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In-kitchen aerosol exposure in twelve cities across the globe

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ABSTRACT

Poor ventilation and polluting cooking fuels in low-income homes cause high exposure, yet relevant global studies are limited. We assessed exposure to in-kitchen particulate matter ($PM_{2.5}$ and PM_{10}) employing similar instrumentation in 60 low-income homes across 12 cities: Dhaka (Bangladesh); Chennai (India); Nanjing (China); Medellín (Colombia); São Paulo (Brazil); Cairo (Egypt); Sulaymaniyah (Iraq); Addis Ababa (Ethiopia); Akure (Nigeria); Blantyre (Malawi); Dar-es-Salaam (Tanzania) and Nairobi (Kenya). Exposure profiles of kitchen occupants showed that fuel, kitchen volume, cooking type and ventilation were the most prominent factors affecting in-kitchen exposure. Different cuisines resulted in varying cooking durations and disproportional exposures. Occupants in Dhaka, Nanjing, Dar-es-Salaam and Nairobi spent > 40% of their cooking time frying (the highest particle emitting cooking activity) compared with ∼ 68% of time spent boiling/stewing in Cairo, Sulaymaniyah and Akure. The highest average $PM_{2.5}$ (PM_{10}) concentrations were in Dhaka 185 ± 48 (220 ± 58)

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μg m^{-3} owing to small kitchen volume, extensive frying and prolonged cooking compared with the lowest in Medellín 10 ± 3 (14 ± 2) μg m^{-3}. Dual ventilation (mechanical and natural) in Chennai, Cairo and Sulaymaniyah reduced average in-kitchen $PM_{2.5}$ and PM_{10} by 2.3- and 1.8-times compared with natural ventilation (open doors) in Addis Ababa, Dar-es-Salam and Nairobi. Using charcoal during cooking (Addis Ababa, Blantyre and Nairobi) increased $PM_{2.5}$ levels by 1.3- and 3.1-times compared with using natural gas (Nanjing, Medellin and Cairo) and LPG (Chennai, Sao Paulo and Sulaymaniyah), respectively. Smaller-volume kitchens (<15 m^3; Dhaka and Nanjing) increased cooking exposure compared with their larger-volume counterparts (Medellin, Cairo and Sulaymaniyah). Potential exposure doses were highest for Asian, followed by African, Middle-eastern and South American homes. We recommend increased cooking exhaust extraction, cleaner fuels, awareness on improved cooking practices and minimising passive occupancy in kitchens to mitigate harmful cooking emissions.

1. Introduction

Globally, >2.6 billion people depend on solid fuels including biomass and coal (WHO, 2021a). Approximately 4 million people die prematurely from illnesses attributed to indoor air pollution (IAP) from inefficient cooking practices using polluting stoves operating on solid fuels and kerosene (WHO, 2021a). Fuel combustion, especially for cooking, and emissions from the use of cleaning appliances are major sources of IAP (Jeong et al., 2019). People spend about 80–90% of their time indoors (WHO, 2010). Therefore, managing the IAP has become an essential need for protecting human health.

Improving indoor air quality (IAQ) aligns with the United Nations Sustainable Development Goals (UNSDGs, 2015), about improving health and well-being (Goal 3) by providing affordable and clean energy (Goal 7) in sustainable cities and communities (Goal 11). In addition, reducing IAP is crucial for gender equality (Goal 5) and reducing inequalities (Goal 10), as women in developing countries are disproportionately exposed to emissions from burning of solid fuels such as coal and biomass for cooking, thereby subjecting them to higher risk of IAP-related diseases. Evidence suggests that air pollutant concentrations in the indoor environment consistently exceed those in the outdoor (Leung, 2015) due to confined conditions, which results in a 1000-times higher probability for indoor pollutants to infiltrate the lungs (Zhang and Smith, 2003).

Exposure to high levels of particulate matter (PM) has been linked to numerous adverse health impacts (Heal et al., 2012; Dherani et al., 2008; Kurmi et al., 2010) such as heart diseases, pneumonia, stroke, lung cancer, and chronic obstructive pulmonary disease (WHO, 2021a). The IAP is affected by many factors such as the types of cooking fuel, types of cookstove, structural characteristics, ventilation, geographical location, geographical and meteorological conditions, and exposure time (Balakrishnan et al. 2013; McCreddin et al., 2013; Han et al., 2019; Sidhu et al., 2017). Particles emitted during cooking have been identified as a major IAP source (Abdullahi et al., 2013; Huang et al., 2016; Chen et al., 2016). Epidemiological studies have shown a strong positive correlation between health effects and cooking-related PM (Sumpter and Chandramohan, 2013; Mengersen et al., 2011). Furthermore, exposure to health-damaging pollutants such as $PM_{2.5}$ and black carbon, resulting from incomplete combustion of cooking fuels, has been related to high morbidity and mortality rates (Khafaie et al., 2016).

Improving housing standards has become a priority for many low-income and middle-income countries (LMICs), following the recognition of the impact of poor architectural design of households on human health (Baker, et al., 2016). Significant increase in the concentration of indoor PM, gaseous and volatile organic compounds was found in low-income homes in LMICs (Khan et al., 2017; Vardoulakis et al., 2020). Efforts are therefore being made to enhance access to improved cookstoves such as e-cookers (Leary et al., 2021) and clean fuels (Hashim et al., 2017) to preserve human health and the environment (Yip et al., 2017). This study focused on the exposure to airborne particles with an aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$) and ≤ 10 μm (PM_{10}) in low-income homes in LMICs where very limited studies are currently available as shown by a summary of relevant studies in Table 1. Indoor exposure studies have usually focused on one city or country, restricting the potential of generalisation for many cities across the globe. Furthermore, a very limited number of in-kitchen exposure works have been performed in the studied cities, and the data that is available is often inconsistent and for short durations, with varying sampling methodologies (Table 1). A summary of relevant previous research reveals a lack of studies quantifying and comparing the in-kitchen exposure in low-income homes by using a unified methodology in different cities (Table 1). This study aims to contribute to filling this gap by monitoring indoor aerosol exposures in low-income homes in such cities.

Quantifying personal exposure to various PM fractions in kitchens is crucial to determining the most appropriate methods to mitigate exposure. Abdullahi et al. (2013) highlighted that 'there is a need for in-depth understanding of cooking emissions around the world and of their effects upon human health'. With these considerations, we performed a study to measure $PM_{2.5}$ and PM_{10} concentrations in various types of kitchens in low-income homes across 12 cities. To ensure reliable findings, common data collection procedures and analysis were adopted for all cities, similar standard operating procedures were developed and used in all study sites. The novelty of this work lies in creating a globally comparable dataset that was acquired using a unified monitoring approach for comparing PM levels in homes. The 12 cities represent a wide geographical range encompassing four continents from Asia to the Middle East, Africa, and South America (Sections 2.2 and SI Section S1).

The overall aim of this work was to understand the major factors influencing in-kitchen exposure to fine and coarse particle fractions, and to establish household exposure profiles across a range of low-income homes. The specific objectives were to investigate the in-kitchen PM exposure as a function of fuel, kitchen volume, ventilation conditions and cooking habits; assess concentration densities to capture the peak exposure ranges; derive $PM_{2.5}/PM_{10}$ ratio profiles to identify the extent of fine particle emissions during cooking; and finally quantify the health exposure risks to suggest viable IAP reduction and mitigation measures to homeowners and building designers in developing countries.

2. Methodology

2.1. Study design

To assess IAP exposure of inhabitants during their typical daily cooking activities, we replicated the same experiment in 12 cities across 4 continents: Dhaka (Bangladesh), Chennai (India), Nanjing (China), São Paulo (Brazil), Medellin (Colombia), Cairo (Egypt), Sulaymaniyah (Iraq), Addis Ababa (Ethiopia), Akure (Nigeria), Blantyre (Malawi), Dar-es-Salaam (Tanzania), and Nairobi (Kenya). In each city, five low-income homes were used for one-week continuous air quality monitoring of their kitchens. Mass concentration of particulate matter ($PM_{2.5}$ and PM_{10}) was recorded inside kitchens (Section 2.5) together with the qualitative information of the building and occupants (Supplementary Information, Table S1) and the outdoor surrounding area (Table S2) through the surveys carried out by the field researchers during the monitoring period.

The building surveys provided an overview of factors, such as building location, apartment type, kitchen type, ventilation conditions,

Table 1
Summary of relevant research studies on aerosol exposure assessment in homes and other indoor microenvironments of developing countries. Note that the published literature on the topic areas were not available for some of the cities such as those in Africa or the Middle-East. Therefore, we expanded our search to include all cities in those countries.

City (Country)	Study focus	Key findings	Reference
Dhaka (Bangladesh)	Indoor air quality indicators and toxicity potential in hospitals	• PM levels were lower indoors than outdoors, however gaseous pollutants were higher, except for NO_2. • Indoor volatile organic compounds were about twice that of the outdoor and higher in post-monsoon than in winter.	Zaman et al. (2021)
	PM and gaseous pollutants in indoor environment	• Pb, Zn, and Ni enrichment factors were higher in traffic, industrial, and construction zones. • Dhaka's cumulative hazard ratio (HR) was 9.06, with Khilkhet people (HR = 10.1) having the highest exposure to $PM_{2.5}$, PM_{10}, and NO_2.	Akther et al. (2019)
	Indoor air pollution from PM emissions in different households	• PM concentrations differed significantly based on the kitchen location, fuel type, and ventilation rate. • When liquefied petroleum gas (LPG) generated lower PM concentrations.	Begum et al. (2009)
Chennai (India)	Characteristics of indoor air pollution under varied fuel-type and kitchen-type in rural areas	• PM concentrations were higher in enclosed indoor kitchens than found outdoors and open kitchens due to poor ventilation and lesser area of dispersion. • High $PM_{2.5}$:PM_{10} suggests predominance of fine particles from cooking, intensified in houses with closed kitchens and with partitions.	Deepthi et al. (2019)
	Assessment of PM and bioaerosols in diverse indoor environments	• The Indoor/Outdoor (I/O) mass concentration ratios revealed the impact of outside PM on IAQ. • Coarse mode bacteria and fungi accounted for > 80% of total cultivable bioaerosol load.	Priyamvada et al. (2018)
Nanjing (China)	Spatial distribution of indoor $PM_{2.5}$	• Frequent building ventilation during transitional seasons and in winter or poor outdoor air quality may increase $PM_{2.5}$ intrusions from outdoors. • Socio-economic status variables (home ownership and household income) influence indoor $PM_{2.5}$ concentrations.	Shao et al. (2019)
	Seasonal Indoor fine PM and its determinants	• Outdoor $PM_{2.5}$ is the main source of indoor $PM_{2.5}$ pollution in homes. • In transition seasons, the association between indoor and outdoor $PM_{2.5}$ concentrations was more significant than in winter and summer.	Shao et al. (2017)
Medellín (Colombia)	Exposure levels to $PM_{2.5}$ and black carbon in rural homes	• BC concentrations in rural areas was about 2.5 times higher than in urban areas with heavy traffic and dense population. • The average $PM_{2.5}$ concentrations in homes using firewood were highest (10.9–3303 μg m^{-3}), as were the average BC concentrations (2.6–51.2 μg m^{-3}), compared to gas (2.6–6 μg m^{-3}).	Vallejo et al. (2021)
	Spirometry alteration due to exposure to atmospheric pollutants in rural homes	• Spirometric parameters correlated negatively with indoor air pollutant concentrations. • Pollutants' concentrations were higher in homes using biomass as cooking fuel. The disparities were only statistically significant for BC and CO (p = 0.008 and 0.03, respectively).	Piracón et al. (2021)
São Paulo (Brazil)	Size–segregated PM inside residences of the elderly	• $PM_{2.5}$ predominates, contributing 78% of total PM_{10}. • Indoor sources predominated, with I/O of 1.89 and 1.06 for $PM_{2.5}$ and PM_{10}, respectively.	Segalin et al. (2017)
	Chemical composition of quasi-ultrafine particles and their sources in elderly residences.	• Sulphate and nitrate were dominant ions in qUFP found in residences of elderly people. • The qUFP composition indicated wall painting and cooking as indoor sources. • Vehicles and secondary inorganic aerosols are major outdoor sources of indoor qUFP.	Segalin et al. (2020)
Cairo (Egypt)	Seasonal variation of indoor air pollutant concentrations in residential buildings	• Indoor levels of air pollution during summer were attributable to higher ventilation rates, whereas in winter, it was influenced by increased human activities and inadequate ventilation. • Occupant number and room volume were among established factors influencing indoor levels of PM, CO, and CO_2 in summer and winter.	Abdel-Salam (2021)
	Outdoor and indoor factors influencing PM and CO_2 levels	• Majority of the kitchens studied had higher indoor $PM_{2.5}$ and CO_2 concentrations than the respective living rooms, attributed to inadequate ventilation. • Several household activities (such as smoking, heating, and washing) were attributed to indoor air emissions, including smoking, heating and washing.	Abdel-Salam (2020)
	Indoor PM in urban residences	• $PM_{2.5}$ and PM_{10} had median I/O mass concentration ratios of 0.81 (range: 0.43–1.45) and 0.65 (range: 0.4–1.07), respectively. • Four homes had I/O > 1, establishing indoor sources as major IAP contributors.	Abdel-Salam (2013)
Sulaymaniyah (Iraq)	Enhancing indoor air quality of a residential building in Iraq	• Relative humidity changes in the passive model were more stable than those in the traditional model, where the indoor relative humidity was < 37%. • A local simulation too calculated the energy usage and greenhouse gas effect; energy usage could be cut down by 80%.	Sadaa and Salihb (2017)
Addis Ababa (Ethiopia)	Indoor air pollution from cook-stoves in Ethiopia	• The geometric mean of PM using clean, improved, and traditional stoves ranged as 10.8–235, 23.6–462, and 36.4–591 μg m^{-3}, respectively. • The health risk assessment of an exposed person to $PM_{2.5}$ and PM_{10} revealed that using stoves would not cause health issues from baking. The system contributed up to38% chronic intake.	Embiale et al. (2020)
	Indoor air pollution in slum neighbourhoods	• In households that primarily use solid petrol, kerosene, and clean fuel, the highest 24 h geometric mean $PM_{2.5}$ concentrations were 1134, 637, and 335 μg m^{-3}, respectively. • No substantial difference in mean $PM_{2.5}$ concentration between improved biomass stoves and traditional stoves.	Sanbata et al. (2014)
Akure (Nigeria)	Effect of stove intervention on household air pollution	• Cooking with firewood increased household air pollution and compromised respiratory health.	Oluwole et al. (2013)

(continued on next page)

Table 1 (*continued*)

City (Country)	Study focus	Key findings	Reference
		• The intervention significantly reduced the indoor $PM_{2.5}$ concentration from 1414 to 130.3 μg m^{-3}.	
	Assessment of indoor air quality in Akure, South West, Nigeria	• The average indoor PM_1, $PM_{2.5}$, and PM_{10} values were 11.818, 10.030, and 7.242 μg m^{-3}, respectively. • The indoor PM levels were lower during weekdays than weekends, owing to increased residents' activities during weekends.	Abulude et al., 2019
Blantyre (Malawi)	Pneumonia and household air pollution exposure in children	• No connection existed between CO exposure and pneumonia occurrence. • CO may not be an adequate IAQ indicator. Effective methods to measure PM exposures are required.	Mortimer et al. (2020)
	Biomass cooking fuels and women's health in Malawi	• Shortness of breath, chronic cough, and phlegm were slightly more common with rural cooks than with urban cooks. Phlegm, forgetfulness, and burns were significantly less common. • Household air pollution-related cardiopulmonary and neurologic effects could rise with deforestation and demographic pressures, depending on low-quality biomass fuels.	Das et al. (2017)
Dar-es-Salaam (Tanzania)	Personal and indoor exposure to $PM_{2.5}$ and polycyclic aromatic hydrocarbons	• Average personal $PM_{2.5}$ exposure was 14, 88, 588, 1574 μg m^{-3} for liquid petroleum gas, kerosene/charcoal mix, charcoal, and open wood fires, respectively. • Proper and efficient use of wood stoves decreased estimated exposure to emissions by > 90%; the system could increase indoor air quality dramatically.	Titcombe and Simcik (2011)
	Acute respiratory illness and air quality in biomass fuel users' homes	• PM_{10}, NO_2, and CO concentrations were highest in the kitchen and lowest outdoors. • For all pollutants except CO, kitchen concentrations were highest in the kitchen located in the living room. The levels recorded in kitchens were unaffected by the size of the family.	Kilabuko et al. (2007)
Nairobi (Kenya)	Effect of conventional and improved stoves on household air quality	• In the kitchen, the average of baseline $PM_{2.5}$ and CO concentrations were 586 μgm^{-3} and 4.9 ppm, respectively. • Improved biomass cookstoves released less air pollutants than traditional cookstoves: median reductions were 38.8% for $PM_{2.5}$ and 27.1% for CO.	Yip et al. (2017)
	Household air pollution: sources and exposure to $PM_{2.5}$	• $PM_{2.5}$ concentrations were high and differed widely in households, particularly in the evenings (124.6 and 82.2 μg m^{-3}) and in households using charcoal (126.5 and 75.7 μg m^{-3}) in Korogocho and Viwandani). • Slums' residents were exposed to high levels of $PM_{2.5}$ in their homes.	Muindi et al. (2016)

floor area, kitchen volume, window size, door dimensions, and monitoring location. The occupant survey covered factors such as number of kitchen occupants during cooking, type of cookstoves and fuel used, time and duration of cooking, type of cooking carried out, types of cuisines, and status of natural and mechanical ventilation during cooking. Fig. 1 shows the location of cities and the characteristics of the kitchens are listed in Table 2.

A low-income family generates income amounts that do not exceed certain preset maximum levels, which vary from country to country based on their cultural values and economic strength (Evans and Evans, 2007). However, the approach to measuring public housing affordability is diverse among scholars (Jiburum et al., 2021) and globally. According to the Development Assistance Committee's list of Official Development Assistance recipients, the gross national income of low-income countries (which are not least developed countries) ranged between 1006 and 3955 USD in 2006, but effective for reporting from 2021 (DAC, 2021). Based on these facts, we adopted the suggested traditional rule-of-thumb approach whereby a low-income house is identified based on house affordability and available facilities that ensure comfortable and healthy living (Napoli et al., 2016). We have relied on local knowledge to ensure that the following criterion is met in the studied homes where households making < 80% of the median income in the local area where a dwelling would cost ~ 24% of the area median income (Yglesias, 2015).

To ensure that results were comparable among in-kitchen exposure conditions across the studied homes in all cities, we confirmed the following criteria were met by all the selected homes (Section 2.2): (i) residents belonged to low-income families, (ii) homes were either ground or first floor, (iii) all measurements were made in the kitchen, (iv) monitors were placed at breathing height (1.5 m above ground level) and ~ 1.5 m from the cooking, (v) identical measuring equipment was used, (vi) the same duration of data collection, (vii) the same number of homes in all cities, and (viii) cooking occurred on a daily basis.

2.2. *Description of studied homes*

Due to the variations in economic and social standards within the studied countries (UNDESA, 2020), the choice of monitored homes was based on the local knowledge of researchers to ensure homes within a city and across cities meet a common set of parameters. The following criteria were met for a uniform and comparable selection across all cities: (i) homes had to be located within densely populated areas, (ii) homeowners had to be from the low-income class within the studied city, (iii) occupants must cook on a daily basis, and (iv) each home should have a minimum of one or more occupants. Further details on studied areas are described in SI Section S1.

A brief description of home characteristics in each city are as follows:

- **Dhaka** is a rapidly growing megacity that suffers from high levels of indoor and outdoor air pollution. The total area of Dhaka city is 306 km^2, and it is home to 21.74 million inhabitants in 2018 (UN, 2018). Dhaka is ranked as the number one capital city in the world in terms of poor air quality (IQAir, 2020). Sampling was carried out in five homes at two locations in the city: a relatively low-income area characterized by high pollution levels - southeastern part of the city; a relatively low polluted area within Dhaka University campus - south central part of the city. The homes were two-bedroom apartments that accommodated a minimum of three occupants. DAC2 and DAC3 were surrounded by trees and were situated in the less congested region of Dhaka University than the other homes. All homes were on the ground floor but some were located in buildings that consisted of up to five storeys (counted as first floor). The homes were made of bricks and cement. They were 10–50 m away from moderate traffic roads. All kitchens were allotted small separate rooms with one small window (average size 0.7 m × 0.8 m) and one door, except for DAC5, where the kitchen was combined with the living/dining room. The kitchen dimensions averaged 2.75 m × 1.75 m × 1.75 m, where a maximum of two people could cook at the same time. Some kitchens were equipped with exhaust fans used during cooking. However, none of the homes had heating/cooling systems in the kitchens. The stoves were two-hobed and operated on natural gas (methane) sourced from the national grid. Homeowners utilised the kitchen two to four times a day for frying, grilling, boiling, and reheating. Each cooking session averaged between 30 and 90 min. COVID19 lockdown was observed throughout the survey period, hence public transportation ceased at the beginning and started commuting during the study at DAC3 (Day 2). In addition to the COVID19 lockdown, there were several rainy days reducing the overall concentrations of the ambient $PM_{2.5}$ during sampling in Dhaka city.

- **Chennai**, located on the Coromandel Coast of the Bay of Bengal, is the capital city of the Indian state of Tamil Nadu. Chennai metropolitan area covers 1189 km^2 (CMDA, 2021) with a population of 11.56 million (population density of 10,656 per km^2) (DWUA, 2021). The study focused on middle- and low-income houses located within the residential areas of the city. The houses were single-bedroom apartments that accommodated a minimum of three occupants. The five houses chosen were on the ground or first floor of 3–5 storeyed buildings made of brick and concrete. The kitchens were indoor separate rooms or part of the living/dining space, with at least a door and a window. Doors and windows were kept open during cooking, and extraction fans were used where available (except in CHE1). None of the houses had a heating/cooling system in the kitchen. All the selected houses used LPG cylinders as fuel for their double burner gas stoves. The kitchens were typically small separate rooms with an average size of 3.5 m × 2.5 m × 3.0 m. The kitchens were occupied by 1–2 cooks during each cooking session, which lasted between 30 and 120 min for 2–3 times a day. The cooking activities were mainly frying, boiling, and reheating.
- **Nanjing**, covering an area of 6,587 km^2, is home to over 8.5 million inhabitants (NanG, 2019). This study focused on the over-populated Jiangning district, with many old settlements, reflecting the typical living conditions in Nanjing. The five homes chosen for this study were mainly two-bedroom apartments that accommodated a minimum of three occupants. The apartments were on the lower floors (first) of 7–11 storeyed buildings made of reinforced concrete. The ground floor was used for open non-motorised parking. The apartments were 50–150 m away from city roads. However, most homes were in residential areas, hence neighboring roads were not often heavily congested, except for NKG3, exposed to intense traffic-related air pollution. The kitchens were typically small separate rooms with average size of 2.6 m × 1.9 m × 2.3 m, with just one occupant per cooking session. The kitchens had one small window (average size 1.1 m × 1.4 m) and one door, which were always left open during cooking, except for NKG4 where the window was always closed. All kitchens were equipped with extraction fans used during cooking. Although, the fans were barely cleaned, especially in NKG5 where it had not been cleaned for three years. Also, only NKG2 used a heating system in the kitchen during monitoring. The cookers were stand-alone units composed of two hob stoves, and fueled through the national natural gas grid. Homeowners utilised the kitchen between two and three times a day for frying, grilling, boiling, steaming, and reheating. NKG2 preferred steaming while NKG5 relied on boiling and reheating. Each cooking session lapsed between 15 and 50 min.
- **Medellín:** The metropolitan area of Medellín covers an area of 1.166 km^2 (AMVA 2021) and its population is over 3.7 million (DANE, 2018). Five low-income households in residential areas were studied. Most homes were 2–3 bedroom apartments with 2 to 6 occupants. Except for MDE5, homes were located at ground and first floor of one or two-storeyed residential buildings. All buildings were made of concrete, mortar and bricks, with ceramic tile floors. The apartments were 20–100 m away from moderate-heavy traffic roads. With the exception of MDE4, kitchens were separate rooms. Kitchens in MDE 2, 3 and 5 had windows or openings to the exterior, while kitchens in MDE 1 and 4 had openings onto other home areas. Kitchen areas were between 5 and 10 m^2, and the average window size was 1 m × 0.8 m. All kitchens were connected to the natural gas grid. MDE1, 3 and 5 were equipped with four burner countertops, MDE2 had a two burner gas stove while MDE4 had a 4 burner gas stove with an oven.

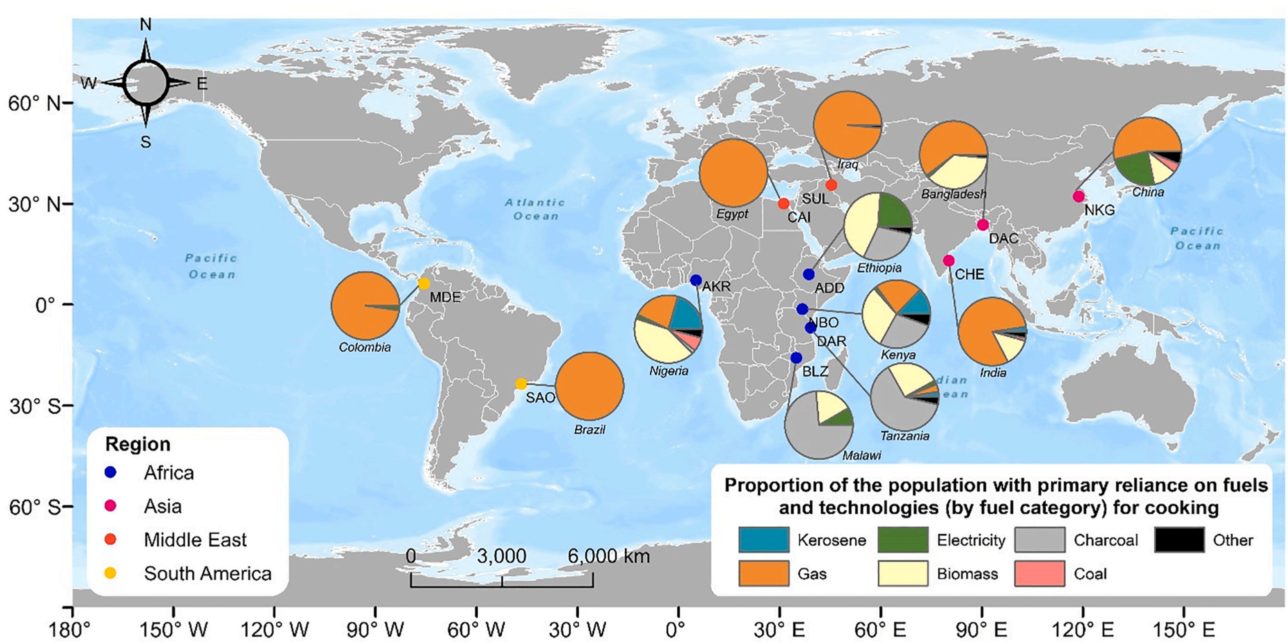

Fig. 1. Location map showing the 12 studied cities where low-income houses in each city were monitored (see Section 2.2). The pie chart shows the proportion of the urban population (%) with primary reliance on fuels and technologies for cooking in each studied country (WHO, 2019). The specific fuels and technologies categories used were: electricity, gaseous fuels (including liquid petroleum gas, natural gas and biogas), kerosene, biomass (unprocessed biomass includes wood, crop residues and dung), charcoal, and coal (WHO, 2019). Abbreviations: Dhaka (DAC), Chennai (CHE), Nanjing (NKG), Medellín (MDE), São Paulo (SAO), Cairo (CAI), Sulaymaniyah (SUL), Addis Ababa (ADD), Akure (AKR), Blantyre (BLZ), Nairobi (NBO), and Dar-es-Salaam (DAR).

Table 2
Details of the studied homes, showing characteristics such as the sampling duration, fuel, cooking duration as well as stove, kitchen and ventilation types. Each city is assigned a code, which is based on the abbreviations of their respective city airports. The kitchen were classified into three ventilation categories: (i) natural ventilation when the window and door was open during cooking, (ii) natural ventilation when only door was open during cooking, and (iii) dual natural plus mechanical ventilation when an extraction fan is used during cooking and either door and window are open or door only.

City (code)	Home ID	Kitchen size (m): L × W × H (volume; m^3)	Fuel type (sampling period)	Kitchen type (open/ separate)/Cooker type	Average cooking duration per day (min)	Ventilation conditions during cooking
Dhaka (DAC)	DAC1	1.8 × 2.0 × 3.0 (10.8)	NG (19–25 April)	Separate Gas stove	128	Natural (open door)
	DAC2	1.5 × 1,5 × 2,75 (6.2)	NG (27 April-05 May)	Separate Gas stove	125	Natural (open window + open door)
	DAC3	1.5 × 1.5 × 2.75 (6.2)	NG (05–11 May)	Separate Gas stove	159	Natural(open window + open door)
	DAC4	2.0 × 1.8 × 2.75 (9.9)	NG (16–22 May)	Separate Gas stove	213	Natural(open window + open door)
	DAC5	2.0 × 1.75 × 2.75 (9.6)	NG (31 May-07 June)	Separate Gas stove	257	Natural(open window + open door)
Chennai (CHE)	CHE1	6.0 × 3.0 × 3.0 (54)	LPG (01–09 July)	Open Double-burner gas stove	240	Natural (open window)
	CHE2	4.2 × 2.8 × 2.8 (32.9)	LPG (13–20 July)	Separate Double-burner gas stove	201	Dual: MechanicalNatural (open window + open door)
	CHE3	2.5 × 3.5 × 3 (26.2)	LPG(21–31 July)	Separate Double-burner gas stove	90	Dual: MechanicalNatural (open window + open door)
	CHE4	2 × 1.5 × 3 (9.0)	LPG(03–11 Aug)	Separate Double-burner gas stove	98.6	Natural (open window + open door)
	CHE5	3 × 2 × 3 (18.0)	LPG(11–18 Sept)	Separate Double-burner gas stove	163	Natural (open door)
Nanjing (NKG)	NKG1	2.1 × 1.65 × 2.8 (9.7)	NG(10 April-16 April)	Separate Gas cooker	85	Dual: Mechanical Natural (open window + open door)
	NKG2	2.94 × 2.04 × 2.34 (14.0)	NG(26 April-03 May)	Separate Gas cooker	96	Dual: MechanicalNatural (open window + open door)
	NKG3	2.03 × 2.3 × 2.24 (10.5)	NG(09–15 May)	Separate Gas cooker	113	Dual: MechanicalNatural (open window + open door)
	NKG4	2.94 × 2.04 × 2.34 (14.0)	NG(17–23 May)	Separate Gas cooker	37	Dual: Mechanical Natural (open door)
	NKG5	2.9 × 2.12 × 2.4 (14.7)	NG(25–31 May)	Separate Gas cooker	46	Dual: MechanicalNatural (open window + open door)
Medellín (MDE)	MDE1	3.15 × 3.25 × 3.20 (32.8)	NG (15–21 July)	Separate 4-burner gas stove	119	Natural (open window + open door)
	MDE2	3.4 × 1.55 × 2.18 (11.5)	NG (31 July-12 August)	Separate 2-burner gas stove	116	Natural (open window + open door)
	MDE3	3.35 × 2.11 × 2.2 (15.5)	NG (18–25 August)	Separate 4-burner gas stove	165	Natural (open window + open door)
	MDE4	2.8 × 2.3 × 2.2 (14.2)	NG (04–12 September)	Open 4-burner gas stove	116	Natural (open window + open door)
	MDE5	2.7 × 2.7 × 2.2 (16.0)	NG (16–24 September)	Separate 4-burner gas countertop stove	84	Natural (open window + open door)
São Paulo (SAO)	SAO1	4.0 × 2.6 × 2.5 m (26.0)	LPG (13–19 May)	Separate 5-mouth stove + oven	75	Natural (open window + open door)
	SAO2	3.2 × 2.9 × 2.6 (24.1)	LPG (25–31 May)	Separate 4-mouth stove + oven	24	Natural (open window)
	SAO3	1.5 × 2.8 × 2.4 + 1.2 × 1.9 × 2.4 (15.5)*	LPG (16–22 June)	Open 4-mouth stove + oven	74	Natural (open door)
	SAO4	5.3 × 2.5 × 2.4 (31.8)	LPG (09–15 July)	Open 4-mouth stove + oven	83	Natural (open window + open door)
	SAO5	5.9 × 2.45 × 2.72 (39.3)	LPG (24–30 August)	Separate 4-mouth stove + oven	52	Natural (open window + open door)
Cairo (CAI)	CAI1	2.15 × 2.5 × 5 × 3.1 (16.7)	NG (25 April-01 May)	Separate 4-mouth stove + oven	152	Natural (open window + open door)
	CAI2	3.8 × 2.6 × 2.7 (26.7)	NG (02–09 May)	Separate 5-mouth stove + oven	181	Dual: MechanicalNatural (open window + open door)
	CAI3	3.1 × 2.2 × 2.5 (17.1)	NG (15–22 May)	Separate 5-mouth stove + oven	190	Dual: MechanicalNatural (open window + open door)
	CAI4	2.86 × 2.86 × 2 (16.4)	NG (01–07 June)	Separate 5-mouth stove + oven	86	Dual: MechanicalNatural (open window + open door)
	CAI5	2.15 × 2.55 × 3.1 (17)	NG (13–21 June)	Separate 4-mouth stove + oven	85	Natural (open window + open door)
Sulaymaniyah (SUL)	SUL1	2.9 × 1.93 × 2.93 (16.4)	NG (30 March–06 April)	Separate 5-burner gas hob	125	Dual: MechanicalNatural (open window + open door)
	SUL2	3.12 × 1.6 × 3.1 (15.5)	NG (07–15 April)	Separate 5-burner gas hob	140	Dual: MechanicalNatural (open window + open door)
	SUL3	4.0 × 2.23 × 2.85 (25.4)	NG (15–22 April)	Separate 5-burner gas hob	117	Dual: MechanicalNatural (open door)
	SUL4	1.1 × 1.8.5 × 2.3 (4.7)	NG (01–08 May)		120	

(continued on next page)

Table 2 (*continued*)

City (code)	Home ID	Kitchen size (m): L × W × H (volume; m^3)	Fuel type (sampling period)	Kitchen type (open/ separate)/Cooker type	Average cooking duration per day (min)	Ventilation conditions during cooking
				Separate 5-burner gas hob		Dual: MechanicalNatural (open door)
	SUL 5	3.7 × 3.8 × 2.7 (37.9)	NG (08–15 May)	Separate 5-burner gas hob	75	Dual: MechanicalNatural (open door)
Addis Ababa (ADD)	ADD1	2.5 × 2.5 × 3 (18.7)	Electric + Charcoal (20–26 July)	Open Electric stove	240	Natural (open door)
	ADD2	2 × 2 × 2.8 (11.2)	Electric and charcoal (27 July-03 August)	Open Electric and charcoal stoves	180	Natural (open door)
	ADD3	2 × 2 × 2.5 (10.0)	Electric and charcoal (04–11 August)	Separate Electric and charcoal stoves	210	Natural (open door)
	ADD4	3 × 1.5 × 2.5 × 0.5 (5.6)	Electric + Charcoal (12–19 August)	Separate Electric and charcoal stoves	240	Natural (open door)
	ADD5	4 × 5 × 3 (60.0)	Electric + Charcoal (23–30 August)	Open Electric stove	137	Natural (open window + open door)
Akure (AKR)	AKR1	2.3 × 1.5 × 2.09 (7.21)	LPG and Electric (06–13 August)	Separate LPG + Electric stove	244	Natural (open window + open door)
	AKR2	2.3 × 1.5 × 2.09 (7.21)	LPG and Electric (28 August-06 September)	Separate LPG + Electric stove	192	Natural (open window + open door)
	AKR3	2.3 × 1.5 × 2.09 (7.21)	LPG and Electric (14–25 September)	Separate LPG + Electric stove	244	Natural (open window + open door)
	AKR4	3 × 3 × 2 (18)	LPG (25 September-02 October)	Open LPG stove	283	Natural (open window + open door)
	AKR5	4 × 2 × 3 (24)	LPG and Kerosene (05–15 October)	Separate LPG + Kerosene stove	359	Natural (open window + open door)
Blantyre (BLZ)	BLZ1	4 × 4 × 6 (96)	Electric and charcoal (18–25 July)	Open 4-plate cooking stove	150	Natural (open window + open door)
	BLZ2	4 × 4 × 6 (96)	Electric and charcoal (10–18 August)	Open 4-plate cooking stove	90	Natural (open window + open door)
	BLZ3	5 × 4 × 3 (60)	Electric and charcoal (21 August-04 September)	Open 2-hot plate stove	104	Natural (open door)
	BLZ4	3 × 3 × 4 (36)	Charcoal (07–15 September)	Open Charcoal burner	90	Natural (open window + open door)
	BLZ5	4 × 5 × 6 (120)	Electric and NG (18–26 September)	Open 4-plate cooking stove	124	Natural (open window + open door)
Dar-es-Salaam (DAR)	DAR1	2.5 × 3.0 × 3.0 (22.5)	NG and charcoal (15–21 April)	Separate 2-plate gas and charcoal stove	120	Natural (open door)
	DAR2	2.5 × 3.0 × 3.0 (22.5)	NG (21–28 April)	Open 2-plate gas stove	120	Natural (open door)
	DAR3	2.3 × 1.8 × 2.0 (8.3)	NG (10–17 May)	Separate 2-plate gas stove	150	Natural (open window + open door)
	DAR4	3.0 × 2.3 × 2.5 (17.2)	NG and charcoal (17–24 May)	Separate 2-plate gas stove	168	Natural (open window + open door)
	DAR5	4.0 × 2.5 × 2.0 (20)	NG and charcoal (25 May-01 June)	Separate 2-plate gas stove	87	Natural (open window + open door)
Nairobi (NBO)	NBO1	4.0 × 4.0 × 2.5 (40)	Kerosene (18–25 April)	Open Kerosene stove	210	Natural (open door)
	NBO2	5.0 × 5.0 × 4.0 (100)	Kerosene (26 April-07 May)	Separate Kerosene stove	200	Natural (open door)
	NBO3	4.0 × 3.0 × 2.0 (24)	Electric coil and kerosene (07–17 May)	Open Kerosene stove and ethanol burner	210	Natural (open window + door)
	NBO4	4.0 × 4.0 × 2.0 (32)	Kerosene (17–24 May)	Open Kerosene stove	240	Natural (open door)
	NBO5	4.0 × 4.0 × 2.5 (40)	LPG and kerosene (24–31 May)	Open LPG stove and kerosene stove	180	Natural (open door)

Note: LPG: Liquefied Petroleum Gas; NG = Natural Gas (Propane gas bottled); Mechanical ventilation refers to 'Extractor Fan' available and used during cooking; *L-shaped kitchen.

Except for kitchens in MDE2 and 4, all kitchens had an under-cabinet range covered with a fan that was not used. Homeowners used the kitchen one to four times a day to fry, boil and reheat. Most cooking sessions lasted between 10 and 40 min.

- **São Paulo:** The Metropolitan Area of São Paulo (MASP) is the most economically important region in Brazil, covering 7,947 km^2 (SEADE, 2021). In 2018, it was home to over 21 million inhabitants (UN, 2018). The five homes chosen for this study were in a slum area called Jardim Colombo, located in the Paraisópolis complex, west zone of São Paulo city. The slum is home to approximately 18,000 residents in an area of 0.15 km^2 i.e. a population density of 120,805 inhabitants/km^2 compared to 2,674 inhabitants/km^2 in MASP (SEADE, 2021). The homes selected were made of brick and cement. Each had a separate kitchen with one window and at least one door. The door was usually connected to other rooms, such as the living room, a bedroom, or bathroom, except SAO2 where the door led to outside. There were no mechanical ventilation fans or heating/cooling systems in the kitchens. These houses were single floor.

However, due to the high population density and declivity of the region, the houses were usually on top of the other, making the houses higher than the street level. The streets were very narrow and traffic was low, except for SAO2, located next to a street at the entrance to the slum, with intense traffic (cars and buses). In addition, SAO2 differs from others in that it was below street level (~2 m). Cookers were stand-alone units composed of four to six hob stoves and an oven. They were all fueled through LPG cylinders. Homeowners utilised the kitchen between one and four times a day for frying, grilling, boiling, oven baking, and reheating. Each cooking session lasted from 3 to 90 min.

- **Cairo:** Greater Cairo covers an area of 3,085 km^2 (Madbouli et al., 2012), and is home to over 20 million inhabitants in 2018 (UN, 2018). This study focused on central and over-populated districts (including Rod El-Farag, Shobra and El-Zeitoun) that reflected the typical living conditions in Greater Cairo. The five homes chosen for this study were mostly two-bedroom apartments that accommodated a minimum of four occupants. The apartments were on the lower floors (counted as first floor) of 5–10 storeyed buildings, made of bricks and cement. The ground floor was used for commercial purposes. The apartments were 30–50 m away from heavy traffic roads. The kitchens were small separate rooms with an average size of 3 m × 2 m × 2 m where a maximum of two people could cook at the same time. All kitchens had one small window (average size of 0.5 m × 0.6 m) and one door. Doors and windows were always left open during cooking except at CAI1 where the window was always closed. All kitchens were equipped with extraction fans used during cooking, excluding in CAI1. However, none of the homes had heating/cooling systems in their kitchens. Cookers were stand-alone units composed of four to five burner gas hobs and an oven. They were fueled through the national natural gas grid. Homeowners utilised the kitchen between two and four times a day for frying, grilling, boiling, oven baking, and reheating. Each cooking session lasted between 30 and 50 min.
- **Sulaymaniyah** is the largest city in the Kurdistan Region of Iraq. The city is located between two chains of mountains (Goyzha and Glazarda), with an area of 20,144 km^2 and a population of approximately 1.9 million (CP, 2019). Two neighborhoods were chosen: one at the center of the city near the marketplace and the other in the east of the city. The five homes used in this study were mostly two-bedroom apartments accommodating a minimum of four people. The homes were on the ground and first floors of concrete buildings. The apartments were 40–70 m away from heavy traffic. The kitchens were separate rooms, with an average size of 3.1 m × 2.2 m × 2.8 m where a maximum of two people could cook concurrently. All kitchens had one window (average size of 1.3 m × 0.7 m) and one door, except SUL4 and 5 where no windows were present. The doors and windows were always open during cooking except at SUL3 and 5. All kitchens were equipped with extraction fans used during cooking. However, none of the homes had heating/cooling systems in the kitchens. Cookers, fuelled through natural gas bottles (LPG or propane), were standalone stoves with an oven. The residents used their kitchen between two and three times a day for frying, grilling, boiling, oven baking, and reheating. Each cooking session lasted for 30 to 90 min.
- **Addis Ababa** is the capital city of Ethiopia, covering an area of 527 km^2. The households used in this study were located in Arada Sub-city, at the center of the city. It is one of the early settlements dating back over a hundred years. The households were part of a community with 20 households, 10 m away from traffic. These households were located in slums. Four to five people lived in a single room with no windows. The kitchens were small separate rooms, with an average size of 2.5 m × 2.5 m × 3 m, where a maximum of two people could cook simultaneously. Some of the households had the kitchen in the single room they occupied, while others had their kitchen outdoors, attached to the main house. All the households used electricity and charcoal for cooking, and baking injera - a sour fermented flatbread made of teff flour. Stoves are either dual tabletop electric and charcoal stoves or just charcoal stoves. Each cooking session averaged 60–120 min.
- **Akure** is the state capital of Ondo State, one of the Niger-Delta, oil-rich states in the southwest geo-political zone of Nigeria. It is located 700 km southwest of Abuja and 311 km north of Lagos State of Nigeria (Akinwumiju et al., 2021). The study homes were located in Akure, the metro capital city of Ondo State, Southwestern Nigeria. The five homes chosen for this study were mostly two-bedroom apartments that accommodated a minimum of four occupants. The apartments were bungalows, made of bricks, woods, and cement. The homes were residential and not used for commercial purposes. The apartments were 50–100 m away from heavy traffic roads, but within unpaved roads. The kitchens were small separate rooms with an average size of 2.3 m × 1.5 m × 2.09 m where a maximum of four people could cook at the same time. All kitchens had one small window (average size of 0.85 m × 0.68 m) and one door. Doors and windows were always left open during cooking. None of the kitchens was equipped with extraction fans and heating/cooling systems. Cookers were stand-alone units composed of one to three burner gas hobs and an oven. Homeowners utilised the kitchen between two and three times a day for frying, grilling, boiling, oven baking and heating. Each cooking session lasted between 65 and 240 min.
- **Blantyre**, with an area of 240 km^2, is the oldest and second-largest city in Malawi. It was established by the Scottish missionaries in the 1870 s and was declared a planning area in 1897. It is the main commercial city in Malawi, hosting most private sector headquarters in the country (NSO, 2018). Blantyre is home to 451,220 inhabitants. The homes had 2 to 3 bedrooms and were made of bricks, sand, and cement. The households were located 10–20 m away from heavy traffic. The kitchens were small, separate rooms, with an average size of 3 m × 2 m × 3 m, where a maximum of two people could cook at the same time. All the kitchens had one window (average size of 1.5 m × 1 m) and two doors, which were always left open during cooking. The kitchens had neither an extraction fan nor a heating/cooling system. The cookers were standalone units composed of four hobs and an oven. They were all powered through the national electricity grid. Homeowners utilised the kitchen between two and four times a day for frying, grilling, boiling, oven baking, and reheating. Each cooking session averaged between 30 and 50 min.
- **Dar es Salaam** is the largest business hub in Tanzania, covering an area of 1,393 km^2 (DCC, 2017). It is home to over 5 million inhabitants, resulting in an average population density of > 3,000 persons/km^2. The study was conducted within the high-density settlement of Magomeni Mapipa of Kinondoni municipality, a good representative of over-populated and low-income streets of Dar es salaam. The study homes were situated along the busy highway of Morogoro, about 50–300 m from the highway. The homes were mostly three-bedroom ground floor houses that accommodated up to six residents. All the houses were made of bricks and cement, roofed with iron sheets and had either ceramic floor tiles or concrete floors. With the exception of DAR2 and 5, the kitchens were small separate rooms with an average size of 2.5 m × 2 m × 2 m, with one window (average size of 1.3 m × 1 m). The kitchen for DAR2 had no window connected to the outdoor environment, and DAR5 had two windows. Windows and doors were adjacent to each other and always open during cooking. None of the kitchens had extraction fans nor heating/cooling systems. Cookers were either a two-plate gas stove or one unit of charcoal-fueled stove. Data collection for DAR1 and 2 was done during the fasting month of Ramadan, hence, cooking was in the evening. As for the rest of the homes, cooking took place three times a day (i.e., morning, afternoon, and evening), and by one person. Each cooking session lasted between 15 and 90 min.
- **Nairobi:** Nairobi city covers an area of 704 km^2 and is home to over 4.3 million people (KNBS, 2019). 60% of the inhabitants reside in

large-scale informal settlements (CURI, University of Nairobi and Muungano wa Wanavijiji, 2014), located on marginal land with no legal land entitlements (Egondi et al., 2013) and limited access to basic amenities and services (such as water and sanitation, waste management, and education). This study was conducted in the informal settlement of Korogocho - one of the largest informal settlements in the city located 7 km north east of Nairobi. The social-economic dynamics in Korogocho are similar to most slums in the city; characterized by polluted environment, overcrowding, poor infrastructure, high levels of violence, and absolute poverty. Korogocho consists of 9 segments used as the sampling units. The five homes chosen for this study were mostly one-bedroom apartments on the ground floor, made of mud-wall or tin-sheets, and could accommodate a maximum of four occupants. The homes were 50–100 m away from heavy-traffic roads. Kitchens were typically attached within the living room or bedrooms, with one door or no permanently barricaded windows nor exhaust fans. In addition, none of the homes had heating/cooling systems in the kitchens. More than 90% of households in Nairobi's Korogocho cook in the room in which they live and sleep all occupants together (Ngeno et al., 2018). Cookers were stand-alone double or single units, fuelled by liquified petroleum gas, denatured bio-ethanol, or kerosene. Homeowners utilised the kitchen three times a day for frying, grilling, boiling, oven baking, and reheating. Each cooking session ranged between 30 and 90 min.

2.3. Instrumentation

The same Aeroqual Series 500 Portable Air Quality monitor with PM sensor (AEQAL, 2018) for $PM_{2.5}$ and PM_{10} measurements was used to monitor each house in all cities. The PM monitors were factory-calibrated and had been used in previous studies (Anderson and Gough, 2020; Lin et al., 2017; Masey et al., 2018). They were procured just before the kicking-off of experimental campaigns. A laser-based sensor is used to detect light scattered from particles passing through the laser beam. The instrument also has an internal fan that draws air across the particle sensor every 60 s. The S500 with the PM sensor collects data within 1.0–1000 μg m^{-3}, with 1.0 μg m^{-3} minimum detection limit. Operational temperature and relative humidity for the monitor and PM sensor range from 0 to 40 °C, and 0 to 90%, respectively. The S500 Aeroqual monitor was used in this study owing to its portability and ease of configuration. More importantly, the sensor head compensates for relative humidity because moisture could be entrapped by some particles, causing them to appear larger in reality. Considering that the light scattering sensors would likely measure high under humidity such as in kitchens, the moisture entrapment could influence the measurements, which is addressed by the humidity compensation function. Moreover, we also carried out quality control and assurance for all the data collected, which has been explained in Section 2.4.

2.4. Quality control and assurance

Co-location measurements were carried out in the air quality laboratory, using a nebuliser (1% KCl solution aerosol source) to simulate the high PM levels expected in a typical kitchen (for the Aeroqual monitor). The average relative humidity during the co-location was 63 ± 1%, comparable to 60 ± 7% observed during the monitoring in kitchens in all cities. PM data is generally required to be corrected for the hygroscopic growth of particles at the RH higher than 85% (Crilley et al., 2018; Jayaratne et al., 2018). We did not apply any corrections since our data were within the acceptable RH range. Co-location measurements of PM levels were carried out against each other and compared against a high-end optical particle spectrometer (GRIMM model 11-C), as shown in Figs. S1a, S1b and S2. The concentration ranges of the co-location in terms of $PM_{2.5}$ and PM_{10} were 2–138 and 3–394 μg m^{-3}, respectively. The data was recorded at 1-minute intervals to compare concentration values. High agreement was found among all PM monitors as the Pearson correlation coefficient (r) ranged from 0.90 to 0.99 and 0.81 to 0.98 for PM_{10} and $PM_{2.5}$, respectively (Figs. S1a and S1b). A high correlation was found between the PM monitors and the reference monitor, with r ranging from 0.80 to 0.85 and 0.77 to 0.85, for PM_{10} and $PM_{2.5}$, respectively (Figs. S1a and S1b). The PM monitors used in the 12 cities have been widely used in scientific research for various applications (Abbass et al., 2020; Apparicio et al., 2018; Embiale et al., 2019; Lin et al., 2015; McKercher et al., 2017). The conducted quality control and assurance protocols yielded results which permit a quantitative comparison between data from the various cities.

2.5. Data collection

Measurements took place between March and October 2021 (for 24 h in 7 days) continuously in each home. One-minute measurement intervals of $PM_{2.5}$ and PM_{10} were collected in 60 homes (Table 2), for 35 days (840 h) in each city, adding up to 420 days (10,080 h) across all cities (Table S3). Instruments were placed at the average adult breathing height (1.5 m) above the floor and ~ 1.5 m away from the cook/stove. The monitors were reset between homes. Furthermore, homeowners kept track of cooking activities and kitchen conditions during the week. The record provided valuable information that allowed better understanding of some pollution drivers and exposure conditions. Information collected by the surveys (Table S1) included kitchen configurations, the door and window dimensions, and available cooking equipment. Specifically, the type of cooking stove, the cuisines, time and duration of cooking sessions, and the number of kitchen occupants during cooking were recorded. The questionnaire also investigated any other sources of fumes besides cooking, including cleaning and smoking. Ambient temperature and humidity data were also recorded daily (Table S4) as well as information on outdoor sources of pollution (such as traffic, garbage burning, industrial sites or dust storms) and their proximity to the studied homes. In addition, holidays were noted where appropriate. Additional information about the homes, including floor number, number of inhabitants, number of bedrooms in the apartment or studio, was recorded. Data was retrieved from the instrument on a regular basis throughout the week for compilation. Data analysis methods are discussed in Sections 2.6 and 2.7. Further, data processing and statistical analyses (Section 3) were carried out using Microsoft Excel and R statistical softwares (R Core Team, 2019) with the software package openair (Carslaw and Ropkins, 2012).

2.6. Density distribution

We investigated the distribution of $PM_{2.5}$ and PM_{10} concentrations through density plots, which were smoothed versions of the histogram. This density plot represents the data distribution by estimating a continuous curve, which is referred to as the 'density function'. To calculate the density function, we used the kernel density estimation, which is a mathematical function that returns a probability for a given value of a random variable; in our case these variables were $PM_{2.5}$ and PM_{10} concentrations.

Kernel density estimation is a non-parametric estimation method that interpolates the probabilities across a defined range. It has been extensively used in statistical analysis in economics applied studies and it has also been used in air pollution studies (Xiong et al., 2020; Jiang et al., 2020). Eq. (1) represents the density function through the kernel density estimation, which is mathematically expressed as:

$$f(x) = \frac{1}{Nh}\sum_{i=0}^{N} K\left(\frac{x_i - x}{h}\right) \quad (1)$$

where N represents the number of observational values; h represents bandwidth; i represents a group of points varying from 1…N; Xi represents the sample points of $PM_{2.5}$ and PM_{10}; K represents the kernel

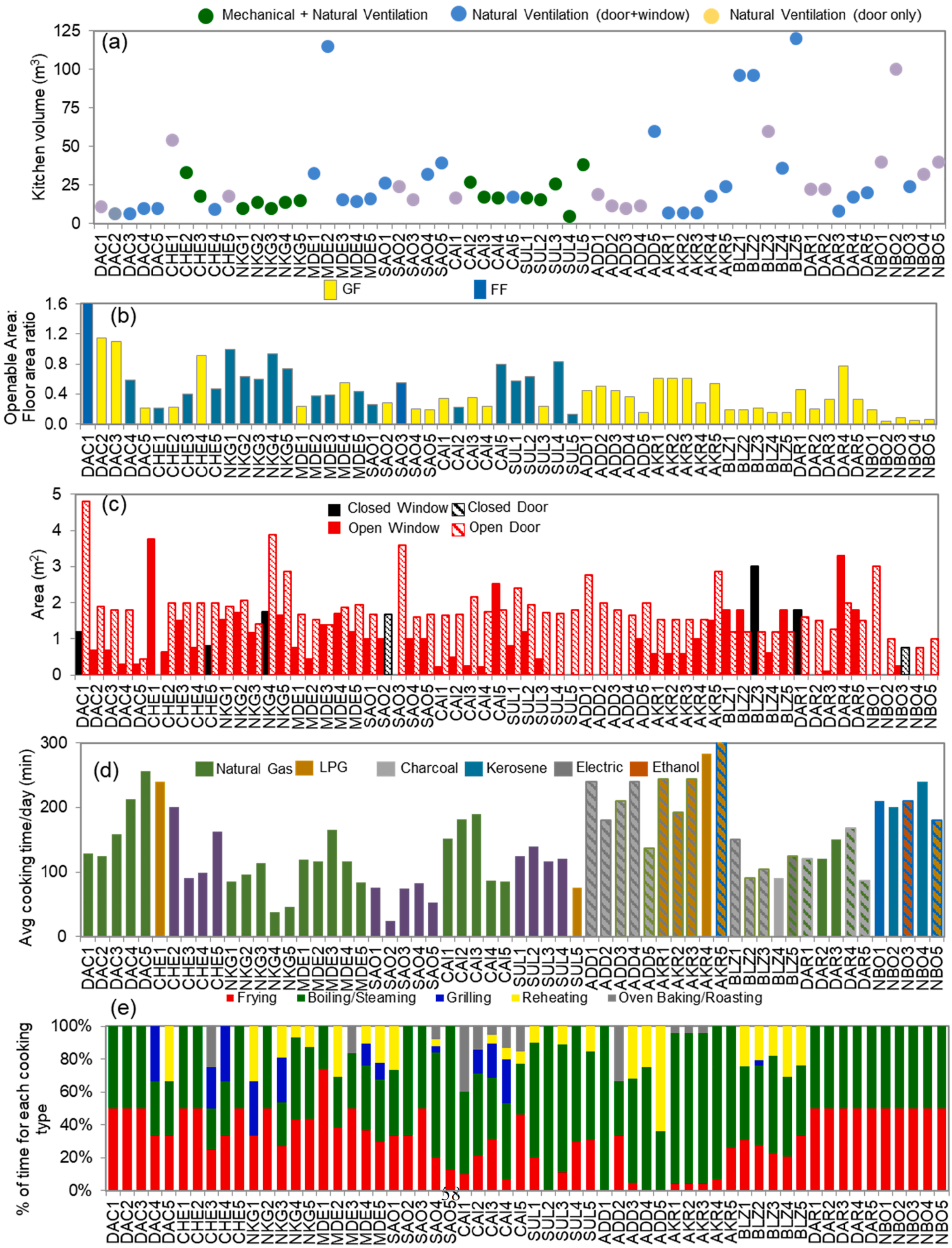

Fig. 2. (a) Scatter plot presenting the kitchen volume (m^3) of each home where colors indicate ventilation type; (b) bar chart showing the ratio of openable area (window + door) to the kitchen surface area where box colors indicate ground or first floor; (c) surface area (m^2) of windows (solid bars) and doors (striped bar) of each kitchen where the bar color indicates window/door status during cooking; (d) bar chart showing the average total time (min)spent cooking in the kitchen per day for each home; color indicates the fuel type used for cooking and striped bars the use of two fuels types; (e) various cooking methods and the percentage of times for each cooking type during the week. Pie Charts summarising the home and kitchen characteristics (f) the frequency of use of extraction fan during cooking; (g) the status of the door and window during cooking; (h) the types of fuel used for cooking; (i) the floor in the building; (j) the type of kitchen; (k) the number of occupants in kitchen during cooking.

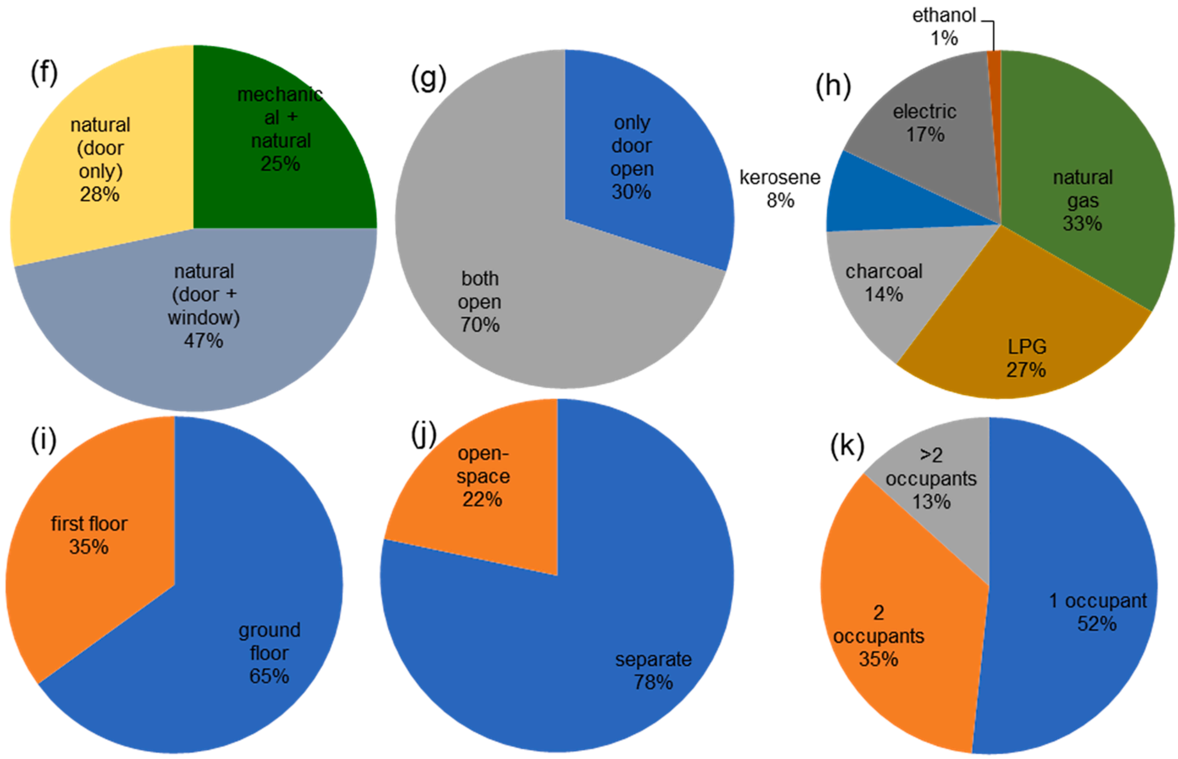

Fig. 2. (*continued*).

weighting function. Some common kernel functions are Gaussian, exponential, and quadratic functions. In this paper, we used the Gaussian kernel function to estimate and analyze the air pollution in the studied cities, as shown in Eq. (2):

$$f(x) = \frac{1}{Nh\sqrt{2\pi}} \sum_{i=0}^{N} e^{-\frac{1}{2}\left(\frac{x_i - x}{h}\right)^2} \quad (2)$$

2.7. Exposure risk assessment

According to the USEPA (1992), the general equation for potential inhaled dose (D_{pot}) for intake processes (inhalation and ingestion) is given by the integration of the chemical intake rate (Concentration (C) × Inhalation rate (IR)) over time by Eq. (3):

$$D_{pot} = \int_{t_1}^{t_2} C(t) \times IR(t)dt \quad (3)$$

Eq. (3) can also be expressed in discrete form as the summation of the doses received during various events *i*:

$$D_{pot} = \sum_i C_i \times IR_t \times ED_i \quad (4)$$

where ED_i = exposure duration for event *i*, IR_i and C_i = inhalation rate and pollutant concentration for event *i*, respectively. In our study, potential inhaled dose (D_{pot}) is given by Eq. (5):

$$D_{pot} = \frac{1}{BW}\sum_{i=1}^{n=1440} C_i \times IR_i \times ED_i \quad (5)$$

where C_i = concentration of PM_{10} or $PM_{2.5}$ in μg m^{-3}, IR_i = inhalation rate in m^3 min^{-1}, EDi = exposure duration (min), and BW = body weight in kg. Table S5 presents the average BW for children and adult females in each country in this study. The $n = 1440$, which is 24 h times 60 min per day. D_{pot} is expressed in μg kg^{-1} day^{-1}. An approximate age (years) and weight (kg) of all occupants in each home is presented in Figs. S3 and S4, and Table S6.

The short-term IR_i for daily activities was stated as 0.0123 m^3 min^{-1} (female) and 0.011 m^3 min^{-1} (children) (USEPA, 2011), and the mean D_{pot} was estimated for each home and each city for adult females and children. The influence of habits or environmental factors on the estimated dose was analyzed. The best and worst scenarios of indoor exposure and dose were discussed for each city studied.

The hazard ratio (HR) of each pollutant was determined by dividing its average concentration by its corresponding reference concentration (RfC) (Datta et al., 2017) using Eq. (6).

$$HR_i = C_i / RfC_i \quad (6)$$

where C_i = measured 24-h average concentration of a pollutant and RfC_i = corresponding reference concentration of the same pollutant. The reference values for $PM_{2.5}$ and PM_{10} for the 24-hour average were 15 and 45 μg m^{-3}, respectively (WHO, 2021b).

3. Results and discussion

3.1. Home and cooking characteristics

The qualitative and quantitative information available in building and occupant surveys (Section 2.1) were assessed to understand the variabilities among the studied homes. The 60 low-income monitored homes were classified according to kitchen occupancy, fuel used, cooking types, ventilation and kitchen volumes to identify the factors affecting aerosol levels within different kitchen environments across the studied homes for the subsequent sections.

Among the investigated households, 1.7 ± 0.96 persons occupied the kitchen on an average during cooking for 147 ± 68 min day^{-1}. Most of the kitchens (78%) were allotted separate rooms (Fig. 2j). Kitchen volumes ranged between 4.7 and 120 m^3 (average 27.8 m^3). About 25% of the kitchens relied on dual ventilation (natural and mechanical) during cooking, 47% used natural ventilation (via both doors and windows) and the remaining 28% used natural ventilation through the door only (Fig. 2f). Kitchens that used dual (natural + mechanical) ventilation during cooking had the extraction fans positioned right above the stove. Nevertheless, all kitchens were naturally ventilated where 70% had both the door and window open and the rest had only the door open (Fig. 2g).

Fig. 2a shows that all homes in NKG and SUL, three homes in CAI and two homes in CHE were dual ventilated (mechanical and natural) during cooking while kitchen volumes were sizable except for SUL4. The remaining homes in the rest of the cities had natural ventilation, showing that adopting mechanical ventilation depends on city culture, affordable and easy access to technology and economic status of the inhabitants; Middle Eastern cities as well as Asian cities in developing countries such as China and India used extraction fans for ventilation. Extraction fans were unavailable in kitchens of less developed Asian, South American and African countries. Most of the kitchens (76%) that did not open the window during cooking, i.e. relied on natural ventilation through doors only, were appropriately sized with volumes > 15 m^3 (within the medium and large size range). The kitchen volumes varied widely for homes using natural ventilation via both doors and windows. We investigated kitchen layouts as part of the occupant survey (Table S1). Images of the kitchens were also taken, showing that the volume of kitchen appliances and furniture were comparable across the studied kitchens to be able to show a significant disproportionate impact on the effective kitchen volume.

The ratio of openable areas (windows + door) to the kitchen floor area was 0.4 ± 0.3 with the highest (1.7) and lowest (0.04) being in DAC1 and NBO2, respectively. A low ratio indicates low natural ventilation opportunities in reference to the kitchen space. SAO, CAI, BLZ and NBO homes along with DAC5, CHE1 and CHE2 had low ratios with these same homes being on ground floor (GF; Fig. 2b). About 65% and 35% of the homes were on the GF and first floor (FF), respectively (Fig. 2b and 2i). These FF homes were essentially considered quasi-ground floors, given that these cities designate ground floor for parking and commercial purposes. Fig. 2c shows that the surface area of the kitchen doors was mostly standard across cities and were always open during cooking, while the window areas varied widely and were either closed or non existent in the kitchen (e.g. SAO3, SUL4-5, ADD1-4, DAR2, NBO1-2 and NBO4-5).

About 33% of homes used natural gas for cooking, followed by LPG (27%), electric stoves (17%), charcoal (14%), kerosene (8%) and ethanol (1%) that was only used occasionally in NBO3 (Fig. 2d and 2h). Almost all African homes used two cooking fuels (i.e. ADD, AKR, BKZ, DAR and NBO) interchangeably as indicated by striped bars in Fig. 2d. We observed that fuel types depend on the country (Fig. 1; Section 2.1). For example, natural gas is used in DAC, NKG, MDE and CAI and in some of the DAR homes; LPG in SAO, SUL, CHE and AKR; charcoal in ADD, BLZ and DAR; and kerosene in NBO and AKR5.

The cooking duration is an important factor affecting the emissions produced in the kitchen environment (Fig. 2d). The cooking duration in all the DAC, ADD, AKR and NBO homes, and most of the CAI homes were on average more than an hour longer than those in other cities (Fig. 2d). Another critical factor affecting emission levels resulting from cooking is the nature of the cooking style; for example, frying in open pans would result in higher emissions than baking/roasting in closed ovens. Furthermore, the types of cooking were consistent across cities despite their geographic and cultural variations. Most homes carried out frying and boiling/steaming, while few did grilling and oven baking (Fig. 2e). Most DAC, NKG, DAR and NBO (Asian and African) homes along with MDE homes spent>40% of their cooking time frying, while CAI and SUL (Middle Eastern homes) along with AKR were engaged in more boiling/steaming (or stewing). This observation shows that cultural variations influenced the cuisine and cooking type, which in turn, could affect the IAP levels in the kitchen, as discussed in Sections 3.2-3.5.

3.2. In-kitchen PM exposure profiles

$PM_{2.5}$ and PM_{10} concentrations varied widely among homes within the same city and across the 12 cities (Table 3). PM concentrations in the kitchen microenvironment differed according to diverse factors highlighted in Section 3.1. The average $PM_{2.5}$ (PM_{10}) concentration was 45 ± 5 (65 ± 61) μg m^{-3} (Table 3). The highest 185 ± 48 (220 ± 58) μg m^{-3} and lowest 10 ± 3 (14 ± 2) μg m^{-3} average $PM_{2.5}$ (PM_{10}) concentrations were found in DAC and MDE homes, respectively. In-kitchen PM_{10} concentrations (Fig. S5) followed the concentration variations of $PM_{2.5}$ (Fig. S6) throughout the whole study period. Average concentration variations for each home are summarised in Fig. 3 in reference to ventilation conditions and cooking fuel used, where DAC homes exhibited $PM_{2.5}$ concentrations at the higher end of the observed concentration range (>100 μg m^{-3}) as opposed to MDE, SUL (except SUL5) and AKR (except AKR1) homes showing the lower end of the concentration range (<20 μg m^{-3}). Fig. S7 shows the corresponding box plots of $PM_{2.5}$ for individual homes. As for the regions, Asia exhibited the maximum average $PM_{2.5}$ concentration of 82 ± 82 μg m^{-3} while the Middle East resulted in the minimum average concentration of 19 ± 18 μg m^{-3} (Fig. 3). For example, DAC in Asia (186 ± 141 μg m^{-3}) recorded the highest $PM_{2.5}$ exposure, followed by ADD in Africa (97 ± 235 μg m^{-3}), NKG in Asia (39 ± 35 μg m^{-3}) and BLZ in Africa (39 ± 75 μg m^{-3}). Lower concentration cities included AKR in Africa (17 ± 64 μg m^{-3}), followed by SUL in the Middle East (13 ± 20 μg m^{-3}) and MDE in South America (10 ± 35 μg m^{-3}).

According to ventilation types, the PM concentration followed the following order: natural ventilation (door only) > natural ventilation (door and window) > dual ventilation (natural and mechanical) (Fig. 4a). Interestingly, relatively higher PM levels were observed in DAC homes despite relying on natural ventilation through both door and window, and using natural gas for cooking, compared with kitchens having similar conditions in other cities (SAO, ADD, BLZ, DAR, and NBO) that exhibited lower PM concentrations (Fig. 3). This observation could be related to the kitchen size in DAC (volume < 10 m^3; Fig. 2a in Section 3.1) and that most of the cooking activities involved frying (Section 3.1), which typically releases high amounts of PM concentrations (Chen et al., 2018; Xiang et al., 2021). Furthermore, cooking periods in DAC consisted of the longest sessions across all the studied homes (Fig. 4d) where frying took place for ~ 40% of the time (Fig. 4e).

MDE, SUL and AKR homes manifested relatively lower $PM_{2.5}$ levels at 10 ± 35, 13 ± 21, 16 ± 64 μg m^{-3}, respectively (Table 3). This might be associated with their relatively large kitchen size (Section 3.1), allowing a better dispersion of cooking emissions resulting in lower concentrations. Moreover, these homes used relatively clean types of fuels for cooking such as natural gas, LPG, and electricity (Table 2, Fig. 4b). CHE2, CHE3, CAI4, and SUL1-5 homes used dual (natural and mechanical) ventilation during cooking; these exhibited significantly lower levels of $PM_{2.5}$ (Fig. 3) because cooking-emitted particles were swiftly removed through this dual mode of ventilation (Kang et al., 2019; Xiang et al., 2021). Exceptions were CAI2, CAI3 and NKG homes that showed relatively higher $PM_{2.5}$ concentrations despite using dual ventilation. This could be attributed to their relatively small-sized kitchens (Section 3.1) and the condition of the fan (i.e. age, cleanliness, speed) as the home surveys confirmed that the fans were too old to effectively remove the cooking emissions. In addition, homeowners in NKG and CAI also noted that they did not operate the fan (mechanical ventilation) consistently during every cooking session.

High $PM_{2.5}$ concentrations were found in ADD, BLZ and NBO homes (Fig. 3) where kitchens were all naturally ventilated, either through only the door or both window and door. Besides the limited ventilation, these levels can also be attributed to the use of relatively less clean cooking fuels such as kerosene and charcoal (Section 3.1). Burning of kerosene and charcoal are well-known to be a major emitter of fine aerosol particles in kitchen microenvironments (Kabera et al., 2020; Shupler et al., 2018). Furthermore, an earlier multinational study focusing on 120 rural communities in eight countries across Asia, Africa and South America, also concluded that using clean primary fuels for cooking substantially lowers in-kitchen $PM_{2.5}$ levels, with natural gas resulting in the lowest concentrations and animal dung causing the highest (Shupler

Table 3
Descriptive statistics of $PM_{2.5}$ and PM_{10} concentrations for each home in all cities. M = mean, SD = standard deviation, MED = median, [min, max] = range of minimum and maximum measured concentrations.

City	Home#	$PM_{2.5}$ (μg m^{-3})			PM_{10} (μg m^{-3})		
		M (SD)	MED	(min, max)	M (SD)	MED	(min, max)
DAC	DAC1	254 (173)	189	(54, 1129)	304 (208)	229	(63, 1319)
	DAC2	186 (108)	158	(56, 1317)	218 (152)	182	(64, 2839)
	DAC3	133 (79)	108	(43, 1067)	156 (95)	125	(50, 1257)
	DAC4	132 (140)	80	(32, 1245)	158 (184)	93	(37, 2593)
	DAC5	222 (144)	188	(32, 1170)	265 (178)	223	(37, 2526)
CHE	CHE1	23 (38)	19	(4, 1265)	32 (40)	27	(6, 1294)
	CHE2	14 (13)	11	(2, 321)	20 (19)	16	(2, 422)
	CHE3	19 (41)	14	(2, 1349)	28 (51)	22	(5, 2268)
	CHE4	36 (111)	16	(4, 1653)	48 (143)	24	(6, 2969)
	CHE5	18 (10)	17	(5, 211)	24 (15)	23	(8, 314)
NKG	NKG1	49 (38)	34	(6, 219)	63 (46)	47	(7, 713)
	NKG2	37 (34)	23	(4, 638)	64 (56)	53	(10, 1656)
	NKG3	54 (46)	39	(3, 941)	84 (98)	57	(5, 2579)
	NKG4	35 (29)	31	(5, 712)	43 (42)	36	(6, 1159)
	NKG5	21 (11)	18	(4, 108)	39 (16)	35	(6, 264)
MDE	MDE1	7 (21)	3	(1, 660)	11 (33)	6	(1, 1126)
	MDE2	15 (41)	7	(1, 1257)	18 (53)	10	(1, 2746)
	MDE3	12 (49)	6	(1, 1143)	14 (52)	8	(2, 1170)
	MDE4	8 (11)	5	(1, 252)	17 (38)	9	(2, 863)
	MDE5	9 (39)	5	(1, 1459)	12 (47)	7	(1, 2229)
SAO	SAO1	26 (41)	17	(1, 1085)	31 (56)	28	(1, 1402)
	SAO2	24 (33)	19	(4, 718)	29 (43)	23	(5, 909)
	SAO3	17 (15)	12	(1, 319)	20 (20)	15	(1, 508)
	SAO4	46 (31)	40	(7, 850)	54 (41)	46	(10, 1319)
	SAO5	42 (62)	31	(1, 1428)	51 (97)	33	(1, 2603)
CAI	CAI1	27 (25)	19	(8, 342)	60 (34)	51	(23, 621)
	CAI2	38 (27)	29	(4, 476)	86 (54)	73	(11, 1290)
	CAI3	18 (19)	15	(5, 935)	50 (38)	44	(10, 1314)
	CAI4	16 (10)	14	(6, 222)	34 (20)	30	(8, 597)
	CAI5	22 (15)	19	(7, 451)	34 (24)	31	(9, 989)
SUL	SUL1	9 (9)	6	(2, 104)	22 (27)	13	(2, 346)
	SUL2	9 (6)	8	(1, 32)	33 (25)	29	(3, 139)
	SUl3	13 (19)	8	(2, 462)	27 (27)	21	(2, 659)
	SUL4	10 (29)	7	(1, 1173)	44 (67)	29	(4, 2423)
	SUL5	25 (29)	14	(3, 361)	52 (33)	46	(5, 377)
ADD	ADD1	124 (289)	25	(2, 1430)	175 (138)	36	(2, 2454)
	ADD2	56 (136)	24	(4, 1413)	73 (186)	34	(4, 2436)
	ADD3	60 (126)	33	(3, 1381)	95 (179)	60	(4, 2318)
	ADD4	133 (295)	35	(7, 1426)	200 (450)	62	(7, 2459)
	ADD5	111 (262)	32	(6, 1414)	144 (357)	45	(7, 2437)
AKR	AKR1	27 (69)	17	(4, 1146)	33 (95)	19	(4,2060)
	AKR2	20 (77)	5	(1, 1246)	26 (95)	9	(1, 2233)
	AKR3	16 (71)	5	(1, 1283)	29 (102)	11	(2, 2395)
	AKR4	9 (47)	3	(1, 1103)	15 (60)	6	(1, 1999)
	AKR5	11 (52)	4	(1, 1121)	16 (57)	7	(1, 1614)
BLZ	BLZ1	31 (82)	14	(3, 1289)	45 (127)	18	(3, 2692)
	BLZ2	35 (80)	20	(9, 1356)	46 (117)	24	(11, 2721)
	BLZ3	39 (68)	25	(10, 1379)	49 (98)	30	(12, 2973)
	BLZ4	44 (71)	27	(7, 1149)	54 (87)	33	(8, 2529)
	BLZ5	47 (74)	31	(7, 1062)	59 (99)	38	(9, 2784
DAR	DAR1	15 (35)	9	(1, 1175)	29 (40)	22	(4, 1209)
	DAR2	25 (86)	10	(2, 1463)	42 (117)	24	(4, 2708)
	DAR3	27 (53)	17	(1, 1488)	53 (77)	39	(3, 2782)
	DAR4	59 (159)	23	(2, 1554)	99 (205)	55	(10, 2883)
	DAR5	37 (69)	21	(2, 1534)	70 (81)	53	(5, 1950)
NBO	NBO1	48 (137)	14	(1, 1587)	73 (182)	28	(1, 2862)
	NBO2	31 (82)	12	(1, 1508)	72 (122)	37	(4, 2711)
	NBO3	31 (61)	17	(2, 1468)	47 (91)	28	(2, 2675)
	NBO4	34 (51)	23	(5, 1283)	75 (90)	54	(8, 2165)
	NBO5	28 (57)	19	(4, 1280)	52 (93)	36	(7, 2341)

et al., 2020).

We noted that PM_{10} follows the same trend as $PM_{2.5}$ across the studied homes (Fig. S8), since $PM_{2.5}$ is a subset of PM_{10}. Fig. S9 shows the corresponding box plots of PM_{10} for individual homes. A summary of these box plots, presented in Fig. 4, shows that DAC, NKG and ADD homes had high average PM_{10} concentrations throughout the monitoring period while others such as those in MDE, AKR and SUL exhibited peaks lower than the 24-h average WHO guideline of 45 μg m^{-3}. As expected, individual homes within each city also exhibited a distinct variation due to different types of cooking activities (e.g. duration and type of cooking) and kitchen conditions (e.g. size and ventilation conditions) (Fig S10). For example, DAC1 and DAC5 showed the highest concentrations, followed by DAC2, DAC3 and DAC4. In addition, Fig. 5 illustrates the heat map of concentrations for each home in different cities. DAC, followed by ADD, had the highest $PM_{2.5}$ concentrations while MDE, SUL and AKR had the lowest $PM_{2.5}$ level. Further distinction is made by plotting the heat map for $PM_{2.5}$ and PM_{10} for each day and hour for individual homes (Figs. S11-S13). These diurnal and daily

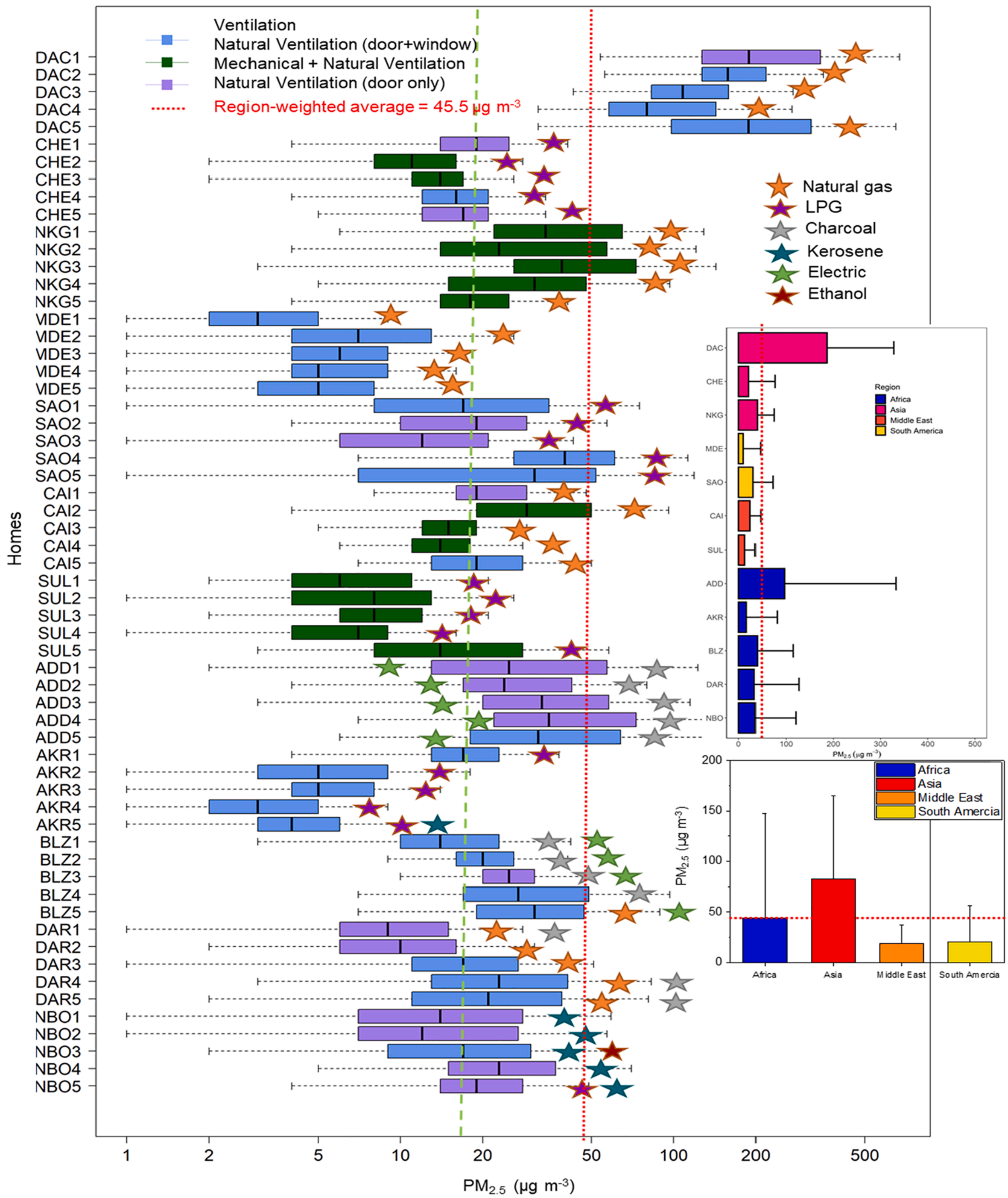

Fig. 3. Box plots of $PM_{2.5}$ concentration measured for all homes in each city as denoted by home code. The embedded figures on the right present the bar plot by city (top) and region (bottom). The top, middle, and bottom line of the box represent the 75th, median, and 25th percentiles, respectively. The bar color indicates the types of ventilation and the star color indicates fuel type used for cooking as shown in the figure legend. The green dashed line indicates 24-h average $PM_{2.5}$ guideline value by the WHO (2021). Red dashed line represents region-weighted average $PM_{2.5}$ concentration. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

concentration heat maps substantiate the earlier observations that the selection of types of fuel, kitchen size, cooking type and ventilation condition were the most important factors that can significantly impact the exposure to in-kitchen aerosol particle exposure.

The mean $PM_{2.5}$ (Fig. 4) and PM_{10} (Fig. S10) concentrations based on the average cooking time in individual homes were estimated according to the ventilation type (Fig. 4a and S10a), fuel type (Fig. 4b and S10b) and kitchen volume (Fig. 4c and S10c). These results substantiate the earlier observations that the average PM concentrations are minimum for homes using dual (natural and mechanical) ventilation during cooking while those using natural ventilation through doors only have higher average concentrations, highlighting the benefits of having extraction fans turned on during cooking (Fig. 4a and S10a). Average PM concentrations were highest in kitchens using charcoal during cooking, which is considered a less clean fuel type that is resorted to in low-income homes of Africa (Fig. 4b and S10b). Grouping of kitchens according to their volume showed that smaller-volume kitchens (<15 m^3) were associated with higher average PM levels. However, average

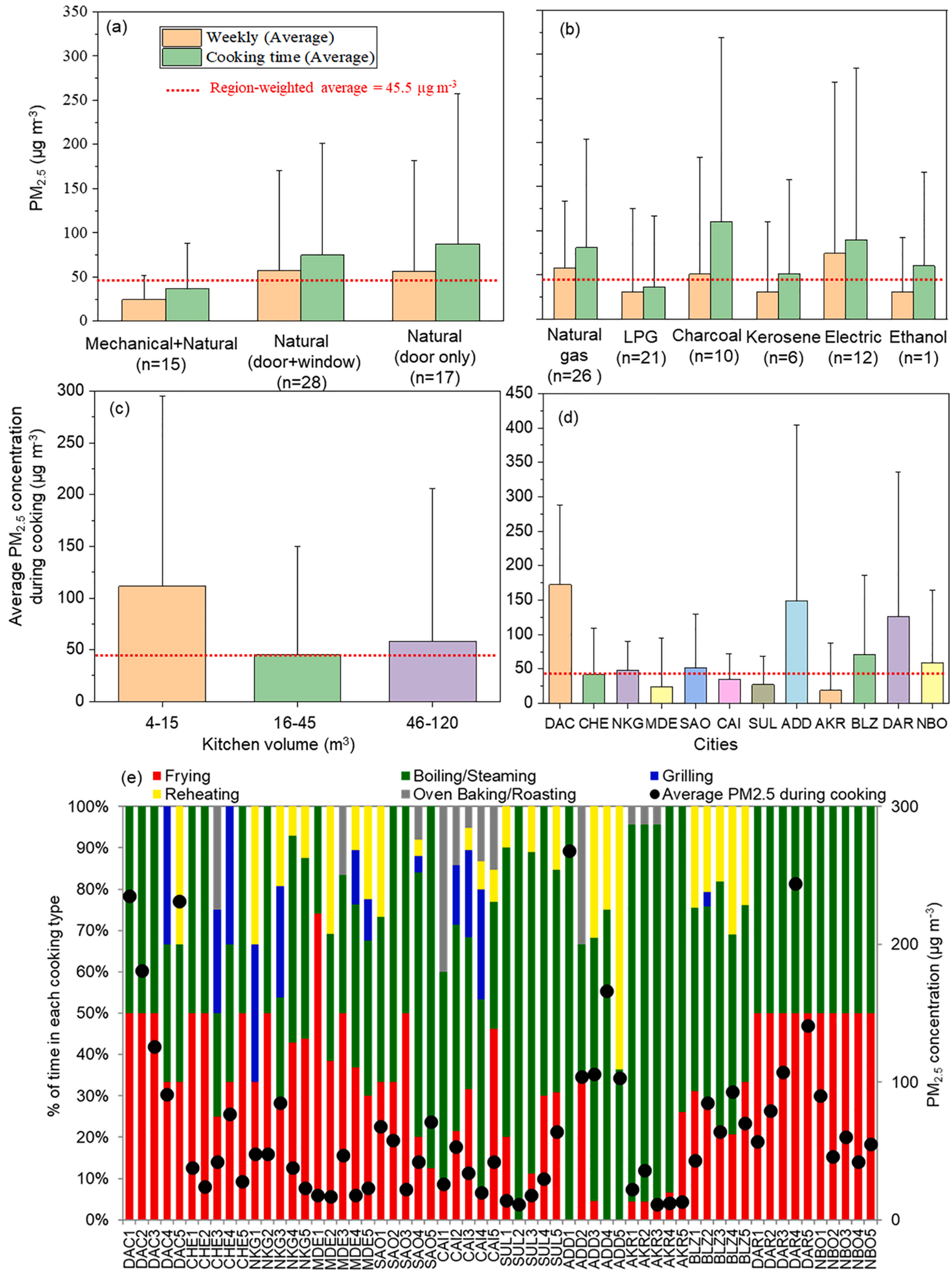

Fig. 4. The average $PM_{2.5}$ concentrations in contrast with kitchen conditions; x-axis indicates the groups and *n* is the number of kitchens in each group. The average concentration for the whole monitoring period and the average concentration during cooking sessions of kitchens grouped according to (a) ventilation type; (b) cooking fuel type (homes using two types of fuel during cooking have been double counted under both categories; hence the total *n* is more than 60); (c) volume (m^3). Bar chart presents (d) average $PM_{2.5}$ concentration during cooking for all homes (averaged five homes) in each city; (e) the percent of time spent on different cooking types and the average cooking time concentration for each of the 60 homes. Red dashed line represents the region weighted average $PM_{2.5}$ concentration. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

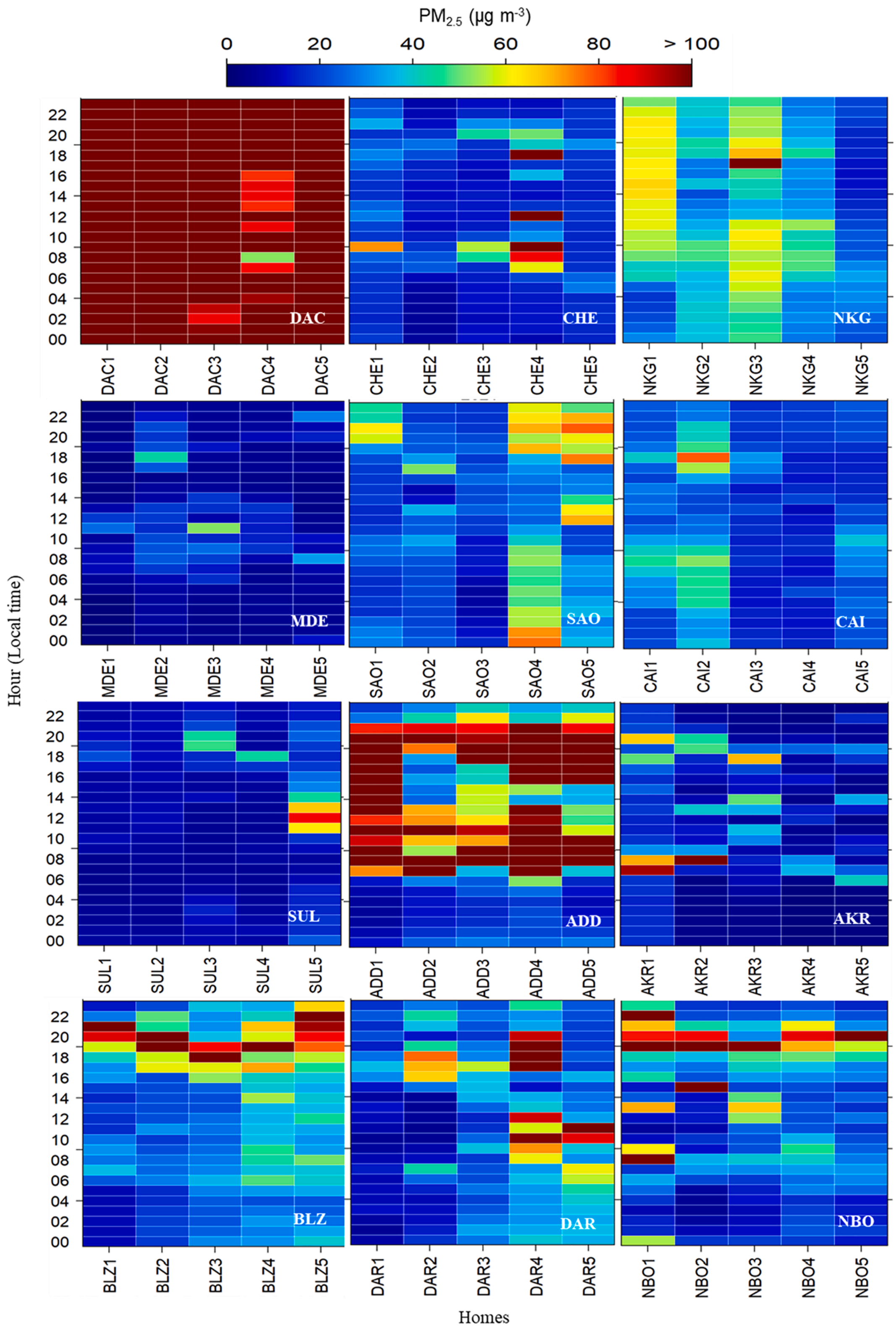

Fig. 5. Comparison of $PM_{2.5}$ concentration (μg m^{-3}) trend level plots for each home (home one to five) in different cities. Colour coded based on the $PM_{2.5}$ concentrations which started from blue (lowest level) to red (highest level). Each column in each city plot represents one home. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

concentrations for large-volume kitchens (46–120 m^3) were slightly higher than those for medium-volume kitchens (16–45 m^3), indicating mixed trends due to possible dominance of factors such as ventilation and cooking conditions (Fig. 4c and S10c). Finally, homes that do a significant amount of frying caused greater exposure of $PM_{2.5}$ (Fig. 4d) and PM_{10} (Fig. S10d) to their occupants, which is evident in DAC1, DAC2, ADD1, ADD4 and DAR4. We conclude that the fuel type, kitchen size, cooking type and ventilation conditions were the most crucial

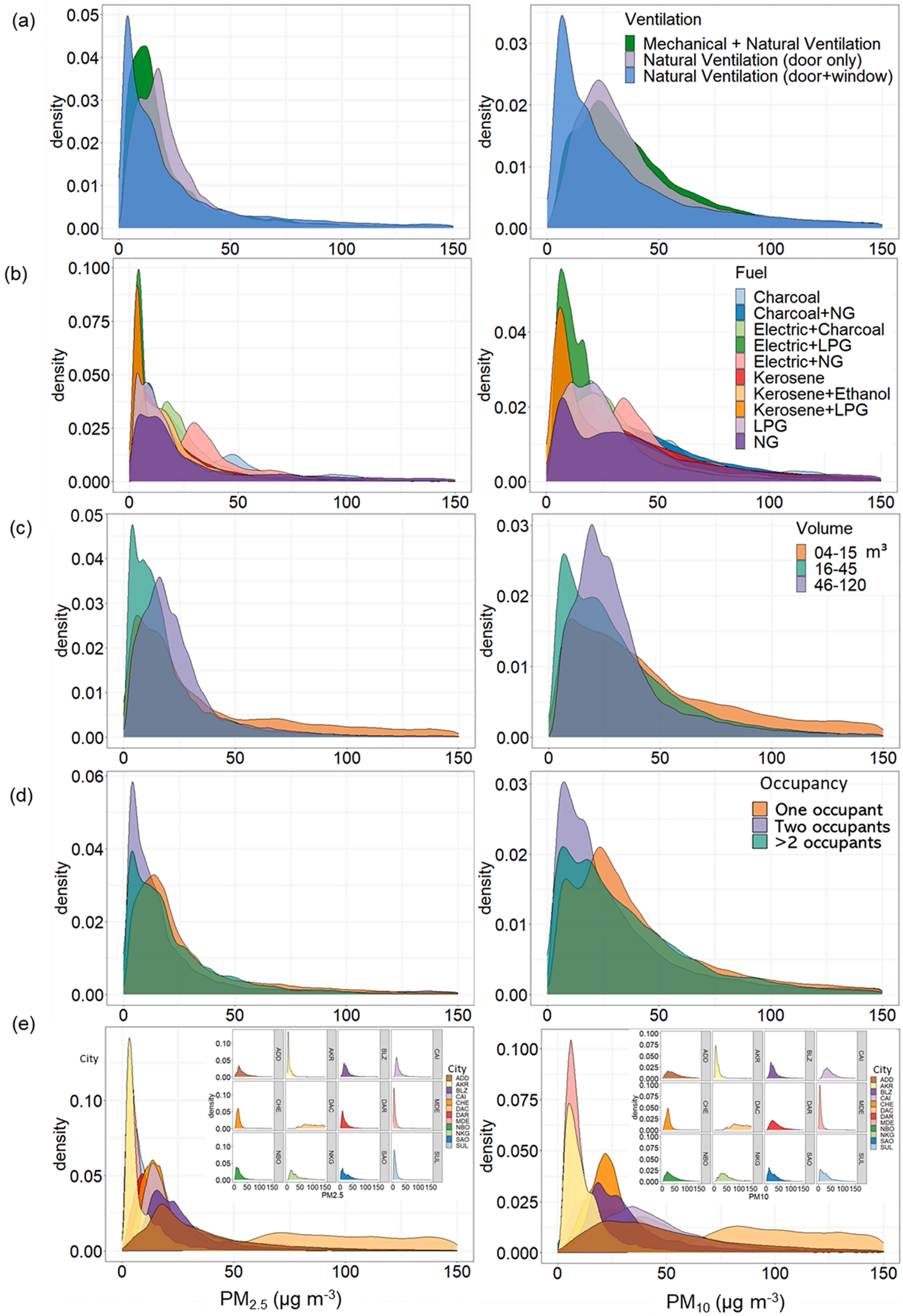

Fig. 6. Density plots of one-minute averaged $PM_{2.5}$ (left column) and PM_{10} (right column) concentrations in all the studies homes grouped by (a) ventilation type, (b) fuel used for cooking, (c) kitchen volume (m^3), (d) kitchen occupancy, and (e) city.

factors significantly affecting in-kitchen exposure to aerosol particles. The installation and use of extraction fans, especially during extensive activities such as frying, as well as opening both the door and windows in the absence of mechanical ventilation, can significantly reduce the in-kitchen exposure during cooking.

3.3. *Peak frequencies*

To illustrate the difference among the distribution of $PM_{2.5}$ and PM_{10} concentrations in the studied homes, we created density plots grouped by ventilation types, fuel type, kitchen volume and occupancy during cooking (Fig. 6a-d). A density plot is a smoothed version of a histogram that represents the distribution of a data through the estimation of a continuous curve, also known as the density function. Higher density values indicate higher probability of occurrence for a given concentration value. We also calculated the 90th percentile (P90) for the same groups to allow evaluating the behaviour of extreme concentrations in the tails of the density plots (Fig. S14). The density functions of $PM_{2.5}$ and PM_{10} concentrations varied with reference to the ventilation type (Fig. 6a). Kitchens with natural ventilation (door and window open) showed a peak density (local maxima) concentrated in lower $PM_{2.5}$ concentration range (0–5 μg m^{-3}), followed by kitchens with dual (natural and mechanical) ventilation (6–15 μg m^{-3}) and natural ventilation with only the door open (16–20 μg m^{-3}). We also observed a peak density concentrated in smaller PM_{10} concentration ranges in kitchens with natural ventilation (door and window open). Kitchens with dual (natural and mechanical) ventilation and natural ventilation (only the door) showed a more frequent PM_{10} concentration between 20 and 25 μg m^{-3}. This result suggests that having dual or natural ventilation with door and window open contributes more effectively to reduce $PM_{2.5}$ frequency level than having only the door open. However, for PM_{10}, neither mechanical ventilation nor natural ventilation with only the door open seem to effectively reduce PM_{10} levels frequency when compared to having natural ventilation with both the door and window open. Looking at the tail of the density plots (Fig. 6a), it is challenging to see differences among the ventilation types. However, smaller P90 values for $PM_{2.5}$ and PM_{10} concentrations can be seen in homes with dual ventilation, meaning that during 90% of the time the concentrations are smaller than 57 and 90 μg m^{-3} for $PM_{2.5}$ and PM_{10}, respectively (Fig. S14). Thus, higher concentrations of $PM_{2.5}$ and PM_{10} are more likely to occur in homes with both natural ventilation types.

Looking at the density plot grouped according to fuel type used for cooking (Fig. 6b), the narrow peaks of density occurred in lower $PM_{2.5}$ concentrations (0–5 μg m^{-3}) and were observed in homes using electric plus LPG (AKR1, AKR2, and AKR3) and kerosene plus LPG (NBO5). In other words, the probability of having smaller $PM_{2.5}$ concentrations in these homes is higher than in others. Homes that used LPG (CHE, SAO, and SUL) or natural gas (CAI, NKG, DAC, and MDE) exclusively also showed peaks in lower $PM_{2.5}$ concentrations but with a wider peak in the 0–20 μg m^{-3} range. As expected, the PM_{10} density plot manifested the same pattern as for $PM_{2.5}$ (Fig. 6b). We expected that kerosene fueled homes would have higher density peaks of $PM_{2.5}$ concentration in high concentration range and also higher P90 value due to being a less clean fuel. Still, homes with charcoal or electric plus natural gas fuels, located mostly in low-income African homes, depicted a greater likelihood of higher $PM_{2.5}$ concentrations in the ranges of 46–50 μg m^{-3} and 26–30 μg m^{-3}, respectively (which is in line with the observations noted in Section 3.2), and also showed P90 values higher than 76 μg m^{-3} (Fig. S14). For PM_{10}, the use of natural gas solely or the combination of charcoal along with natural gas in some homes showed a higher likelihood of having concentrations of PM_{10} higher than 50 μg m^{-3} because of their taller right tails in the density plot, and showing P90 values of 108 μg m^{-3} and 197 μg m^{-3} (Fig. S14). Homes fueled with charcoal also exhibited a modest peak around 90 μg m^{-3} for $PM_{2.5}$ with P90 at 88 μg m^{-3}, and for PM_{10} near 115 μg m^{-3} with a P90 at 105 μg m^{-3} (Fig. 6b).

As for the kitchen volume (Fig. 6c), the density function reached peak values which were skewed towards the low $PM_{2.5}$ concentration range of 3–4 μg m^{-3} in kitchens with 4–15 and 16–45 m^3 of volume. Conversely, the density function reached peak values between 12 and 15 μg m^{-3} for 46–120 m^3 volume. Smaller volumed kitchens (4–15 m^3) showed wider density function tail in higher concentration range for both $PM_{2.5}$ and PM_{10}, hence higher probability of occurrence of larger concentration range. Fig. S14 confirms the previous observations with higher P90 values among the three kitchen volume categories. During 90% of the time, kitchens with 4–15 m^3 showed concentrations smaller than 189 (230) μg m^{-3} for $PM_{2.5}$ (PM_{10}), while in larger kitchens P90 values were lower. Clearly a larger kitchen volume either through a larger surface area or larger heights could be another measure in reducing the peak kitchen exposure (Section 3.2).

Concerning the kitchen occupancy (Fig. 6d), kitchens with two or more occupants showed a higher probability of $PM_{2.5}$ (PM_{10}) concentration ranging between 0 and 5 μg m^{-3} (10–20 μg m^{-3}) compared with those with only one occupant showing a peak in the ~ 13 μg m^{-3} (~25 μg m^{-3}). Furthermore, one-occupant kitchens exhibited a higher likelihood of higher concentrations for $PM_{2.5}$ and PM_{10} as suggested by the taller right tail in the density plot (Fig. 6d), and by the higher P90 values (Fig. S14) when compared to the other occupancy categories. There might not be a direct relationship between the probability of having higher PM concentrations and the number of occupants in the kitchen as concentrations depend on the size of the kitchen or fuel used and not necessarily on the fact that it is occupied by only one person. For example, two people may spend a shorter amount of time preparing meals than a single person cooking more than one meal in one cooking session as it was reported in MDE homes.

Fig. 6e shows the $PM_{2.5}$ and PM_{10} concentration distribution of homes grouped by city. The lowest most frequent $PM_{2.5}$ (PM_{10}) concentrations were 4 (8), 5 (10) and 6 (9) μg m^{-3} for AKR, MDE and SUL homes, respectively. The highest most frequent $PM_{2.5}$ and PM_{10} concentrations among the cities were ~ 78 and 92 μg m^{-3}, respectively, for DAC. Furthermore, cities that had a greater probability of higher $PM_{2.5}$ concentrations included African (ADD, NKG) and Asian (DAC) homes where the stretched tail towards the right side of the density function was evident. These cities also showed higher $PM_{2.5}$ median values (Table 3) and P90 values (Fig S14) than other cities, which translates into occupants having a higher probability of spending more time exposed to higher concentrations. PM_{10} follows the same trend as for $PM_{2.5}$ but with a wider density function tail.

3.4. In-kitchen $PM_{2.5}/PM_{10}$ ratios

Indoor emission sources, such as occupant activities (including smoking, vacuuming, frying and grilling), human movement and cleaning (Nasir and Colbeck, 2013), ventilation, cooking method, fuel type, room arrangement and layout, and combustion devices (Abdullahi, et al., 2013) contribute to in-kitchen fine aerosol concentrations. Since fine and coarse fractions are usually produced from different sources, $PM_{2.5}/PM_{10}$ ratios were derived for each home to understand the characteristic of in-kitchen particle pollution and the factors influencing their levels (Fig. 7a). This ratio is usually indicative of the factors such as the nature of the food cooked, the cooking method and the in-kitchen emission conditions.

As expected, the predominance of fine particles ($PM_{2.5}/PM_{10} > 0.5$) is evident in 72% of the studied homes (i.e. DAC, CHE, NKG, MDE, SAO, ADD, AKR, BLZ and NBO) despite the wide variations in cooking fuels and food types. However, the ratios of some homes in CAI, SUL, DAR and NBO indicated a significant generation of fine particles owing to extensive frying (Fig. 7). Furthermore, NBO homes used kerosene which is known to generate more fine particles (Lam et al., 2012). Interestingly, the ratios across the DAC, SAO and BLZ homes were in the higher range of ~ 0.8, showing a dominance of fine particles. This could be attributed to the intense frying (for ~ 40% of the time; Section 3.1) and to the poor dispersion conditions owing to the small size of kitchens and absence of extraction fans in DAC and BLZ homes (Fig. 7a, Section 3.1). In addition, DAC homes used natural gas, while BLZ (except BLZ5) used charcoal for cooking (Fig. 7a), which resulted in large quantities of fine particles (Huang et al, 2016). The above observations reiterate that kitchen occupants' predominant exposure to fine fraction ($PM_{2.5}/PM_{10} > 0.5$) is owed to cooking activities resulting from primary emissions (such as combustion of fuels/cooking oil) and secondary aerosol formation from volatile organic and inorganic (sulphate and nitrate) compounds (Avery et al., 2019; Farmer et al., 2019).

All homes in CAI (except CAI5), SUL and DAR showed $PM_{2.5}/PM_{10} < 0.5$ (Fig. 7a), indicating the predominance of coarse particles. This occurrence could be ascribed to the water-based cooking i.e. boiling and

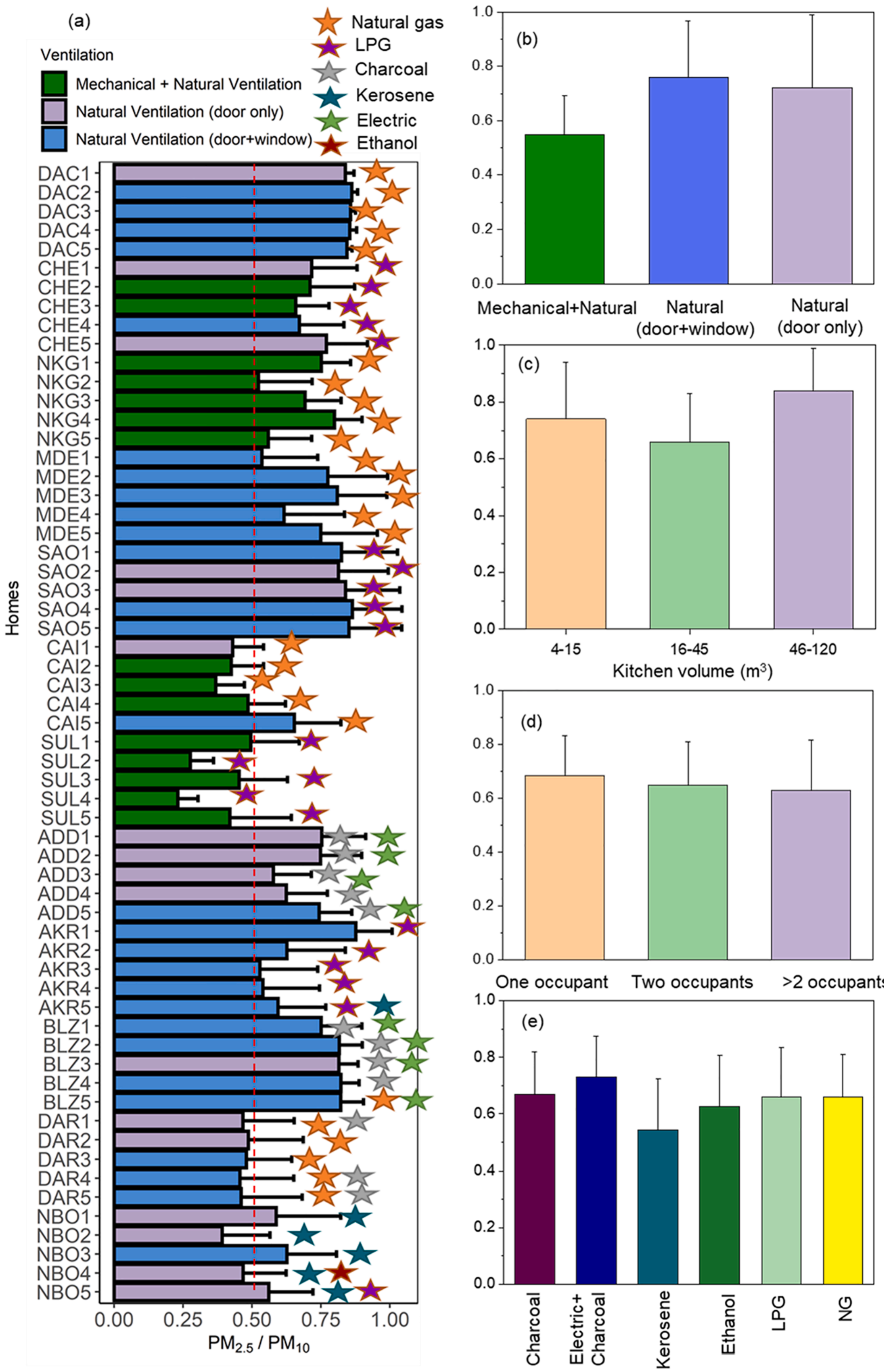

Fig. 7. (a) Bar plots of $PM_{2.5}/PM_{10}$ ratios for all homes in each city. The dashed line indicates $PM_{2.5}/PM_{10}$ of 0.5. The average ratio for the whole monitoring period in each home is grouped according to (b) ventilation type; (c) kitchen volume; (d) kitchen occupancy; and (e) type of fuel. Error bars represent the standard deviation of the average values. Only positive standard deviation values are added to maintain the clarity of the figure.

stewing (Alves, et al., 2021; Zhao and Zhao, 2018, Zhao et al., 2019), the resuspension of fugitive floor dust and due to the usual high background levels of coarse particles typical of such arid environments (Abbass et al., 2018). Moreover, SUL and CAI (CAI2-CAI4) used natural and mechanical ventilation and had relatively larger kitchens, thereby improving the convective mixing (dilution) and dispersion of the fine particles generated.

The average $PM_{2.5}/PM_{10}$ in individual homes are also analysed according to ventilation type (Fig. 7b), kitchen volume (Fig. 7c), kitchen occupancy (Fig. 7d) and fuel type (Fig. 7e). The average $PM_{2.5}/PM_{10}$ shows the highest $PM_{2.5}/PM_{10}$ for natural ventilation (door + window) of 0.75, followed by natural (only door) of 0.72, while the dual ventilation shows the lowest ratio of 0.55 Fig. 7b). Thus, it becomes evident that dual ventilation (mechanical and natural) helped to reduce fine particles in kitchens.

As regards to kitchen volume, the average of $PM_{2.5}/PM_{10}$ shows the highest value of 0.84 in larger-volume kitchens (46–120 m^3, Fig. 7c). The lowest ratio (0.66) was observed in the medium-volume kitchens (16–45 m^3), followed by small-volume kitchens (4–15 m^3) with a ratio of 0.74. The ratio of the large-volume kitchens was higher by 1.3- and 1.1-times the medium-volume (16–45 m^3) and small-volume (4–15 m^3) kitchens, indicating they had the maximum average fine PM fraction. $PM_{2.5}/PM_{10}$ ratios do not seem to follow a consistent trend when analysed in reference to kitchen volume variations, indicating that the other factors discussed above might be more impactful. The $PM_{2.5}/PM_{10}$ ratios did not vary appreciably with the different occupancy (Fig. 7d) as they were 0.68, 0.65 and 0.63 for one, two and more than two occupants, respectively.

Fig. 7e shows the average of $PM_{2.5}/PM_{10}$ for the different types of fuels used in all homes. The ratios showed the predominance of fine particles ($PM_{2.5}/PM_{10} > 0.5$; ranging 0.54–0.73) regardless of fuel type used. Nevertheless, homes using charcoal showed the highest range of $PM_{2.5}/PM_{10}$ ratios (0.67–0.73) amongst other fuels (Fig. 7e), substantiating the large quantities of fine particle emissions from charcoal burning (Huang et al, 2016) as also highlighted in Section 3.2.

The above findings indicated that the type of cooking had a largest impact on the $PM_{2.5}/PM_{10}$ ratios as the frying generates more fine particles and water-based cooking generates more coarse particles. The dual ventilation (mechanical and natural) had a notable impact on reducing fine particles. The $PM_{2.5}/PM_{10}$ is also influenced by the fuel type where the use of charcoal emitted more fine particles with highest fine- to- coarse PM ratios amongst other fuels, within the range of 0.67–0.73. However, the occupancy did not show a clear impact on the $PM_{2.5}/PM_{10}$.

3.5. Exposure risk assessment

3.5.1. Inhaled dose

We assessed the inhaled doses for home occupants (females and children under 5 years) since they spend relatively more time indoors. As the trend of results for both these occupant groups are similar, below we discuss female doses for brevity reasons.

An overview of females daily inhaled dose for all homes in each city and by ventilation type, fuel type, occupancy, and kitchen volume for $PM_{2.5}$ and PM_{10} are shown in Figs. 8 and S15, respectively. The corresponding plots for children are shown in Figs. S16 and S17, respectively. Asian cities showed the highest dose for PM_{10} ($PM_{2.5}$) 32.9 μg $kg^{-1}day^{-1}$ (26.3 μg $kg^{-1}day^{-1}$), followed by African 20.2 μg $kg^{-1}day^{-1}$ (13.3 μg $kg^{-1}day^{-1}$), Middle Eastern 10.2 μg $kg^{-1}day^{-1}$ (4.3 μg $kg^{-1}day^{-1}$), and South American 6.7 μg $kg^{-1}day^{-1}$ (5.4 μg $kg^{-1}day^{-1}$) cities (Figs. 8 and S15). The highest PM_{10} ($PM_{2.5}$) daily inhaled dose was estimated for homes in DAC, ranging from 50.4 μg $kg^{-1}day^{-1}$ (43.0 μg $kg^{-1}day^{-1}$) in DAC3 to 99.4 μg $kg^{-1}day^{-1}$ (83 μg $kg^{-1}day^{-1}$) in DAC1. These homes used natural ventilation (door and window), except DAC1 which used only the door. All DAC homes used natural gas as primary fuel. Two of the homes had 2 occupants in the kitchen (DAC1 and DAC2), while the others had only one occupant during cooking time. The second city with the higher daily inhaled dose is ADD, ranging from 23.1 μg $kg^{-1}day^{-1}$ (17.8 μg $kg^{-1}day^{-1}$) in ADD2 to 63.7 μg $kg^{-1}day^{-1}$ (42.4 μg $kg^{-1}day^{-1}$) in ADD4. Most of the homes used natural ventilation (door only), except ADD5 which had natural ventilation (door and window). These homes used natural gas and charcoal for cooking, and only one occupant was present during cooking in each home. The lowest daily inhaled dose was often estimated for MDE, ranging from 2.92 μg $kg^{-1}day^{-1}$ (1.7 μg $kg^{-1}day^{-1}$) in MDE1 to 4.7 μg $kg^{-1}day^{-1}$ (3.9 μg $kg^{-1}day^{-1}$) in MDE2. All homes in MDE used natural ventilation (door and window) as well as natural gas being the primary fuel. Regarding kitchen occupancy, only MDE1 had 2 occupants during cooking, while others had only one occupant. These findings suggest better ventilation conditions inside kitchen reduces PM exposure of the occupants: dual (natural and mechanical) residents are inhaling lower doses of PM_{10}($PM_{2.5}$) 12.3 ± 7.9 (6.7 ± 5.8) μg $kg^{-1}day^{-1}$, followed by natural ventilation (door and window): 19.6 ± 22.6 (15.1 ± 19.0) μg $kg^{-1}day^{-1}$, and natural ventilation (door only): 25.7 ± 27.6 (17.8 ± 21.9) μg $kg^{-1}day^{-1}$.

As for the fuel type, the highest dose was estimated for residents using charcoal plus electric stoves: 32.5 ± 25 (22.9 ± 17.2) μg $kg^{-1}day^{-1}$ as opposed to the lowest doses when using LPG alone, or in combination with secondary fuels such as kerosene or electricity, ranging from 8.2 to 9.1 μg $kg^{-1}day^{-1}$ for PM_{10}, and from 4.7 to 6.0 μg $kg^{-1}day^{-1}$ for $PM_{2.5}$ (Figs. 8 and S15).

As for the kitchen occupants, the inhaled dose seems to decrease while the number of occupants increases, i.e. 22.0 ± 22.4 (15.7 ± 17.7) μg $kg^{-1}day^{-1}$ for one occupant, 17.6 ± 24.5 (12.7 ± 21.0) μg $kg^{-1}day^{-1}$ for two occupants, and 13.8 ± 8.2 (8.4 ± 4.9) μg $kg^{-1}day^{-1}$ for more than two occupants (Figs. 8 and S15). Concerning the kitchen volume, the highest doses were estimated for the small-volume kitchens (4–15 m^3) – 31.5 ± 30.7 (23.8 ± 25.9) μg $kg^{-1}day^{-1}$ - which did not decrease consistently with the increase in kitchen volume. For example, kitchens with the largest volumes (46–120 m^3) showed higher inhaled dose compared with the middle-sized kitchens (16–45 m^2). This is because these larger kitchens were not separated from other rooms in the home (Table 2), and are mainly used in Africa and Asia, where the use of unclean fuels such as coal and biomass are more frequent.

The inhaled doses are dependent on the PM concentrations in the kitchens, on the exposure time, and also on the body weights of the exposed population. Hence, we evaluated the doses grouped by regions, in order to highlight the discrepancies in PM concentration as well as the discrepancies in the population biotypes of each region. Figs. 8 and S14 show the box plot of daily potential inhaled dose for females by region for $PM_{2.5}$ and PM_{10}, respectively. The corresponding plots for children are depicted in Figs. S16 and S17.

The Asian population is the most affected among the study groups, expressed here as the daily inhaled dose, as high concentrations of PM inside kitchens (due to polluted fuels and lack of ventilation inside kitchen) together with the low body weight values resulted in higher inhaled dose values for this population. In Asia, female body weight varied from 47.8 (CHE) to 59 kg (NKG), followed by Africa ranging from 51.3 (ADD) to 57.1 kg (AKR), South America 63 (SAO) and 65.1 kg (MDE), and with the highest body weight both cities in Middle East: 72.4 kg (CAI and SUL) (Table S5). For children under 5 years, Asia also presented the lower values of body weight from 10.2 (CHE) to 11.1 kg (NKG), followed by Africa ranging from 10.4 (ADD) to 11.1 kg (BLZ and DAR), Middle East 12.3 kg (CAI and SUL). South American cities had the highest value of body weight for children: 13.8 (MDE) and 14.9 kg (SAO), resulting in lower inhaled doses for these population groups in comparison with other cities. The ratio between doses for children and adults for PM_{10} ranged from 4.3 in SAO to 6.7 in SUL, and from 4.7 in SAO to 7.1 in NKG for $PM_{2.5}$ (Fig. S18), showing that children are much more affected by indoor exposures. It must be highlighted that the impact of air pollution on children compromises their health and affects their social and cognitive development, reducing their chances of overcoming the situations of vulnerability experienced.

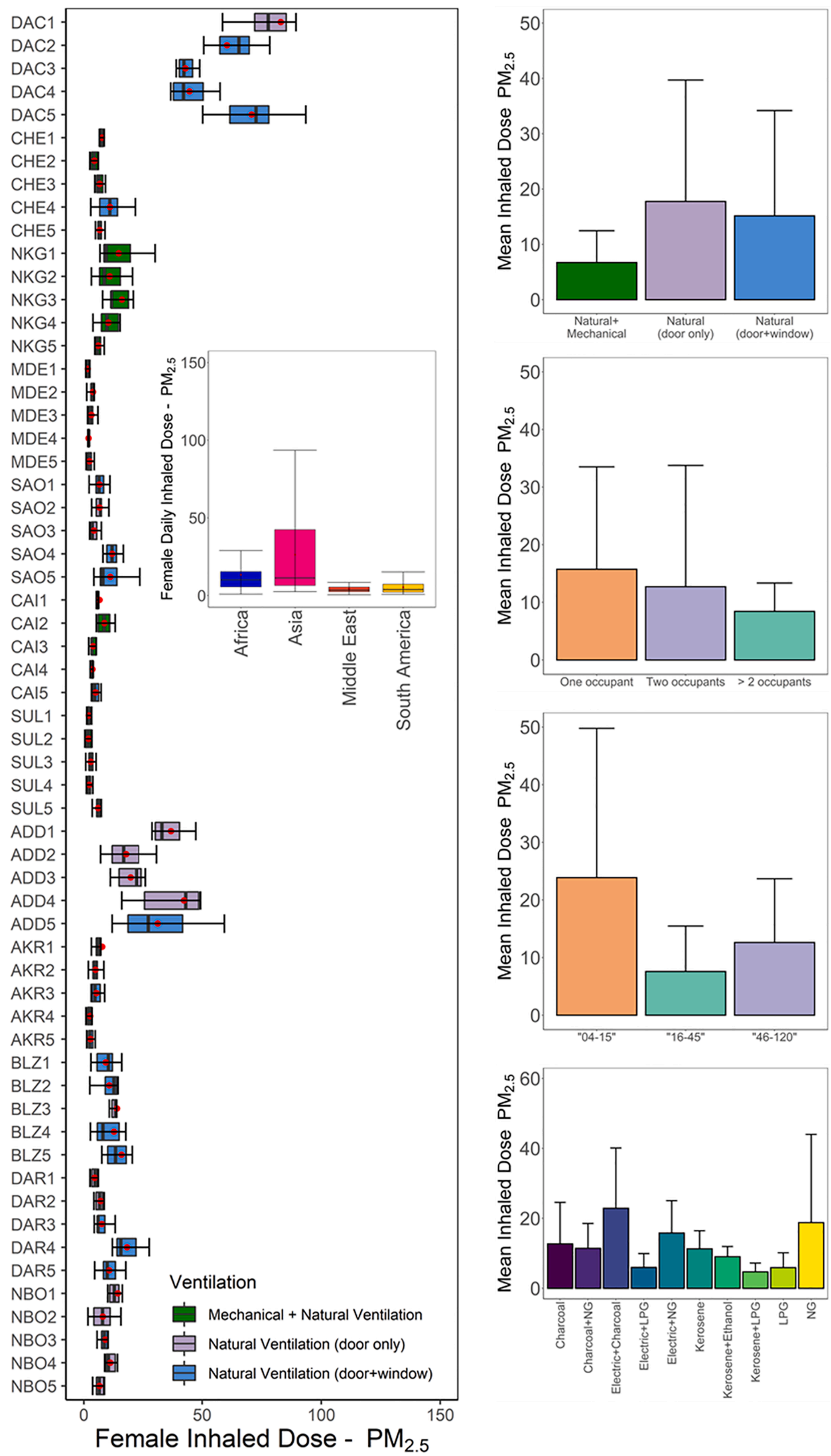

Fig. 8. Box plot of females daily inhaled dose for $PM_{2.5}$ (left panel) for all homes in each city by type of ventilation. The embedded figure on the left presents the box plot by region. On the right, bar plots present the average value for all types of ventilation, kitchen occupancy, kitchen volume, and type of fuel. Error bars represent the standard deviation of the average values. Only positive standard deviation values are added to maintain the clarity of the figure.

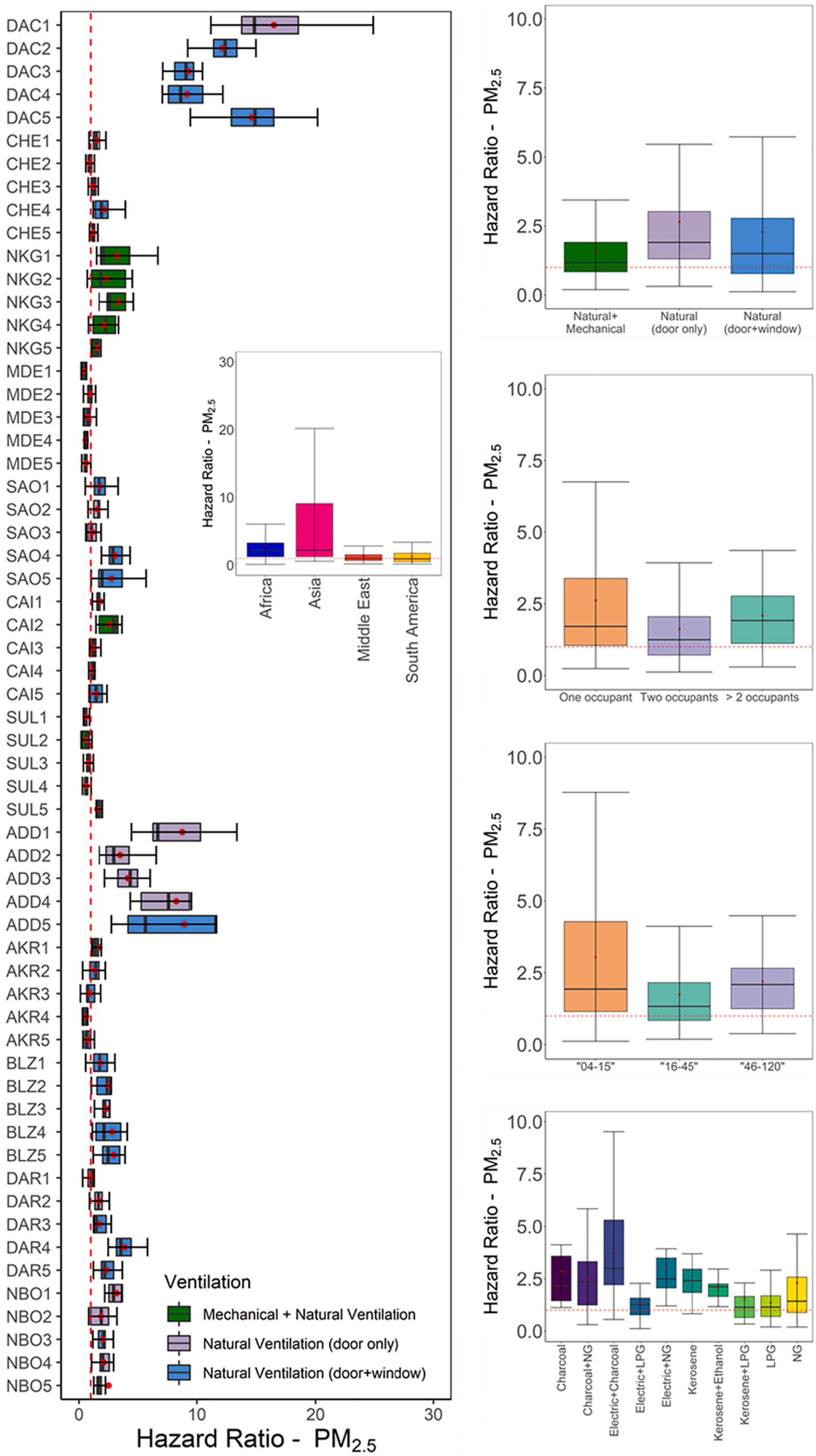

Fig. 9. Box plot of Hazard Ratio (HR) for $PM_{2.5}$ (left panel) for all homes in each city by type of ventilation. HR values were estimated for exposure in reference to WHO recommendations for $PM_{2.5}$ (15 μg m^{-3}). The embedded figure on the left presents the box plot by region. On the right, box plots present the values for all types of ventilation, kitchen occupancy, kitchen volume, and type of fuel. Red dashed line represents a ratio of 1.0. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Many recent studies have been dedicated to estimating the inhalation dose of air pollutants (Zwozdziak et al, 2017; Faria et al., 2020; Song et al., 2021) as it is strongly influenced by people's daily activities, such as commuting to work, physical activity, time spent outside and inside homes, as well as by the conditions of housing, equipment and resources used for food preparation, among others (Dias and Tchepel, 2018). Although differences in their approaches make it difficult to directly compare their results, these studies have contributed to enhancing knowledge of the factors that determine exposure conditions, as well as the differences observed in the burden of disease between populations and/or subgroups. Here, we highlight that no one remains unaffected by dirty air, but the adverse impacts of air pollution fall most heavily upon vulnerable populations, such as children, women, and people living in poverty, groups to whom stakeholders have special obligations under international human rights law.

3.5.2. Hazard ratio

We assessed the exposure risk using the HR that points to the risk when the $PM_{2.5}$ and PM_{10} concentration values exceeded the WHO's 24-hr average recommended values of 15 and 45 μg m^{-3}, respectively. As expected, the HR for each pollutant varied among different kitchen environments. Fig. 9 represents the box plot of HR for $PM_{2.5}$ by home, region, ventilation type, kitchen volume, kitchen occupancy, and fuel type. The corresponding plots for PM_{10} are shown in Fig. S19. Africa and Asia had the worst conditions, both with more than 75% of the total data with values greater than one. Asia presents the most critical situation, with values ranging from 0.6 to 35.2, while Africa varies from 0.1 to 26.5. In the other regions, HR ranged from 0.2 to 5.7 (South America) to 3.7 (Middle East). The highest HR was observed for homes in DAC, with median values ranging from 9.2 in DAC 4 to 16.0 in DAC1. The lowest HR was often estimated for MDE, with median varying from 0.5 (MDE1) to 0.9 (MDE2).

Assessing by type of ventilation, the worst conditions were for natural ventilation (only door), median 2.2, followed by natural ventilation (door plus window) median 1.7, and by dual ventilation (natural + mechanical) median 1.2. It is noteworthy that natural ventilation (door only) had a 10th percentile value of 1.0, which indicates that 90% of data for this type of ventilation had a value greater than one. Regarding the kitchen volume, the group of small-volume kitchens (4–15 m^3) and largest volumes (46–120 m^3) were similar for the 25th percentile (P25) value (~1.3), meaning that 75% of data for these groups was in poor air quality conditions. However, it is noteworthy that the values for the small-volume kitchens reached higher values. For instance, the 90th percentile (P90) value for this group was 13.2, in contrast to 4.8 (largest-volume kitchens) and 3.5 (medium-volume kitchens). As for the kitchen occupants, the trend is not clear. The worst conditions were observed for a group for more than two occupants and a group of one occupant. The 25th percentile (P25) value of these two groups was 1.1, indicating that more than 75% of the population in this group was in poor air quality conditions. By type of fuel, adverse conditions appeared when polluting fuels were used, either as primary or secondary fuel, combining coal or kerosene, with median HR ranging from 2.1 to 3.4. However, it is important to highlight that even for other fuels considered clean, the medians were greater than one, indicating that at least 50% of this population was in poor air quality conditions.

Since household fuel combustion is a major contributor to the IAP, meeting WHO Air Quality Guidelines will require community-level transition to clean cooking fuels, and potentially emission reductions from other ambient pollution sources. As highlighted in our findings, access to good cooking practices, clean fuels and technologies is distributed unevenly across the globe. Therefore, to achieve UN Sustainable Development Goal 7 "Ensure access to affordable, reliable, sustainable and modern energy for all" it is still necessary to increase the proportion of population with primary reliance on clean fuels and modern technologies. For instance, in 2019, 2.6 billion people still lacked access to clean cooking and relied primarily on inefficient and polluting cooking systems (WHO, 2021c).

4. Conclusions, recommendations and future outlook

For the first time, this study presents a global assessment of human in- kitchen exposure to PM in 60 low-income homes in 12 cities across four continents. PM monitoring in all cities was carried out using a similar set of laser particle counters to produce an internationally comparable dataset, using a unified methodology. This allows for a global comparison between different cities. The key conclusions drawn from this study are as follows:

- Only 23% of homeowners used extraction fans during cooking while the rest relied on natural ventilation through open doors and windows (47%) or open door only (28%). Our studies showed that 33% of kitchens used natural gas, 27% used LPG and 17% used electricity as the cooking fuel; the rest (mostly African homes) used more pollution-emitting fuels, such as kerosene and charcoal. 52% of homes had one occupant present whilst cooking and hence directly affected by cooking fumes, and the remaining had more than one occupant present. Knowledge of such information together with kitchen dimensions and cooking type and duration were used as a basis to understand the factors affecting in-kitchen exposure.
- The fuel type, kitchen size, cooking type, duration and ventilation conditions were the most crucial factors significantly affecting aerosol particles in-kitchen exposure. Mechanical ventilation can decrease the in-kitchen exposure by a factor of 2 compared with natural ventilation. The high $PM_{2.5}$ concentrations measured in DAC were attributed to small kitchens, extensive frying and long cooking durations. Homes in ADD, BLZ and NBO experienced ~ 1.3-times the average $PM_{2.5}$ levels observed in other cities; this may be due to the use of kerosene and charcoal for cooking.
- Homes that used kerosene and LPG or electricity and LPG showed higher probability among the fuels of having $PM_{2.5}$ concentrations below 15 μg m^{-3}. Charcoal fueled homes, located in the African region, exhibited greater probability of $PM_{2.5}$ concentrations above 16 μg m^{-3}. We observed that in smaller kitchens, there was a greater probability of elevated $PM_{2.5}$ concentrations since they showed wider tails in higher concentration range for both $PM_{2.5}$ and PM_{10}. Kitchens with two or more occupants present showed a higher probability of $PM_{2.5}$ concentration ranging between 0 and 5 μg m^{-3} than with only one occupant.
- The $PM_{2.5}/PM_{10}$ ratio was > 0.5 observed in most cities. In DAC, CHE, NKG, MDE, SAO, ADD, AKR and NBO, the $PM_{2.5}/PM_{10}$ values were > 0.5, highlighting the dominant contribution of fine particles from cooking types, especially frying. All homes in CAI (except CAI5), SUL and DAR showed $PM_{2.5}/PM_{10} < 0.5$, indicating that the dominant contribution of coarse particles are those from food boiling or fugitive dust resuspension in the kitchens.
- MDE and SUL showed relatively lower hazard ratio (HR) values due to the clean fuels used for cooking in MDE (natural gas) and SUL (LPG). Homes in DAC showed relatively higher HR values followed by ADD for $PM_{2.5}$ and PM_{10}. From the 60 homes in this study, at least 47 homes show HR median values greater than one, indicating that the WHO recommendations for PM were exceeded in at least 50% of the monitoring time in the kitchens.
- Homes in Asian cities resulted in the highest values of mean potential inhalation dose for PM_{10} and $PM_{2.5}$ followed by African cities. The lowest potential inhalation dose values were observed in South America cities. The inhalation dose for children under 5 years old was up to 7-times (NKG) that of the adult female dose, highlighting the greater vulnerability of this group due to their lower body weight.

The best strategy to reduce the in-kitchen exposure during cooking is to eliminate the emissions at the source by using sustainable means such as solar-driven e-cookstoves. However, such a change would be gradual. Below, we give recommendations easy to implement and are based on the above findings and therefore evidence-based.

- **Use of extraction fans reduced the average in-kitchen $PM_{2.5}$ and PM_{10} exposure by about 2.3- and 1.8-times, respectively, compared with natural ventilation conditions through doors only.** Irrespective of a kitchen's physical and cooking characteristics, the kitchens using dual ventilation (mechanical and natural) during cooking showed up to 2-times and 1.4-times lower $PM_{2.5}$ and PM_{10} concentrations, respectively, compared with those relying on natural ventilation through doors and windows. This highlights a clear benefit of installing extraction fans and using them during cooking for reducing in-kitchen exposure. In addition, it is recommended that windows are kept open during cooking, whenever possible, to enhance natural ventilation when it is not possible to install extractor fans.
- **The use of charcoal fuel increased the average $PM_{2.5}$ exposure during cooking sessions by 1.3- and 3.1-times to those observed for kitchens using natural gas and LPG, respectively.** The highest inhalation doses were also estimated for residents using charcoal, which were about 7-times to those estimated for kitchens using LPG. Likewise, kerosene had resulted in 1.4-times the average $PM_{2.5}$ concentrations during cooking compared with kitchens using LPG. The use of less clean fuels (e.g. charcoal and kerosene) is common for low-income homes in Africa. This study has highlighted this local issue in a global context when comparing in-kitchen particle levels with other developing countries. Although the best strategy in the long run to reduce in-kitchen PM exposures is promoting the use of green fuels such as solar based e-cooking, the use of cleaner cooking fuels like natural gas or LPG should be encouraged in the short term.
- **Frying was generally the most particle emitting activity during cooking.** Irrespective of the kitchens having dual ventilation that showed the lowest exposure, and using relatively clean fuels such as natural gas, the homes (e.g. DAC, NKG) using extensive frying showed the highest particle exposure. Hence, increased ventilation in such kitchens becomes even more important. Consistent usage during frying along with regular cleaning and maintenance of extraction fans is therefore highly recommended.
- **Small volumes of kitchens (<15 m^3), despite using cleaner fuels, showed increased cooking exposure compared with their larger-volume counterparts.** Although the trend for the impact of volume on concentration exposure was not clearly evident, the exposure concentrations were highest for the lowest-volume kitchens that decreased in large/medium-volume kitchens. In small kitchens, higher concentrations were more frequent when compared with medium (16–45 m^3) and large (46–135 m^3) volume kitchens. This was expected due to the limited volume of space available for dispersion in small kitchens. The simplest strategy for existing kitchens is to strengthen their exhaust extraction system to increase the volume of mixing air to minimise the daily exposure of occupants. The other mitigation measures would be to dedicate larger surface areas for kitchens in new homes (if possible), or having higher ceilings to increase kitchen volumes, and/or having larger-sized windows.
- **Passive occupancy should be minimised during cooking.** Kitchen occupancy did not show clear indication of increased or decreased cooking exposures. For example, average $PM_{2.5}$ exposure concentrations for kitchens with one occupant were equal to and 1.7-times higher than those of kitchens with two occupants and more than two occupants, respectively. Keeping away from passive occupancy (i.e. the occupants, such as children, who are not participating in cooking) in the kitchen is recommended to capitalise on the clear benefit of avoiding their in-kitchen exposure altogether.
- **Cultural and cuisine differences across cities were reflected in variations in cooking times where some cities exhibited much longer cooking times (>60 min extra) compared with those in other cities.** Minimising the time spent in kitchens during cooking, whenever possible, can reduce exposure to harmful particles. For example, the kitchen area can be evacuated during prolonged sessions of slow cooking that do not require continuous supervision. Moreover, increasing awareness among the occupants of the low-income households about the cooking duration, ventilation conditions, cooking and fuel type, and passive occupancy (i.e. people not having an active role in cooking) is important to empower them with the understanding of the impact of cooking emissions on their health.

This study demonstrated an application of affordable laser particle counters in low-income home monitoring across 12 cities across the globe and built the first global dataset of in-kitchen PM exposure. An assessment of in-kitchen PM hazard ratio and potential inhaled doses have also been estimated for all cities. We showed that exposure concentrations during cooking vary widely, depending upon factors such as food type, kitchen size, fuel type, style of cooking and ventilation condition. Improved fume extraction and mechanical ventilation of cooking emissions above the stove indicated significant improvements in exposure concentrations. The ingress of outdoor PM concentrations can affect the in-home concentrations. Therefore, simultaneous monitoring inside and outside homes would be ideal to have a reasonable estimate of the outdoor pollution ingress to homes. However, the focus of this work was to understand the in-kitchen cooking exposure and provide insights on the main determinants of cooking emissions. Therefore, simultaneous outdoor monitoring was beyond the scope of current work. Further studies are recommended to build a similar database that incorporates the simultaneous monitoring of inside and outside the homes to build a holistic understanding of the ingress of outside pollutants to homes. There is also a need for building a similar database for developing a holistic understanding of exposure concentrations and associated mitigation measures among different income groups. We also recommend further studies to develop the chemical composition profiles (including PAHs, elements and inorganic ions) of PM originating from the cooking process for more accurate estimates of health risks and associated economic impacts.

CRediT authorship contribution statement

Prashant Kumar: Conceptualization, Funding acquisition, Resources, Methodology, Supervision, Project administration, Writing – original draft, Writing – review & editing. **Sarkawt Hama:** Writing – original draft, Data curation, Visualization, Validation, Formal analysis, Writing – review & editing. **Rana Alaa Abbass:** Formal analysis, Investigation, Writing – original draft, Investigation, Writing – review & editing. **Thiago Nogueira:** Formal analysis, Investigation, Writing – original draft, Investigation, Writing – review & editing. **Veronika S. Brand:** Formal analysis, Investigation, Writing – original draft, Investigation, Writing – review & editing. **Huai-Wen Wu:** Investigation, Writing – review & editing. **Francis Olawale Abulude:** Investigation. **Adedeji A. Adelodun:** Writing – review & editing. **Partibha Anand:** Investigation, Writing – review & editing. **Maria de Fatima Andrade:** Writing – review & editing. **William Apondo:** Investigation. **Araya Asfaw:** Writing – review & editing. **Kosar Hama Aziz:** Investigation, Writing – review & editing. **Shi-Jie Cao:** Writing – review & editing. **Ahmed El-Gendy:** Writing – review & editing. **Gopika Indu:** Investigation. **Anderson Gwanyebit Kehbila:** Investigation, Writing – review & editing. **Matthias Ketzel:** Writing – review & editing. **Mukesh Khare:** Writing – review & editing. **Sri Harsha Kota:** Writing – review & editing. **Tesfaye Mamo:** Investigation. **Steve Manyozo:** Investigation. **Jenny Martinez:** Investigation. **Aonghus McNabola:** Writing – review & editing. **Lidia Morawska:** Writing – review & editing. **Fryad Mustafa:** Investigation. **Adamson S. Muula:** Writing – review & editing. **Samiha Nahian:** Investigation, Writing – review & editing. **Adelaide Cassia Nardocci:** Writing – review & editing. **William Nelson:**

Investigation. **Aiwerasia V. Ngowi:** Writing – review & editing. **George Njoroge:** Investigation. **Yris Olaya:** Writing – review & editing. **Khalid Omer:** Writing – review & editing. **Philip Osano:** Writing – review & editing. **Md Riad Sarkar Pavel:** Investigation. **Abdus Salam:** Writing – review & editing. **Erik Luan Costa Santos:** Writing – review & editing. **Cynthia Sitati:** Investigation. **S.M. Shiva Nagendra:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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