate medians, plus signs denote means, and whiskers extend to minimum and maximum non-outlier values. Statistical differences were assessed using the Kruskal–Wallis test followed by Dunn's post hoc comparisons; significant differences are indicated on the plots (**P≤0.01, *p < 0.05), while non-significant comparisons are marked as ns*

Kitchens with block brick walls showed significantly higher temperatures (35 ± 4 °C) and lower relative humidity (33 ± 10%) compared to those with mud and thatch walls (p = 0.05). Carbon monoxide concentrations ranged from 20 to 105 ppm (mean 60 ± 19 ppm), showing positive but non-significant correlations with $PM_{2.5}$ (r = 0.188, p = 0.199). Kitchen size variables show moderate to strong negative correlations between categories of small and medium sizes (r = -0.900), indicating distinct size classifications. Window size categories (small vs. large) are very strongly negatively correlated (r = -0.887). Weak, non-significant positive correlations were observed between kitchen size and particulate matter and CO (r = 0.15 to 0.19), while window absence had negligible correlation with pollutant levels. These findings indicate that kitchen location and building materials significantly influence particulate pollution and indoor microclimate, whereas CO and kitchen size relate less strongly.

Discussion

Indoor air pollutant and microclimate profiles in SBF using kitchens

This study documented consistently elevated $PM_{2.5}$ (median 247 µg/m³), PM_{10} (247 µg/m³), and CO (60 ppm) during cooking across all 153 kitchens, exceeding WHO 24-h limits ($PM_{2.5}$: 15 µg/m³; PM_{10}: 45 µg/m³) and 1-h CO limit (26 ppm) by 5-16 fold (Table 2). The strong $PM_{2.5}$-PM_{10} correlation (r=0.921, p<0.001; Table 3) confirms shared biomass combustion origins (Limmongkon et al., 2021)., consistent with Tanzanian studies reporting similar indoor levels 10-50× ambient urban $PM_{2.5}$ (Shayo et al., 2022; Mkunda et al., 2024). The magnitude of the measured PM points to a serious household air pollution problem in urban kitchens of Tanzania that aligns with similar findings in low-income or densely populated settings (Wernecke et al., 2021).

Charcoal dominated (81%; Table 1) due to its high energy density, transportability, and urban availability over firewood (Zulu et al., 2013). Studies indicate that burning firewood in indoor environments can produce up to four times air pollutants compared to burning charcoal alone, which is associated with significant emissions of particulate matter, particularly $PM_{2.5}$ and PM_{10}, with emission factors ranging from 1.4 g/kg to 7.4 g/kg for $PM_{2.5}$ and 4.6 g/kg to 8 g/kg for PM_{10} (Simões et al., 2016; Santos et al., 2019). Mixed charcoal-firewood use (19%) amplified exposures, aligning with regional findings linking biomass cooking to acute respiratory infections in Tanzanian children (OR 1.5-2.0). (Kilabuko et al 2007; Shayo et al., 2022). The finding of this study aligns with Mbanya and Sridhar (2017), who reported that wood users are exposed to significantly higher levels of PM_{10} during cooking compared to charcoal users in uncontrolled environments.

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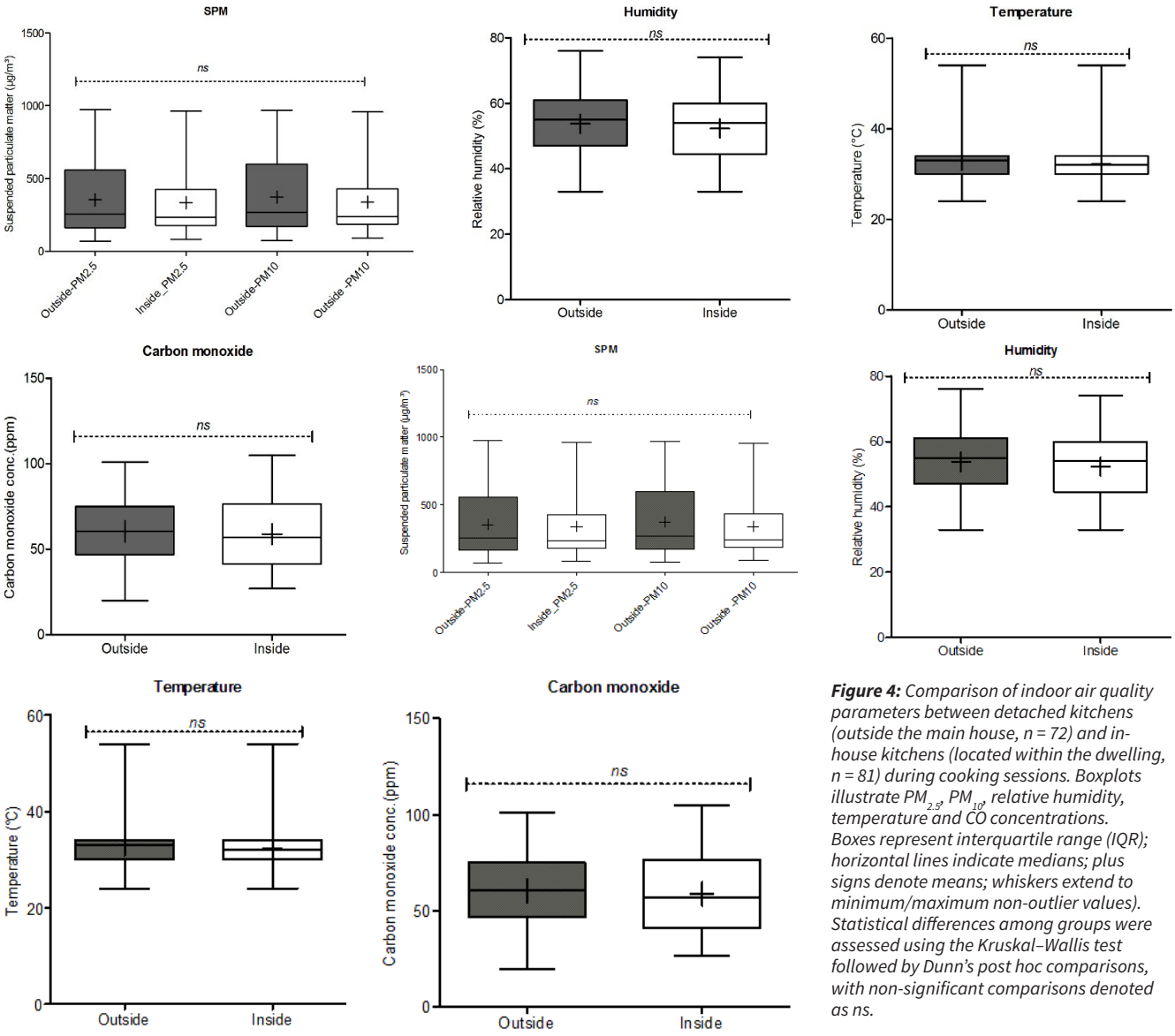


Figure 4: *Comparison of indoor air quality parameters between detached kitchens (outside the main house, n = 72) and in-house kitchens (located within the dwelling, n = 81) during cooking sessions. Boxplots illustrate $PM_{2.5}$, PM_{10}, relative humidity, temperature and CO concentrations. Boxes represent interquartile range (IQR); horizontal lines indicate medians; plus signs denote means; whiskers extend to minimum/maximum non-outlier values). Statistical differences among groups were assessed using the Kruskal–Wallis test followed by Dunn's post hoc comparisons, with non-significant comparisons denoted as ns.*

Such indoor concentrations are far higher than what is typically recorded even in outdoor urban settings in some African cities, where studies have shown daily $PM_{2.5}$ averages often oscillating around tens of micrograms per cubic meter (Moletsane et al., 2021).

CO exceedances signal incomplete combustion in poorly ventilated spaces (Van Tran et al., 2020; US-EPA., 2025)., causing acute symptoms such as headaches, dizziness, sneezing, coughing, and breathing difficulties, WHO (2021), and chronic risks such as respiratory and cardiovascular diseases (Rafael et al., 2015), allergic reactions, cancers, and premature mortality (WHO., 2024b), disproportionately affecting women/children spending 3-5 h daily cooking (Fullerton et al., 2008; Smith et al., 2017; WHO, 2024b). Therefore, the combined use of charcoal and firewood in a poorly ventilated kitchen further increases the risk of human exposure to particulate matter and other harmful gases such as carbon monoxide (CO), sulfur oxides (SO_x), and nitrogen oxides (NO_x), depending on the content of the SBF used (Van Tran et al., 2020). Humidity (median 54%, range 33-76%) lacked thresholds but >60% RH in 30% of kitchens may prolong PM suspension; temperatures (median 32°C, 75% >30°C, Figs 2-5; Table 2) exceeded comfort ranges, exacerbating heat stress (Giwa et al., 2022), increased occupant discomfort (US-EPA., 2025) and pollutant inhalation (Shayo & Bintabara 2022; WHO, 2024) Indoor temperatures in a few kitchens were > 50 °C, possibly influenced by kitchen size, cooking behavior, ventilation, and construction materials. High temperatures can enhance pollutant suspension, increasing exposure to airborne particulate matter. Prolonged exposure to extreme temperatures, up to 54 °C, may also cause heat stress or heat exhaustion during cooking (Alam et al., 2022). Continuous exposure to high temperatures > 40 °C can also impair cognitive function and decision-making abilities (Saenz et al., 2018), which can trigger kitchen users to cause accidents. Unlike commercial kitchens, which experience higher pollutant emissions due to intense cooking activities and equipment use (Chen et al., 2023), residential kitchens generally have less frequent and less

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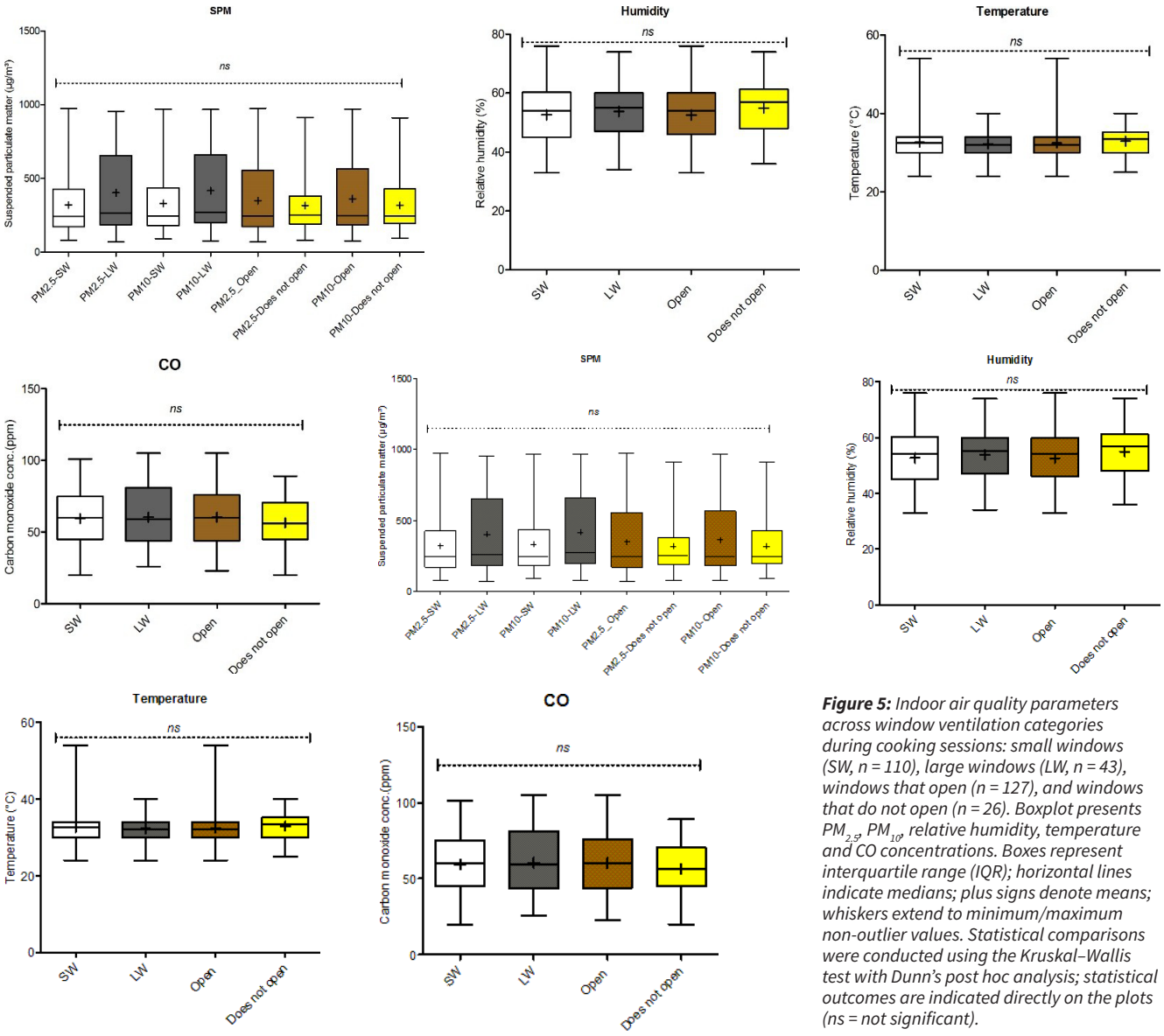


Figure 5: *Indoor air quality parameters across window ventilation categories during cooking sessions: small windows (SW, n = 110), large windows (LW, n = 43), windows that open (n = 127), and windows that do not open (n = 26). Boxplot presents $PM_{2.5}$, PM_{10}, relative humidity, temperature and CO concentrations. Boxes represent interquartile range (IQR); horizontal lines indicate medians; plus signs denote means; whiskers extend to minimum/maximum non-outlier values. Statistical comparisons were conducted using the Kruskal–Wallis test with Dunn's post hoc analysis; statistical outcomes are indicated directly on the plots (ns = not significant).*

intensive cooking, leading to lower levels of heat, humidity, and airborne pollutants. Integrating building materials, ventilation, cleaner fuels, and improved stove designs with better ventilation are critical to mitigating these health risks (Cuesta-Mosquera et al., 2025).

For instance, in-house kitchens (53%) showed higher PM (251 vs 235 µg/m^3; Table 3), emphasizing fuel type and structural determinants over ventilation alone. These findings highlight an urgent need for clean fuel transitions (LPG/biogas), improved stoves, and detached SBF kitchen designs per Tanzania's Clean Cooking Strategy 2024-2034 to curb ~19,000 annual pollution-attributable deaths (Ndunguru, 2024). As of 2024, the 74.7%) urban electricity access in Tanzania (World Bank, 2024), contrasts persistent SBF reliance due to high tariffs (Philip et al., 2022; AfDB., 2024), appliance costs, frequent power outages (Trading Economics, 2022), and cultural preferences (SID., 2024). Tanzania loses ~33,000 lives annually to household air pollution, with 90%+ households still biomass-dependent despite 75% urban electricity access (URT, 2024). Therefore, effective mitigation of indoor air pollution from SBF in Tanzanian urban kitchens requires a multifaceted approach integrating cleaner energy adoption, improved stove technologies, and enhanced ventilation measures. Besides, it needs policy interventions and sustainable community awareness raising campaigns to slowly transitioning households from charcoal and firewood to cleaner fuels such as liquefied petroleum gas, biogas, or electricity for health and economic benefits. Since, affordability, accessibility, and cultural acceptance remain considerable barriers to widespread adoption of clean energy, necessitating targeted national subsidy schemes and community engagement campaigns tailored to urban and peri-urban contexts is very crucial.

Influence of kitchen structural features and location on indoor air quality

Kitchen structure and location significantly affected pollutant concentrations. In-house kitchens (n=81, 53%) showed

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Table 3: *Correlation coefficients between air quality parameters, kitchen characteristics (location, size, ventilation) and building materials in the surveyed household kitchens (n=153). Bolded r- values indicate the strength and direction of the linear relationship: $|r| \geq 0.7$ (very strong), $0.5 \leq |r| < 0.7$ (strong), $0.3 \leq |r| < 0.5$ (moderate), $0.1 \leq |r| < 0.3$ (weak), and $|r| < 0.1$ (negligible). Positive values denote a positive correlation and negative values denote a negative correlation.*

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Air quality parameters																	
(1) $PM_{2.5}$	1.000																
(2) PM_{10}	0.921	1.000															
(3) R. humidity	-0.061	0.007	1.000														
(4) temperature	-0.099	-0.036	-0.104	1.000													
(5) CO	0.188	0.168	-0.095	-0.039	1.000												
Building materials																	
(6) block	-0.154	-0.076	0.054	0.085	-0.035	1.000											
(7) mud	0.154	0.076	-0.054	-0.085	0.035	**-1.000**	1.000										
Kitchen size																	
(8) small	0.068	0.068	0.030	-0.181	0.097	**-0.349**	**0.349**	1.000									
(9) medium	-0.081	-0.093	-0.003	0.087	-0.110	**0.314**	**-0.314**	**-0.900**	1.000								
(10) large	0.028	0.055	-0.060	0.213	0.026	0.086	-0.086	-0.246	-0.202	1.000							
Kitchen locations																	
(11) outsides	0.042	0.071	0.077	0.082	0.041	0.141	-0.141	-0.017	0.011	0.014	1.000						
(12) insides	-0.042	-0.071	-0.077	-0.082	-0.041	-0.141	0.141	0.017	-0.011	-0.014	-1.000	1.000					
Windows																	
(13) small size	-0.159	-0.166	-0.055	0.032	-0.021	-0.093	0.093	0.160	-0.139	-0.049	-0.139	0.139	1.000				
(14) large size	0.030	0.086	0.050	-0.003	-0.022	0.203	-0.203	-0.180	0.147	0.077	0.187	-0.187	-0.887	1.000			
(15) not present	0.281	0.181	0.015	-0.064	0.090	-0.211	0.211	0.021	0.002	-0.051	-0.081	0.081	-0.350	-0.121	1.000		
Door																	
(16) open	0.052	0.071	-0.094	-0.033	0.076	0.105	-0.105	0.090	0.002	-0.206	-0.306	0.306	-0.051	0.005	0.099	1.000	
(17) Closes	-0.052	-0.071	0.094	0.033	-0.076	-0.105	0.105	-0.090	-0.002	0.206	0.306	-0.306	0.051	-0.005	-0.099	-1.000	1.000

significantly higher $PM_{2.5}$ (251 vs. 235 µg/m^3) and PM_{10} (269 vs. 237 µg/m^3) than detached kitchens (n=72; $p<0.05$; Table 3), confirming enclosure restricts pollutant dispersion into living areas (Nibagwire et al., 2025). This aligns with Tanzanian studies where indoor cooking elevates household smoke exposure risk 2 – 4 folds vs. outside / detached (76% high SER prevalence) (Mbanya et al., 2017). Kitchens primarily using firewood were often constructed separately from the dwelling house due to their higher emissions of PM, CO_2, and CO compared to charcoal. Other studies in Tanzania, indicate that firewood-using kitchens were predominantly detached due to higher emissions (Ahmad et al., 2022).

Block-brick walls (88%, n=135) produced hotter (35.4°C) and drier (33% RH) conditions than mud walls (Mann-Whitney U, $p<0.05$; Figure 2), likely due to thermal mass retaining combustion heat (Ramalho et al., 2020). Elevated temperatures (>30°C in 75%) may prolong PM suspension and induce heat stress during cooking sessions. While concrete-cement blocks or soil-molded burnt blocks are widely used in urban areas of Tanzania due to their abundancy and ease of modification, plastered walls potentially limit the escape of particulate matter from the kitchen, increasing the risk of exposure for occupants (Makenya et al., 2017). Tighter walls and finishes can reduce air exchange, leading to the buildup of particulate and gaseous contaminants indoors (Pekdoğan, 2024).

Contrary to expectations, window presence/size (small n=110, large n=43, open n=127, non-opening n=26) and kitchen size (small n=80, medium n=65, large n=8) showed no significant PM/CO reductions (Kruskal-Wallis all $p>0.05$; Figures 3 - 5). The use of low-tech stoves often results in incomplete combustion, and when coupled with inadequate ventilation, it can lead to the accumulation of carbon monoxide (González-Pedraza et al., 2024), especially during periods of intense cooking or when multiple meals are prepared in succession.

The orientation of windows and doors toward prevailing outdoor airflows potentially improves indoor-outdoor air exchange rates, thereby enhancing ventilation efficiency (Liu et al., 2020). Wind plays a crucial role in dispersing both outdoor and indoor pollutants when favorable air exchange rates are present.

Weak kitchen size-pollutant correlations (r=0.15-0.19) and negligible window effects suggest high baseline emissions overwhelmed passive ventilation, consistent with Tanzanian

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urban kitchen findings where airflow direction and user behavior dominate (Liu et al., 2022; Lenz et al., 2023; Nibagwire et al. 2025). Smaller kitchen enclosures may have limited air circulation during cooking periods, resulting in higher indoor air pollution levels (Vardoulakis et al., 2020). Therefore, kitchen size should be considered based on factors such as the number of occupants during cooking, the space required for kitchen tools and structures, and the ease with which pollutants can disperse. $PM_{2.5}$/CO correlation was weak (r=0.188, p=0.199; Table 3), reflecting divergent emission dynamics, particulates from smoldering vs. CO from flaming combustion. These complex interactions highlights that structural features alone insufficiently mitigate SBF pollution without cleaner fuels/ stoves (Heltberg, 2003).

Therefore, this study provides baseline information for policy and decision makers to prioritize on the importance of structural and engineering campaigns for size, detached kitchen designs, porous wall materials (Dasgupta et al., (2007), and active ventilation (chimneys/hoods) alongside Tanzania's Clean Cooking Strategy. Optimal window orientation and behavioral training (consistent opening) could enhance passive systems despite limitations.

Effects of fuel choices and behavioral practices on kitchen air pollution

Charcoal dominated (81%, n=124) yet produced hazardous $PM_{2.5}/PM_{10}$ > (247 µg/m^3) and CO (60 ppm) exceeding WHO limits 5-16 folds, confirming even "cleaner" charcoal generates significant emissions in open stoves typical of Tanzanian urban kitchens. Mixed charcoal-firewood kitchens (19%, n=29) showed greater variability, consistent with firewood's 2-4 folds higher PM emission factors (1.4 - 7.4 g/kg $PM_{2.5}$) vs. charcoal (Simões et al., 2016; Santos et al., 2019; Tran et al., 2020; Mkunda et al 2024).

No significant PM/CO differences by fuel type emerged (limited n=29 firewood), suggesting combustion efficiency and enclosure overshadowed fuel choice. Research shows indoor air quality is influenced by a complex mix of organic and inorganic particles, which vary by activity, season, and location (Ryan et al., 2015). These findings align with international studies showing that user practices may significantly modify exposure outcomes even when fuel type remains constant (Shupler et al., 2020; Kumar et al., 2022).

Behavioral practices proved insufficient in influenced exposure patterns: 72% open windows (n=110), 82% open doors (n=126) failed to reduce pollutants (Figure 5, p>0.05), overwhelmed by high emission loads from predominantly traditional 3-stone wood or metal-clay / charcoal stoves. No improved combustion system observed. CO variability (20-105 ppm) reflects stoking/ smoldering phases, where incomplete combustion spikes emissions 2-10× guidelines (Figures 2-5).

Behavioral practices strongly influenced exposure patterns. Many households kept doors and windows open during cooking, but this was insufficient to compensate for high emission loads and the limited efficiency of traditional cook stoves. Therefore, user practices (SBF management, cooking intensity) modify exposures even with identical fuels, explaining null structural correlations despite open features.

This highlights the need for comprehensive, coordinated and collaborative intervention approaches that combine cleaner fuels, improved stove technologies, behavioural training, (on fuel management, safe ventilation), and fiscal incentives as key drivers to reduce indoor air pollution from cooking. This integrated model may foster sustainable clean energy adoption by addressing economic, cultural, and environmental barriers, aligning with the Tanzania Strategy's goal of achieving 80% clean cooking solutions adoption by 2034.

Conclusion

This study comprehensively assessed indoor air quality in urban Tanzanian kitchens using solid biomass fuels, primarily charcoal and firewood, during the end of the rainy season. The findings reveal that suspended particulate matters ($PM_{2.5}$ and PM_{10}) and carbon monoxide concentrations frequently exceeded recommended health guidelines, posing substantial risks to household occupants, especially women and children who spend considerable time near cooking areas. Structural factors such as floor and walling materials, ventilation status, kitchen size and location significantly influence pollutant accumulation and indoor microclimate, while behavioral practices and ventilation patterns alone show limited mitigation effects. These results highlight the critical need for integrated interventions that combine the promotion of cleaner cooking fuels, behavioral change, and improved stove efficiency with low-cost ventilation enhancements to reduce indoor air pollution exposure. Policies that prioritize LPG subsidies and support the adoption of energy-efficient cooking technologies can further accelerate exposure reduction. With Tanzania's Clean Cooking Strategy (2024-2034) targeting a large-scale transition to cleaner energy by 2034, this study provides empirical evidence to guide policy prioritization, public awareness, and technological uptake efforts. Future research should explore seasonal variability and intervention efficacy while continuing to address socioeconomic and cultural barriers to adopting clean cooking solutions.

Ethical considerations

This study was conducted following the ethical standards and with approval number SUA/CoNAS/ST/24/133 from the Sokoine University of Agriculture Research Ethics Committee. Permission numbers OAMK/MFS/2024 and OAMK/MFG/2024 were granted by the local government offices in the selected wards before engaging with the respondents. At the households, a verbal consent was obtained after a full explanation of the project purpose to the adult person (+18 years) found at the household during the survey period. Only those who accepted the consent were considered viable for this study.

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Limitation of the study

Several methodological limitations should be noted. First, the kitchens varied considerably in size, which may have influenced particulate matter concentrations per unit volume. In addition, airflow conditions differed due to variations in window and door dimensions and their orientation to outdoor air movement. To minimize the impact of these differences, a standardized protocol was applied, including consistent device placement, sampling during comparable cooking periods, documentation of ventilation status, and sufficiently long measurement durations to reduce short-term variability. Despite these measures, uncontrolled environmental variability, high outdoor humidity, and the absence of field co-location calibration may introduce measurement uncertainty. Besides, this study did not explicitly quantify stove type, fuel moisture content, or cooking intensity, all of which can influence pollutant emissions. These unmeasured factors may have contributed to variability in observed concentrations and should be considered when interpreting the results. Finally, data collection was restricted to the end of rainy season (April–May 2024), which may limit temporal generalizability, as indoor pollutant levels can vary seasonally with changes in fuel use, ventilation practices, and combustion efficiency. Rainy-season timing minimized ambient PM interference but likely underestimates dry-season concentrations (2-3× higher per regional data); multi-season studies are needed for annual exposure profiles. Future studies should incorporate multi-season sampling to better capture temporal variability and improve representativeness.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Credit authorship contribution statement

Silvia Francis Materu: Conceptualization, Methodology, Data curation, Writing – original draft, review and editing. Gideon George Sway: Methodology, Data curation, Visualization, Formal analysis, Writing – original draft, review and editing.

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