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CO_2 exposure, ventilation, thermal comfort and health risks in low-income home kitchens of twelve global cities

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ABSTRACT

In-kitchen air pollution is a leading environmental issue, attributable to extensive cooking, poor ventilation and the use of polluting fuels. We carried out a week-long monitoring of CO_2, temperature and relative humidity (RH) in five low-income residential kitchens of 12 global cities (Dhaka, Chennai, Nanjing, Medellín, São Paulo, Cairo, Sulaymaniyah, Addis Ababa, Nairobi, Blantyre, Akure and Dar-es-Salaam). During cooking, the average in-kitchen CO_2 concentrations were 22.2% higher than the daily indoor average. Also, the highest CO_2 was observed for NV_d (natural ventilation-door only; 711 ± 302 ppm), followed by NV_{dw} (natural ventilation-door +

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Table 1
Summary of relevant previous studies of CO_2 concentrations, ventilation and thermal comfort in kitchens and other indoor microenvironments of the studied cities. Some of the African and Middle-Eastern cities do not have specific published literature on the topic, so we extended our search to include country-wide studies.

City (Country)	Title of studies	Key findings	Reference
Dhaka (Bangladesh)	Indicators of hospital IAQ and possible toxicity	• Aeroqual 500 series sampler measured NO_2, CO_2 and TVOC levels. • The total average concentration of IAQ indicators were 104.1 ± 67.6 (PM_1), 137.4 ± 89.2 ($PM_{2.5}$), and 159.0 ± 103.3 (PM_{10}) μg m^{-3}; 0.11 ± 0.02 (NO_2), 1047.1 ± 234.2 (CO_2), and 176.5 ± 117.7 (TVOC) ppm.	[34]
	Indoor air pollutants and respiratory problems among households	• CO_2 (≥600 ppm), formaldehyde (≥0.1 ppm), CO (1–5 ppm) and hydrocarbon (≥600 ppm) were found in 67.0%, 35.1%, 17.5%, and 9.3% of the households, respectively. • Residents suffer mainly from respiratory diseases, particularly at high CO_2, and hydrocarbon levels.	[39]
Chennai (India)	Indoor air quality characteristics of air-conditioning systems in hospitals in Tamil Nadu	• Air conditioning systems increase CO_2 levels and lower O_2 levels compared to natural ventilation. • CO_2 levels were 459–1147 ppm throughout the day.	[29]
	Indoor air quality assessment in a school building	• Hourly CO_2 concentration inside school rooms was 927 ppm in the mornings. • CO_2 concentrations were close to the National Institute for Occupational Safety and Health, USA standard (1000 ppm).	[33]
Nanjing (China)	Human responses to high levels of CO_2 and air temperature	• CO_2 levels at 8000–12000 ppm induced headache, fatigue, agitation and depression. • Text-typing performance and systolic blood pressure decreased significantly at this exposure, while diastolic blood pressure and thermal discomfort increased significantly.	[32]
	Field-measurement of CO_2 level in general hospital wards	• Variation in indoor CO_2 levels is associated with patients' living habits. • Natural ventilation keeps indoor CO_2 levels at <1000 ppm in the transition season, but much higher during winter due to closed windows and doors to maintain thermal comfort.	[31]
Medellín (Colombia)	Indoor Air Quality Assessment in Passivhaus Home of Latin America	• CO_2 and total-VOC annual average levels were respectively 143.8 ppm and 81.47 μg m^{-3} in the Passivhaus home, lower than the standard levels. • Passivhaus homes can provide healthier IAQ than the standard homes in Latin America.	[40]
	Levels of indoor CO pollution in households using natural gas appliances in a 73-home sample in Bogotá.	• CO_2-based estimated ventilation rates in home's kitchens were 5–90 L/s/person without using natural gas appliances. • 60% of homes (especially low-income households with poor kitchen ventilation) did not meet ASHRAE 2013 standards. • Opening windows when using natural gas appliances significantly reduced indoor CO concentrations.	[28]
	Thermal comfort assessment in naturally ventilated offices located in Bogotá	• No strong relationship between indoor and outdoor temperatures. • The comfort operative temperature of 23.47 °C in Bogotá achieved 96.58% thermal acceptance.	[41]
São Paulo (Brazil)	Particulate and CO_2 levels in a surgical room with AC system in Brazil	• CO_2 concentrations during surgeries significantly exceeded acceptable values and a simultaneous increase in particle number concentration was observed. • High risk of contamination occurs between surgeries in the same surgical room from residual contaminants unremoved by the AC.	[30]
	Indoor environmental quality in a public library	• CO_2 levels were below the recommended standards. • Internal CO_2 levels were slightly higher than outdoor levels, highlighting that natural ventilation blends IAQ with outdoor air quality.	[42]
Cairo (Egypt)	Seasonal variations of IAP in homes	• IAP highly depends on atmospheric levels in summer due to higher ventilation rates, while indoor concentrations were more influenced by indoor sources in winter (due to increased indoor activities and less ventilation). • Indoor PM, CO, and CO_2 levels were influenced by the number of occupants and the volume of rooms in both seasons.	[43]
	PM and CO_2 levels are influenced by both outdoor and indoor conditions.		[44]

(continued on next page)

Table 1 (*continued*)

City (Country)	Title of studies	Key findings	Reference
Sulaymaniyah (Iraq)	Assessment of relative humidity, indoor temperature and CO_2 in, Iraq	• Most kitchens had higher indoor $PM_{2.5}$ and CO_2 concentrations than living rooms due to insufficient ventilation. • Indoor air pollutants are produced by a variety of home activities: heating, cleaning and smoking. • Higher CO_2 levels were found in buildings operating with non-centralised heating and un-ventilated systems than those with centralised systems. • Weather conditions and the position of the buildings influence thermal comfort.	[45]
Addis Ababa (Ethiopia)	Analysis of air quality in temporary shelters on three continents	• Spot measurements of CO_2 levels were performed in 286 shelters in winter. CO_2 levels ranged 1359–5000 ppm. • CO_2 levels ranged 4001–5000 ppm in 32% of the shelters, mainly due to poor ventilation, overcapacity (≤25 people) and in-shelter coal-based cooking.	[46]
	Emissions and fuel use performance of two improved stoves in southeastern Ethiopia	• Changing from traditional metal stoves to Merchaye and Lakech stoves significantly reduced CO_2 and CO emissions. • Merchaye and Lakech stoves reduced CO_2 (CO) from traditional charcoal stoves by 22 (28) and 8 (15) folds, respectively.	[47]
Akure (Nigeria)	Thermal comfort in a sub-Saharan African city	• Occupants in naturally ventilated buildings experienced comfort operative temperature between 24.88 °C and 27.66 °C. • 59%, 25% and 16% of the time, the indoor RH levels were higher, equal and lower than the outdoor levels.	[48]
Blantyre (Malawi)	Optimising the Envelope Thermal Design of Urban Residential Buildings in Malawi	• The most important contribution to the ultimate residential building thermal performance is air infiltration. • Controlled air infiltration through the use of operable air bricks with flexible operational surface areas has been shown to be highly successful in improving building comfort levels.	[49]
Dar-es-Salaam (Tanzania)	A novel approach to studying airborne disease transmission	• CO_2 levels and social contact data generated rebreathed air volume from which potential airborne disease transmission was estimated. • CO_2 levels follow the trend: prisons (1892 ppm) > nightclubs (1,488) > social halls (1,262.9) > public transport (941) > market (730) > schools (655) > religious halls (629).	[27]
Nairobi (Kenya)	Evaluation of energy efficiency and indoor air quality in green buildings	• ACH rates were determined using metabolic CO_2 as a tracer gas. • Green buildings had 80%–86% higher ACH rates than non-green buildings showing a higher probability to inhale contaminated air.	[50]

window; 690 ± 319 ppm) and DV_{mn} (dual ventilation-mechanical + natural; 677 ± 219 ppm). Using LPG and electric appliances during cooking exhibited 32.2% less CO_2 than kerosene. Larger kitchens (46–120 m^3) evinced 28% and 20% less CO_2 than medium (16–45 m^3) and small (4–15 m^3) ones, respectively. In-kitchen CO_2 with >2 occupants during cooking was 7% higher than that with one occupant. 87% of total kitchens exceeded the ASHRAE standard (RH >40%, temperature >23 °C) for thermal comfort. Considering the ventilation type, both the ACH (air change rate per hour) and ventilation rate followed the order: $NV_{dw} > NV_d > DV_{mn}$, while the trend for weekly average CO_2 concentration was $NV_d > DV_{mn} > NV_{dw}$. Larger kitchens presented 22% and 28% less ACH, and 82% and 190% higher ventilation rate than medium- and small-volume ones, respectively. Forty-three percent kitchens had ACH <3 h^{-1} and ventilation rate <4 L/s/person, hence violated the conditions for ideal ventilation. Moreover, 10% of the Hazard Ratio values for 25% kitchens exceeded the CO_2 reference value (1000 ppm). Consequently, our findings prompted several recommendations towards improving in-kitchen ventilation and environmental conditions of low-income homes.

1. Introduction

Indoor carbon dioxide (CO_2) is an important parameter for understanding ventilation conditions that directly affect indoor air quality (IAQ) and thermal comfort of the occupants [1–4]. Improving IAQ and environmental conditions are also essential for achieving many of the Sustainable Development Goals suggested by the United Nations [5], which include improving well-being and human health (Goal 3), promoting gender equality (Goal 5), providing clean and affordable energy for households (Goal 7), reducing inequalities (Goal 10) and developing communities and sustainable cities (Goal 11).

CO_2 is a natural, non-toxic and colourless greenhouse gas. However, prolonged exposure to high concentrations of CO_2 (especially during essential human exhalation in enclosed spaces) imposes detrimental effects on human health [1]. CO_2 is essential for regulating the acid-base balance in the human bloodstream, but excess CO_2 can lower the blood pH or increase the partial pressure of CO_2 (pCO_2), causing acute or chronic respiratory acidosis [6]. Acute worsening of chronic respiratory acidosis results in headache, fatigue, drowsiness, nausea, anxiety, confusion, nose and throat ailments and stupor (CO_2 narcosis) [3,7]. Slowly and steadily developing respiratory acidosis is less deleterious, but may still induce memory loss, disturbances in sleep cycle, excessive daytime drowsiness and behavioural changes [1]. Azuma et al. [1] reported the association of exposure to indoor CO_2 >500 ppm with physiological changes. As CO_2 concentrations increase, heart rate problems and their variability, blood pressure and peripheral blood circulation may ensue. For CO_2 concentrations >700 ppm, sick-building syndrome (SBS) symptoms [8] were observed; at >1000 ppm, inhibition of cognitive performance, decision-making, problem-solving and mathematical computations were observed in school children [1]. Elevated respiratory rate, metabolic stress, respiratory acidosis, oxidative stress, aggravated brain blood flow, demineralization of bones, kidney calcification, endothelial dysfunction and increased minute ventilation were reported for exposure to indoor CO_2 concentration >10, 000 ppm [6]. For acute exposure, Jacobson et al. [6] stated that CO_2 retention was found at indoor concentrations of 1000–5000 ppm for <4 h exposure. Inflammation and cognitive defects occurred at 2000–4000 ppm (2 h) and 1000–2700 ppm (1–6 h) of exposure, respectively. Consequently, indoor CO_2 concentrations of ≤1000, 1000–1500 and >1500 ppm indicate good, moderate and poor IAQ, respectively [9], whereas the maximum permissible concentration in enclosed spaces may range between 800 and 1000 ppm [10]. Nevertheless, CO_2 concentrations in densely occupied indoor spaces with insufficient ventilation may quickly exceed 3000 ppm [11, 12].

Indoor CO_2 concentrations and associated health risks have become increasingly important, particularly because of the increased amount of time spent indoors, owing to comfort and activities, and more recently, because of COVID-19-derived restrictions. Furthermore, since COVID-19 patients exhale CO_2 along with aerosols containing SARS-CoV-2, it is used as a proxy for ventilation conditions and the potential risk of respiratory infection indoors [2,3,13,14]. Therefore, indoor CO_2 measurements can help determine indoor transmission risk of respiratory diseases such as COVID-19 [14]. Also, the relative indoor infection risk increases with elevated CO_2 concentrations, further justifying the need to keep CO_2 within a healthy range through adequate ventilation [14]. This renders CO_2 as an IAQ indicator and an indoor air pollutant, depending on its concentration and exposure duration [15]. Hence, it is necessary to monitor and control indoor CO_2 concentrations.

Although indoor CO_2 levels are generally higher than those outdoors (due to the confined spaces of the former), kitchens are the major indoor microenvironment that exhibit much higher acute concentrations of anthropogenic and natural CO_2 than other indoor spaces, arising from combustion and human exhalation, respectively [16]. Usually, the ventilation settings in a residential microenvironment directly determine CO_2 concentrations. For instance, ventilation conditions and occupancy levels during cooking inside kitchens directly affect CO_2 concentrations. Furthermore, cooking fuel types, stoves, kitchen volume and ventilation conditions influence CO_2 levels within the kitchen microenvironment [17,18]. Deriving air change rate per hour (ACH) and ventilation rate for a building or room helps understand the ventilation conditions because proper ventilation potentially regulates indoor moisture and removes pollutants [19–23]. When sufficient, ACH and ventilation rate can improve IAQ as well as a building's energy consumption and heat loss [19,22,24–26].

Indoor CO_2 monitoring has been widely reported (Table 1). However, some cities, especially in Africa and the Middle East, lack literature on the topic. Therefore, this study is designed to include country-wide studies, focusing on these regions (Table 1). CO_2, among other indoor pollutants such as PM, TVOCs and CO are generally higher in concentrations than found outdoors. Much higher CO_2 concentrations were recorded at crowded indoor places in Dar-es-Salam [27], worsened by lack of sufficient ventilation systems. Similar scenarios were reported in Tamil Nadu, Nanjing, Bogota and Sao Paulo [28–31], which could eventually compromise human health, as also reported for Nanjing [32]. However, in some cases, the indoor CO_2 concentrations did not exceed the upper permissible limits (1000 ppm) in schools in Chennai and hospital wards in Nanjing and Dhaka [31,33,34]. Other international studies include a study in the Netherlands that employed questionnaires and passive sampling to investigate the impact of cooking appliances, type of cooking fuel, ventilation provision and kitchen size on the generation and dispersion of CO_2 (among other indoor air pollutants, water vapour, and temperature) and human exposure to the pollutants [35]. This work was conducted over a week in 74 kitchens where a close similarity was observed in the average CO_2 concentrations generated from gas-based (658.9 ± 174.0 ppm) and electric-based (654.2 ± 164.4 ppm) cooking [35]. Later, Francisco et al. [36] researched combustion gas concentrations from unvented fireplaces in 30 households in Illinois, USA. Measurements were taken at 1-min intervals for three to four days, where the CO_2 levels (mean = 2000 ppm; range = 20–2798 ppm; background = 500 ppm) did not exceed the permissible limit of the Health Canada CO_2 guideline of 3500 ppm (long-term average) [36]. Half a decade later, a numerical study was carried out on CO_2 emissions in kitchens of urban homes in developing countries. Taking measurements at breathing height (73 cm) and 33 cm from the burners, high CO_2 levels (5000 ppm) were observed and considered injurious to human health from chronic exposure [37]. Another study conducted in some Italian schools showed that 54% of classrooms had mean CO_2 levels >1000 ppm, despite ensuring air ventilation through open doors and windows [13]. Moreover, the study emphasised on the urgency of monitoring CO_2 concentrations towards understanding and controlling airborne infections [13]. Overall, studies have shown that monitoring indoor CO_2 concentrations can act as a proxy for ensuring adequate ventilation, estimating ACH and occupancy levels, and assessing infection risks from respiratory infection via the estimates of re-breathed CO_2 concentrations.

Cooking is one of the most air polluting indoor activities in low-income homes [38]. When combined with suboptimal ventilation conditions, cooking poses high risks to human health. Furthermore, the adverse impacts of cooking on IAQ and human health are not properly recognised. Thus, adopting feasible adjustments to cooking behaviours and kitchen conditions is uncommon. Poor IAQ is more prevalent in low-income homes in populous cities of developing countries. More studies and efforts are needed in such locations to first determine the impact of cooking on the IAQ. Then, efforts should be made to understand the factors (such as kitchen conditions and cooking habits) influencing IAQ in such indoor environments towards proposing possible control measures for homeowners and building designers. Therefore, the current study encompasses a wide geographical range (Asia, South America, Middle-East and Africa; Section 2.2 and Supplementary Information, Section S1) to evaluate in-kitchen environmental parameters (CO_2 concentrations, air temperature, RH, ACH, ventilation rates and hazard ratios) for 60 low-income homes. Quantifying these parameters is crucial to understand the underlying factors affecting IAQ and propose appropriate and effective actions to ensure good IAQ and preserve residents' respiratory health.

The overall objective of this study is to investigate the enormity of the predetermined factors that influence in-kitchen CO_2 exposure and thermal comfort conditions in low-income homes of developing nations. We discussed the variation among the in-kitchen CO_2 concentrations and associated health risks, thermal comfort, ACH and ventilation conditions among 60 low-income homes in reference to variations in kitchen conditions (such as natural and mechanical ventilations, cooking fuel, kitchen volume, occupancy, cooking method and city/regional variations in cuisine habits). The data were analysed for establishing tentative household exposure profiles, and providing viable IAQ improvement strategies that would be applicable and beneficial to the global community.

2. Methodology

2.1. Study design

To understand the influence of in-kitchen ventilation conditions on human exposure to CO_2 during cooking carried out in homes on a daily basis, we designed a study involving twelve major cities from four global regions (Asia, South America, Middle-East and Africa; Fig. 1). The cities included were: Dhaka (DAC; Bangladesh), Chennai (CHE; India), Nanjing (NKG; China), São Paulo (SAO; Brazil), Medellin (MDE; Colombia), Cairo (CAI; Egypt), Sulaymaniyah (SUL; Iraq), Addis Ababa (ADD; Ethiopia), Nairobi (NBO; Kenya), Blantyre (BLZ; Malawi), Akure (AKR; Nigeria), and Dar-es-Salaam (DAR; Tanzania). City codes are based on their respective airport's abbreviations [38].

Table 2 presents detailed characteristics of the kitchens. In each city, CO_2 concentrations, temperature and relative humidity (RH) were continuously monitored for a week in each of the five kitchens of low-income homes. In addition, qualitative information (Table S1) about occupant activities, kitchen conditions, and outdoor conditions (Table S2) were obtained concurrently through building and occupant surveys. Important information was collected through the surveys such as; the homes' geographical location,

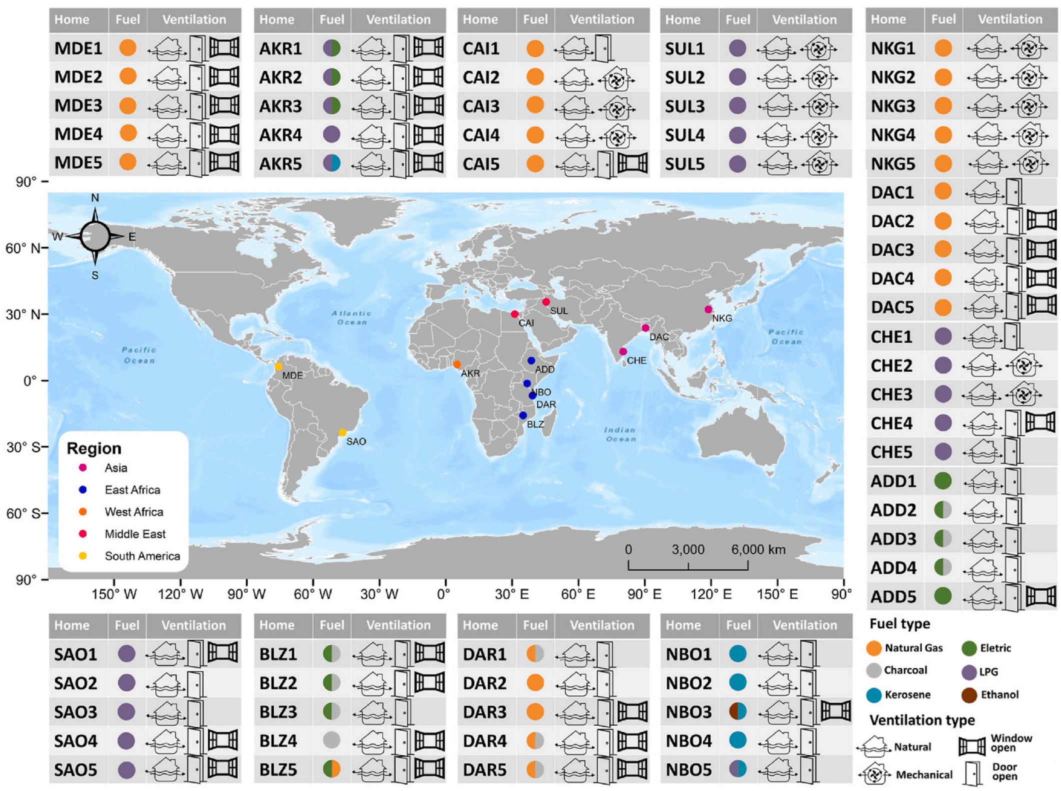

Fig. 1. Location map showing the cities where the 60 low-income homes were situated. The tables around the map show the types of cooking fuel and ventilation in the kitchens. Dhaka (DAC), Chennai (CHE), Nanjing (NKG), Medellín (MDE), São Paulo (SAO), Cairo (CAI), Sulaymaniyah (SUL), Addis Ababa (ADD), Blantyre (BLZ), Nairobi (NBO), Akure (AKR) and Dar-es-Salaam (DAR).

Table 2
Kitchen characteristics in five low-income homes in each of the 12 cities across the world. Dhaka (DAC), Chennai (CHE), Nanjing (NKG), Medellín (MDE), São Paulo (SAO), Cairo (CAI), Sulaymaniyah (SUL), Addis Ababa (ADD), Blantyre (BLZ), Nairobi (NBO), Akure (AKR) and Dar-es-Salaam (DAR). Ventilation conditions represent conditions during cooking; natural (open door), natural (open window + open door) and dual (mechanical + natural) ventilations are referred to as NV_d, NV_{dw} and DV_{mn}, respectively.

Home ID	Kitchen size (m): L × W × H (volume; m^3)	Cooking fuel type	Kitchen type (open/separate)	Ventilation type during cooking	No. of kitchen occupants during cooking	Average cooking duration per day (min)
DAC1	1.8 × 2.0 × 3.0 (10.8)	NG	Separate	NV_d	2	128
DAC2	1.5 × 1,5 × 2,75 (6.2)	NG	Separate	NV_{dw}	2	125
DAC3	1.5 × 1.5 × 2.75 (6.2)	NG	Separate	NV_{dw}	1	159
DAC4	2.0 × 1.8 × 2.75 (9.9)	NG	Separate	NV_{dw}	1	213
DAC5	2.0 × 1.75 × 2.75 (9.65)	NG	Separate	NV_{dw}	1	257
CHE1	6.0 × 3.0 × 3.0 (54)	LPG	Open	NV_d	1	240
CHE2	4.2 × 2.8 × 2.8 (32.9)	LPG	Separate	DV_{mn}	2	201
CHE3	2.5 × 3.5 × 3 (26.25)	LPG	Separate	DV_{mn}	1	90
CHE4	2 × 1.5 × 3 (9)	LPG	Separate	NV_{dw}	1	98.6
CHE5	3 × 2 × 3 (18)	LPG	Separate	NV_d	1	163
NKG1	2.1 × 1.65 × 2.8 (9.70)	NG	Separate	DV_{mn}	1	85
NKG2	2.94 × 2.04 × 2.34 (14.03)	NG	Separate	DV_{mn}	1	96
NKG3	2.03 × 2.3 × 2.24 (10.46)	NG	Separate	DV_{mn}	1	113
NKG4	2.94 × 2.04 × 2.34 (14.03)	NG	Separate	DV_{mn}	1	37
NKG5	2.9 × 2.12 × 2.4 (14.75)	NG	Separate	DV_{mn}	1	46
MDE1	3.15 × 3.25 × 3.2 (32.7)	NG	Separate	NV_{dw}	2	118.6
MDE2	3.4 × 1.55 × 2.18 (11.5)	NG	Separate	NV_{dw}	1	115.7
MDE3	3.35 × 2.11 × 2.2 (15.6)	NG	Separate	NV_{dw}	1	165
MDE4	2.7 × 2.7 × 2.2 (16.03)	NG	Open	NV_{dw}	1	116
MDE5	4 × 2.6 × 2.5 (26)	NG	Separate	NV_{dw}	1	84
SAO1	4.0 × 2.6 × 2.5 (26.0)	LPG	Separate	NV_{dw}	2	75
SAO2	3.2 × 2.9 × 2.6 (24.13)	LPG	Separate	NV_d	1	24
SAO3	1.5 × 2.8 × 2.4 + 1.2 × 1.9 × 2.4 (15.55)*	LPG	Open	NV_d	3	74
SAO4	5.3 × 2.5 × 2.4 (31.8)	LPG	Open	NV_{dw}	3	83
SAO5	5.9 × 2.45 × 2.72 (39.32)	LPG	Separate	NV_{dw}	2	52
CAI1	2.15 × 2.5 × 5 × 3.1 (16.7)	NG	Separate	NV_{dw}	1	152
CAI2	3.8 × 2.6 × 2.7 (26.7)	NG	Separate	DV_{mn}	2	181
CAI3	3.1 × 2.2 × 2.5 (17.1)	NG	Separate	DV_{mn}	2	190
CAI4	2.86 × 2.86 × 2 (16.4)	NG	Separate	DV_{mn}	1	86
CAI5	2.15 × 2.55 × 3.1 (17)	NG	Separate	NV_{dw}	1	85
SUL1	2.9 × 1.93 × 2.93 (16.4)	NG	Separate	DV_{mn}	2	125
SUL2	3.12 × 1.6 × 3.1 (15.5)	NG	Separate	DV_{mn}	2	140
SUL3	4.0 × 2.23 × 2.85 (25.4)	NG	Separate	DV_{mn}	2	117
SUL4	1.1 × 1.8.5 × 2.3 (4.7)	NG	Separate	DV_{mn}	1	120
SUL 5	3.7 × 3.8 × 2.7 (37.9)	NG	Separate	DV_{mn}	1	75
ADD1	2.5 × 2.5 × 3 (18.75)	Electric + Charcoal	Open	NV_d	1	240
ADD2	2 × 2 × 2.8 (11.2)	Electric + Charcoal	Open	NV_d	1	180
ADD3	2 × 2 × 2.5 (10)	Electric + Charcoal	Separate	NV_d	1	210
ADD4	3 × 1.5 × 2.5 (11.25)	Electric + Charcoal	Separate	NV_d	1	240
ADD5	4 × 5 × 3 (60)	Electric + Charcoal	Open	NV_{dw}	1	137
AKR1	2.3 × 1.5 × 2.09 (7.2)	Electric + LPG	Separate	NV_{dw}	2	244
AKR2	2.3 × 1.5 × 2.09 (7.2)	Electric + LPG	Separate	NV_{dw}	2	192
AKR3	2.3 × 1.5 × 2.09 (7.2)	Electric + LPG	Separate	NV_{dw}	2	244
AKR4	3 × 3 × 2 (18)	LPG	Open	NV_{dw}	4	283
AKR5	4 × 2 × 3 (24)	LPG + Kerosene	Separate	NV_{dw}	2	359
BLZ1	4 × 4 × 6 (96)	Electric + Charcoal	Separate	NV_{dw}	2	150
BLZ2	4 × 4 × 6 (96)	Electric + Charcoal	Separate	NV_{dw}	2	90
BLZ3	5 × 4 × 3 (60)	Electric + Charcoal	Separate	NV_d	1	104
BLZ4	3 × 3 × 4 (36)	Charcoal	Separate	NV_{dw}	1	90

(*continued on next page*)

Table 2 (*continued*)

Home ID	Kitchen size (m): L × W × H (volume; m^3)	Cooking fuel type	Kitchen type (open/separate)	Ventilation type during cooking	No. of kitchen occupants during cooking	Average cooking duration per day (min)
BLZ5	4 × 5 × 6 (120)	Electric + NG	Separate	NV_{dw}	2	124
DAR1	2.5 × 3.0 × 3.0 (22.5)	NG + Charcoal	Separate	NV_d	2	120
DAR2	2.5 × 3.0 × 3.0 (22.5)	NG	Open	NV_d	2	120
DAR3	2.3 × 1.8 × 2.0 (8.28)	NG	Separate	NV_{dw}	1	150
DAR4	3.0 × 2.3 × 2.5 (17.25)	NG + Charcoal	Separate	NV_{dw}	1	168
DAR5	4.0 × 2.5 × 2.0 (20)	NG + Charcoal	Separate	NV_{dw}	2	87
NBO1	4.0 × 4.0 × 2.5 (40)	Kerosene	Open	NV_d	3	210
NBO2	5.0 × 5.0 × 4.0 (100)	Kerosene	Separate	NV_d	6	200
NBO3	4.0 × 3.0 × 2.0 (24)	Electric + Kerosene + Ethanol	Open	NV_{dw}	4	210
NBO4	4.0 × 4.0 × 2.0 (32)	Kerosene	Open	NV_d	3	240
NBO5	4.0 × 4.0 × 2.5 (40)	LPG + Kerosene	Open	NV_d	3	180

Note: NG = natural gas; LPG = liquefied petroleum gas; The term "mechanical ventilation" refers to the usage of a "Extractor Fan" in the kitchen when cooking. *L-shaped kitchen.

number of rooms in each apartment, type of kitchen, ventilation conditions during cooking and throughout the day, kitchen, window and door dimensions and monitoring locations inside the kitchen. Also, the occupant surveys collected information on kitchen occupancy during cooking, type of fuel and stove used for cooking, the duration and time of cooking sessions, cooking type, cuisine and ventilation conditions during cooking (i.e. mechanical (extraction fan) and natural ventilation (door and window)). Fig. S1 shows all three types of ventilation conditions assessed.

We maintained a consistent set of criteria, as used in our earlier work [38], for fair comparison across the studied kitchens (Section 2.2). These criteria included: (i) home occupants are low-income families; (ii) homes were on ground floor or first floor; (iii) data collection took place inside the kitchens using the same set of monitoring equipment; (iv) equipment were set at ~1.5 m above ground level (average adult breathing height); (v) duration of the data collection was fixed and comparable in all homes; (vi) the number of homes were the same in all cities; and (vii) all homes had at least one occupant who undertook cooking every day.

2.2. Details of studied homes

The homes were situated in densely populated areas within the studied cities, representing the typical living conditions of low-income inhabitants. Table 3 summarises the characteristics of each home. Details on the investigated areas are in Section S1.

2.3. Instrumentation and quality assurance

The same model of the CO_2, temperature and relative humidity (RH) monitor [51] was used in each home. The model has been extensively used in previous indoor studies [52-54]. Prior to their deployment, the monitors procured for this study were factory calibrated and equipped with non-dispersive infrared (NDIR) CO_2 sensor technology. Each monitor recorded and transmitted temperature and relative humidity (RH) in monitored spaces using their integrated sensors. The CO_2 monitor allows self- and manual-calibration. Following the manufacturer's advice, manual calibration in ambient conditions was performed before use to ensure good accuracy [51]. The CO_2 sensor has a 1 ppm display resolution, with ±50 ppm accuracy, providing data within the range of 0–5000 ppm. Globally, the daily outdoor average CO_2 levels vary ~400 ppm, depending on the characteristics of the area (urban, semi-urban or rural), year and season [55,56]. Hence, CO_2 concentrations below 350 ppm may not be realistic and were removed from the data as outliers arising from instrumental errors of ±50 ppm accuracy [51].

The HOBO monitor also measured the in-kitchen air temperature and RH level per minute. The temperature sensor had a resolution, accuracy and range of 0.024, 0.21 and 0–50 °C, respectively, while their corresponding values for the RH sensor were 0.01%, ±6% and 20%–90%. Co-location measurements were conducted for CO_2 concentrations in the living room of a home with two/three inhabitants to simulate the kitchen's CO_2 concentrations. The measurement ranges of the co-location for temperature, RH and CO_2 were 14–20 °C, 54–66% and 411–2079 ppm, respectively. The data were recorded per minute for comparison. For the quality assurance and validation of data (Fig. S2), we also carried out a two-day co-location measurement (Fig. S3) for the CO_2 monitors against each other along with a research grade CO_2 monitor (Q-TRAK model 7575; TSI Inc., Shoreview, MN, USA). The obtained Pearson correlation coefficient (r) of 0.98–1.0 showed a high agreement among all the CO_2 monitors and with the Q-TRAK. In addition, co-location measurements for RH (Fig. S4) and temperature (Fig. S5) against each other and Q-TRAK also showed high agreement. This quality control and quality assurance process allowed fair comparison between the different cities in this study.

2.4. Data collection

Measurements were taken continuously in each home for one-week (24 h for 7 days) between March and October 2021. One-minute-interval measurements of indoor CO_2 concentrations, temperature and RH were taken in 60 kitchens of low-income homes in twelve global cities (Table 2), adding up to 840 h (equivalent to 35 days worth of data) in each city, which equals to a total of 10,080 h (420 days) in all cities (Table 1). Instruments were placed at 1.5 m above the floor (average adult breathing height) and at 1.5 m distance away from the cooker. Homeowners were also requested to keep a log of the times and duration of cooking sessions and

Table 3
Detailed overview of the studied homes in each city, including the city characteristics, the areas where the homes were situated, home description and the cooking habits of the occupants. Table S3 shows the sampling period in each city. Studied cities span over four regions: Asia, South America, Middle East and Africa.

City	City characteristics[a]	Area studied	Home description	Cooking habits
DAC	• Area: 306 km^2 • Population: 21.74 million • Capital of Bangladesh	● Two areas: 1. Southeastern part, relatively low-income and high pollution. 2. Dhaka University campus (south central), relatively low pollution and surrounded by trees	• Two-bedroom apartments with ~3 occupants. • Buildings ~5 storeys, made of bricks and cement. • No heating/cooling systems in the kitchen. • 10–50 m distant from busy roads, however owing to COVD-19 lockdown, traffic was sparse. • Stoves were all two-hobed	● 2–4 times a day, the kitchen was utilised to boil, reheat, grill and fry. ● Average cooking lasted 30–90 min per season.
CHE	• Area: 1189 km^2 • Population: 11.56 m • Capital of Tamil Nadu	• Low-income homes. • Located in the city's residential districts.	• Apartments with three occupants in a single bedroom. • Buildings of 3–5 stories composed of brick and concrete. • No heating/cooling systems in the kitchen. • Double burner gas stoves.	● Cooking activities consisted of boiling, reheating and frying. ● Average cooking lasted 30–120 min per season, 2–3 times a day.
NKG	• Area: 6587 km^2 • Population: 8.5 m • Provincial capital in southern China	• Jiangning district is overpopulated, with many old settlements. • Homeowners are low-income, low-class urban dwellers. • Located 50–150 m away from busy roads, mostly in residential areas with low congestion (except NKG3).	• Two-bedroom apartments with ~3 occupants. • 7-11 story buildings made of reinforced concrete. • Open non-motorised parking is located on the ground floor. • No heating systems in the kitchen. • Cookers are self-contained units with two hob stoves.	● 2–3 times a day, the kitchen was utilised for boiling (or steaming), reheating, grilling and frying. ● Average cooking lasted 15–50 min per season.
MDE	• Area: 1.166 km^2 • Population: 3.7 million • Second largest city in Colombia	• Residential areas in the metropolis. • 20–100 m distant from roads with moderate to high traffic.	• 2–6 occupants in 2–3 bedroom apartments. • 1 or 2-story residential buildings with ceramic tile flooring, constructed with concrete, bricks and mortar. • Four/two burner countertops with/without an oven.	● 1–4 times a day, the kitchen was used to boil, reheat and fry. ● Average cooking lasted ~10–40 min per season.
SAO	• Area: 7947 km^2 • Population: 21 million • Most economically important region of Brazil	• Jardim Colombo is a slum region located in the west of the city, having 120,805 inhabitants/km^2.	• Single-floor houses, made of brick and cement • SAO2 is exposed to traffic because it is located at the entrance to the slum. It is around 2 m below street level. • Cookers are self-contained units with an oven and four to six hob stoves.	• 1–4 times a day, the kitchen was utilised for boiling, reheating, oven baking, grilling and frying. ● Average cooking lasted ~ 3–90 min per season.
CAI	• Area: 3085 km^2 • Population: 20 million • Capital of Egypt	• Central, overpopulated districts in Greater Cairo, including El-Zeitoun, Shobra and Rod El-Farag. • Distance from busy roads (heavy traffic): 30–50 m.	• ~4 occupants in 2-bedroom apartments. • Residential buildings (5-10 story) constructed with concrete and bricks. • Cookers are self-contained units with an oven and four to five hob stoves.	● 2–4 times a day, the kitchen was utilised for boiling, reheating, oven baking, grilling and frying. ● Average cooking lasted ~30–50 min per season.
SUL	• Area: 20,144 km^2 • Population: 1.9 million • Largest city in Kurdistan	• Areas are mostly inhabited by low-income residents. • Two neighbourhoods; one in the east of the city, and the other near to the city centre. • Distance from busy roads (heavy traffic): ~40–70 m.	• 2-bedroom apartments with ~4 occupants, in buildings made of concrete. • Cookers are self-contained units with an oven and four to five hob stoves.	● 2–3 times a day, the kitchen was utilised for boiling, reheating, oven baking, grilling and frying. ● Average cooking lasted ~30–90 min per season.
ADD	• Area: 527 km^2			

(continued on next page)

Table 3 (*continued*)

City	City characteristics[a]	Area studied	Home description	Cooking habits
	• Population: 5 million • Capital of Ethiopia	• Arada Sub-city, at city centre, one of the early establishments (over 100 years old). • Distance from busy roads (heavy traffic): ~10 m.	• A single room with no windows houses four to five people. • All of the kitchens are located in small, independent rooms (max. of 2 people), either as part of the single room or attached to the main house outside. • They share a toilet with the community.	● Cooking and preparing injera, a teff flour-based sour fermented flatbread. ● Average cooking lasted ~60–120 min per season.
AKR	• Area: 991 km2 • Population: 691,000 • Major city and the capital of Ondo State, Nigeria.	• The metro capital city of Ondo State. • Distance from busy roads (heavy traffic): ~50–100 m.	• Residential 2-bedroom apartments with ~4 occupants, made of woods, cement and bricks. • Cookers are self-contained units with an oven and one to three hob stoves.	● 2–3 times a day, the kitchen was utilised for boiling, heating, oven baking, grilling and frying. ● Average cooking lasted ~65–240 min per season.
BLZ	• Area: 240 km^2 • Population: 451,220 • Second-largest city in Malawi.	• Majority of the population are low-income families. • Distance from busy roads (heavy traffic): ~10–20 m.	• 2–3 bedrooms made of brick, sand and cement. • Cookers are self-contained units with an oven and four hob stoves.	● 2–4 times a day, the kitchen was utilised for boiling, reheating, oven baking, grilling and frying. ● Average cooking lasted ~30–50 min per season.
DAR	• Area: 1393 km^2 • Population: 5 million • Largest business hub of Tanzania	• Majority of the population are low-income families. • Distance from busy roads (heavy traffic): ~50–300 m.	• 3-bedroom ground floor houses with ~6 occupants, made of cement, and bricks, have concrete floor or ceramic floor and are roofed by iron sheets. • Cookers are charcoal-fueled or a two-plate gas stove.	● 3 times a day, the kitchen was utilised for boiling, reheating, oven baking, grilling and frying. One time (only eneving) for DAR1 and DAR2 (during Ramadan month) ● Average cooking lasted ~ 15–90 min per season.
NBO	• Area: 704 km^2 • Population: 4.3 million • Capital of Malawi	• Homes are located in Korogocho (informal settlement) located 7 km north-east of Nairobi. • Distance from busy roads (heavy traffic): ~50–100 m.	• 1-bedroom ground floor with ~ 1–4 occupants, made of tin-sheets or mud-wall. • Cookers are self-contained double or single units.	● 3 times a day, the kitchen was utilised for boiling, reheating, oven baking, grilling and frying. ● Average cooking lasted ~60 min per season.

[a] Population data is for the most recent years (2018–2021).

kitchen conditions for better understanding of factors affecting indoor CO_2, RH and temperature levels. The surveys provided a schematic of the kitchen. In addition, the type of cooking and cuisine, and the number of kitchen occupants were also monitored. Other sources of emissions, such as cleaning and smoking, were also noted using questionnaires. Daily outdoor temperature and RH for individual cities were also collected (Table S4). Outdoor pollution information, such as dust storms, proximity to traffic, solid waste burning, and industrial areas, was also reported by homeowners. Also, any national holiday or special public event was noted. Table 2 summaries the questionnaires. Table 3 details the number of house occupants, type of apartment and floor number.

Data was retrieved from the monitors regularly throughout the week, compiled and analysed to derive ACH and ventilation rates (Sections 2.5), and the health risk assessment (Section 2.6). R statistical software [57] and Microsoft Excel were used for data processing and statistical analyses (Section 3).

2.5. Estimation of ventilation

2.5.1. ACH

The ACH value is an indication of ventilation levels within a microenvironment such as a kitchen, which influences IAQ, energy efficiency and health [58,59]. ACH is determined using CO_2 as a tracer, and is classified according to occupancy phase or concentration trend derived using three methods: steady state, decay, and build-up [19–21]. The steady state as well as the build-up techniques apply with at least one person in the kitchen, while the decay method applies to unoccupied kitchens [20,24]. The mean and the standard deviation values of ACH in the 60 kitchens were calculated using the above-noted methods (Fig. S6) and their results are summarised in Table S5. These allowed us to compare the ACH among all homes and understand how it is influenced by ventilation type, fuel used, kitchen volumes/occupant and occupancy.

The ACH values were divided into five ranges [60]: low ($<3\ h^{-1}$); bare minimum (3-4 h^{-1}); good (4-5 h^{-1}); excellent (5-6 h^{-1}); and ideal ($>6\ h^{-1}$). We applied the decay and build-up methods to the CO_2 time series during kitchen occupancy periods. Unlike the steady-state requiring much more detailed information such as average CO_2 generated per person for male and female. The decay method was used so that no occupancy is needed, and the build-up method was employed because the CO_2 concentrations changed significantly owing to cooking. Steady-state method was not used since it was not possible to maintain CO_2 levels when people are cooking in the kitchen for long periods (Section S2).

Decay ACH (A_D): When CO_2 decays from its peak level and stabilises at ambient concentrations, A_D (h^{-1}) was calculated using Eq. (1):

$$A_D = 1/\Delta t \ln\{(C_1\text{-}C_R)/(C_0\text{-}C_R)\} \quad (1)$$

Where Δt = time between consecutive measurements (*h*), between C_0 and C_1 (ppm; CO_2 concentrations recorded at start and end of the observation time, respectively), and C_R = minimum CO_2 concentration in the replacement air or the steady state concentration at the lower occupancy (ppm). Compared with other methods, the decay method is not restricted by factors such as the number of the kitchen occupants and the kitchen volume and G_P. We followed the following criteria for each decay sequence: (i) there should be a maximum of 8 h data; (ii) C_1 needs to reach the steady state and should be close to the background CO_2 concentration; (iii) the change in concentration between C_0 and C_1 (ΔCO_2) must be >100 ppm (or higher than the typical instrument accuracy) [19,21].

Build-up ACH (A_B): A_B (h^{-1}) was calculated using the build-profile of the CO_2 concentrations and Eq. (2):

$$A_B = 1/\Delta t \ln\{(C_{SS} - C_0)/(C_{SS} - C_1)\} \quad (2)$$

Where Δt = time (*h*) between C_0 and C_1, which were the CO_2 concentrations (ppm) recorded at start and end of the observation period, respectively. C_{SS} (ppm) was final steady state concentration at equilibrium conditions, which was estimated using Eq. (3):

$$C_{SS} = (C_b^2 - C_0 C_1)/(2 C_b - C_0 - C_1) \quad (3)$$

Where C_b is CO_2 concentration (ppm) measured at the middle of observation period. The build-up method is limited to the time series where (i) C_0 should be close to the CO_2 concentration in replacement air, (ii) C_{SS} cannot be negative, and (iii) the method only works for 20 min of data [19–21]. We also ensured that the correlations (R^2) between the measured and predicted concentrations were ≥0.9 for both these methods.

2.5.2. Ventilation rate

Adequate ventilation removes stale indoor air and draws clean outdoor air [22,23]. Hence, it is essential to estimate the ventilation rate per person (Q_1; L/s/person) in kitchens as it affects IAQ, the well-being of occupants, energy use and heat loss [22,25,26]. Since the studied kitchens are located in different continents, we adopted the European Standard EN15251 [61] for dwellings as the main guideline, following its minimum ventilation rates for kitchen occupants in the following categories: low ($Q_1 \leq 4$ L/s/person); bare minimum ($4 < Q_1 \leq 7$L/s/person); good ($7 < Q_1 \leq 10$ L/s/person); excellent ($Q_1 > 10$ L/s/person). It also has been widely used in many relevant studies [62-66].

The data were analysed in references to different parameters, including ventilation type, fuel used, kitchen volume, occupancy, countries, and regions (Section 3). Ventilation rate (Q) in $m^3\ h^{-1}$ was estimated using Eq. (4) [25]:

$$Q = ACH \times V \quad (4)$$

where ACH (h^{-1}) is the air exchange rate calculated as per Section 2.5.1 and *V* is the kitchen volume (m^3). The ventilation rate per person Q_1 (L/s/person) was calculated using Eq. (5):

$$Q_1 = Q/(3.6n) \quad (5)$$

where *n* denotes the average number of kitchen occupants. The ventilation rate per person per unit area of kitchen floor area (Q_2; L/s/m^2) was estimated using Eq. (6):

$$Q_2 = Q/(3.6A) \quad (6)$$

where *A* is the area of the kitchen floor (m^2) and 3.6 is the conversion factor from $m^3\ h^{-1}$ to L/s. Q_1 was used to analyse indoor ventilation rate for each person, while Q_2 was adopted for indoor ventilation rate. Details on descriptive statistics and relevant box plot of Q_1 for all kitchens are summarised in Table S6 and Fig. S7, respectively.

2.6. Health risk assessment for CO_2

CO_2 concentrations in the atmosphere are generally at around 400 ppm [1]. However, long-term exposure to higher concentrations, which may occur in poorly ventilated indoor spaces, can induce headaches and dizziness, among other health problems [46]. We assessed non-carcinogenic health risks using the Hazard Ratio (HR) based on CO_2 concentrations exceeding the reference value. The HR was calculated by dividing average CO_2 concentration by the reference concentration (RfC) using Eq. (7):

$$HR = C\ /\ RfC \quad (7)$$

where C is the measured 2.5-h average CO_2, and RfC is the corresponding reference CO_2 concentrations (1000 ppm; [67]). To calculate HR, we averaged exposure at 2.5-h intervals throughout the day. This RfC and time average was chosen as there is evidence that affects cognitive performance and decision-making ability [1,6,67]. If HR is <1, the kitchen is considered to have non-cancer health effects. However, if HR >1, then, the kitchen may have some non-cancer risks.

3. Results and discussion

For detailed investigation, the CO_2, RH and air temperature data collected from 60 low-income homes in 12 cities across the world were divided into seven categories: ventilation, kitchen volume, fuel type, occupancy, cities, regions and cooking types [38]. The average occupancy during cooking and cooking duration was 1.7 ± 0.96 persons and 147 ± 68 min day^{-1}, respectively (Table 2). 78% of the kitchens had dedicated discrete rooms. Average kitchen volume was 27.8 m^3 with a range between 4.7 and 120 m^3; 35%, 53% and 7% of the kitchens fall within 4–15, 16–46 and >46 m^3, respectively. During cooking, 25%, 47% and 28% of the kitchens used dual ventilation (mechanical + natural, DV_{mn}), natural ventilation (door + window, NV_{dw}) and natural ventilation (door only, NV_d),

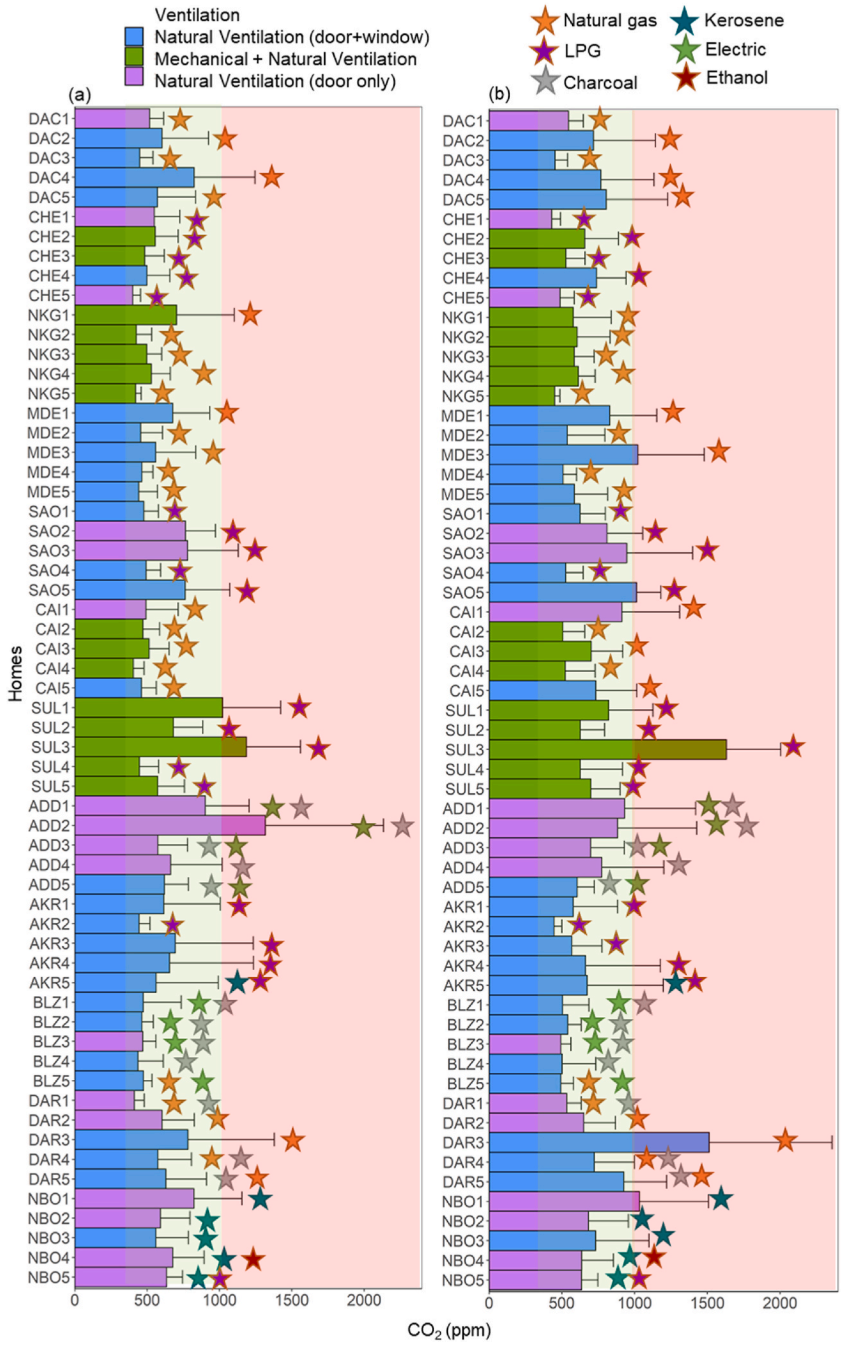

Fig. 2. CO_2 concentrations (a) overall average during the study, and (b) cooking session average for each kitchen. The bar and star colours indicate ventilation and fuel types used for cooking, respectively. The green shaded background indicates CO_2 level ranges: light green is <1000 ppm and red is >1000 ppm, where complaints of drowsiness and poor air have been reported [9]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

respectively. In addition, approximately 33% of the homes used natural gas (NG) for cooking, 27% used liquefied petroleum gas (LPG), 17% used electric stoves, 14% used charcoal, 8% used kerosene while only 1% used ethanol. The cooking types were mostly consistent across the cities where frying and boiling/steaming were the most common, whereas grilling and oven baking were less common.

3.1. In-kitchen characteristics and CO_2 concentrations

The overall average in-kitchen CO_2 concentration across all homes was 567 ± 273 ppm, which increased by 22.2%–693 ± 297 ppm during cooking (Table S7). Over 91% (55 out of 60) kitchens had average CO_2 concentrations between 400 and 1000 ppm during cooking (Fig. 2b). These homes used NV_d (NBO1), NV_{dw} (SAO5, MDE3, DAR3) and DV_{mn} (SUL3). SUL3 had extraction fans but they used them ~25% of the time during cooking, possibly contributing to the high average CO_2 concentrations. Besides ventilation, other factors such as cooking fuel, kitchen volume, occupancy and cooking type can also influence the in-kitchen CO_2, as discussed in subsequent text.

In general, the overall CO_2 averages were comparable for NV_{dw} (561 ± 284 ppm) and DV_{mn} (594 ± 212 ppm). However, NV_{dw} showed 14.5% lower average CO_2 compared with NV_d (656 ± 284 ppm); Fig. 3a. As expected, the average CO_2 concentrations during

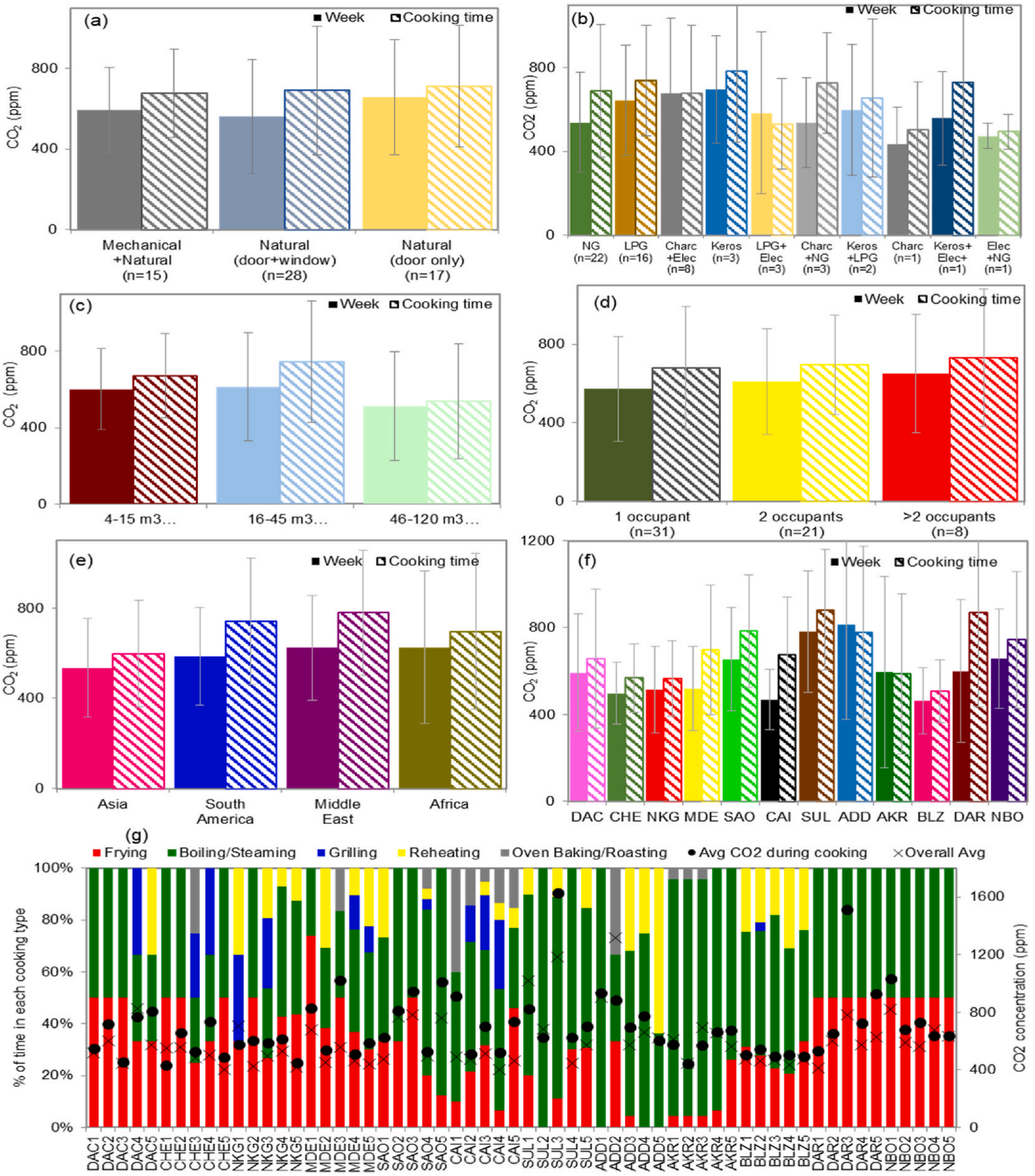

Fig. 3. The weekly and cooking session averaged CO_2 concentrations based on diverse kitchen conditions: (a) type of ventilation, (b) cooking fuel, (c) kitchen volume, (d) occupancy, (e) region and (f) city. Sub-figure (g) shows the % of time spent within the week for each cooking type against the average CO_2 concentration (during cooking) for each of the investigated homes. The x-axis indicates different types of grouping and *n* refer to the number of kitchens per group.

cooking were higher than the overall average noted above, i.e., 711 ± 302, 690 ± 319 and 677 ± 219 ppm for NV_d, NV_{dw} and DV_{mn}, respectively. This observation highlights the importance of enhanced ventilation through doors, windows and extraction fans in the kitchen during cooking to reduce indoor CO_2 concentrations.

Regarding the effect of fuel type, the average CO_2 concentrations (653 ± 275 ppm) during cooking were ~90 ppm higher than the overall mean value of 575 ± 252 ppm (Fig. 3b). All the African homes used more than one cooking fuel. Therefore, we grouped homes according to fuel combinations. This approach reduces the statistical power of observations, e.g. only BLZ4 used charcoal exclusively

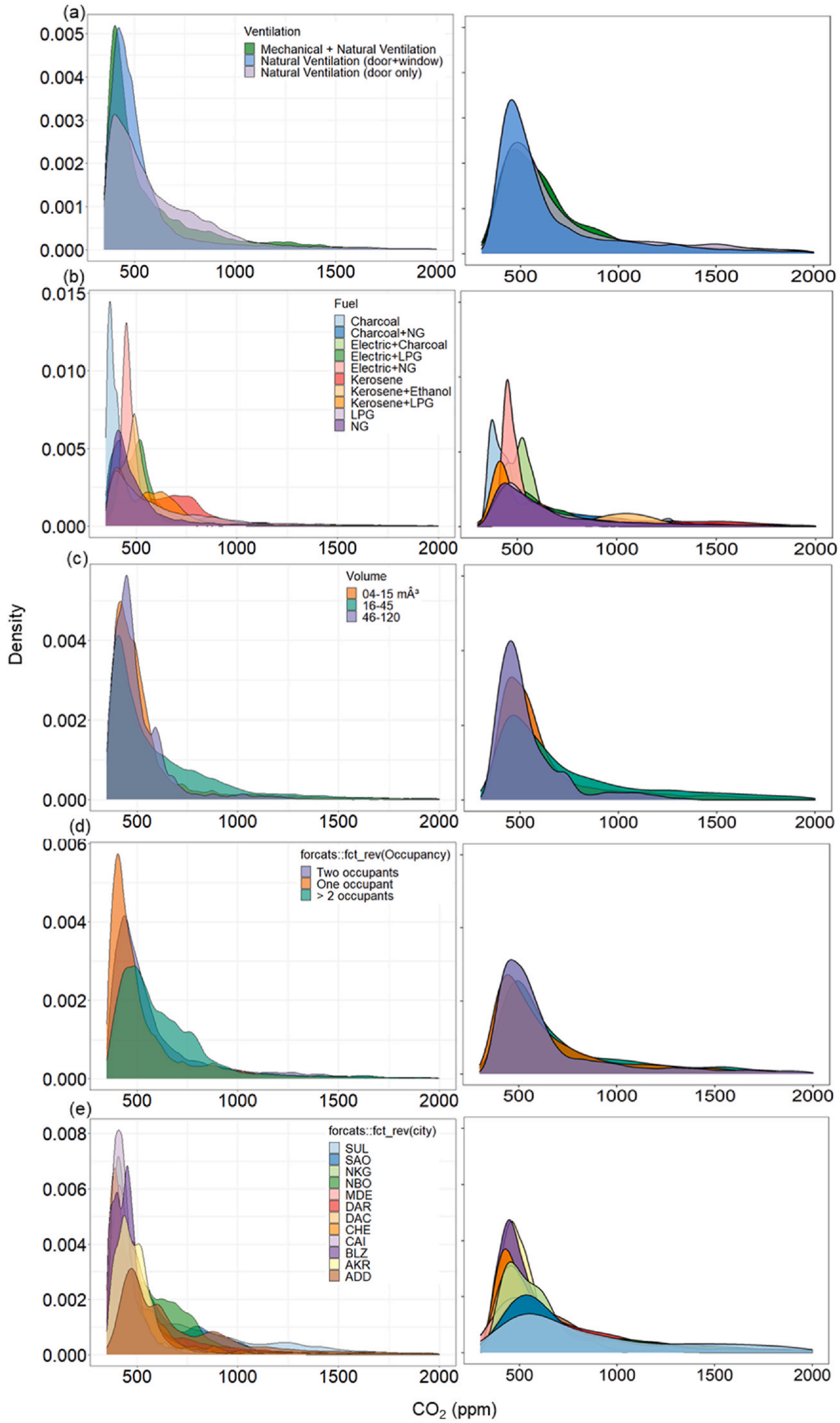

Fig. 4. Density plots of the weekly (left) and cooking session (right) averaged CO_2 concentrations in contrast with the diverse kitchen conditions: (a) types of ventilation, (b) cooking fuel, (c) volume of kitchens, (d) occupancy and (e) city. The x-axis indicates different types of grouping.

which emits high amounts of pollutants [38,68], yet the lowest average CO_2 concentration (437 ± 174 ppm) was observed. Hence, such an observation cannot rightly indicate the disadvantages of cooking with charcoal. Conversely, BLZ5 experienced low CO_2 concentrations (494 ± 85 ppm) during cooking because of its reliance on clean fuels and technologies (i.e., electric stoves and NG). During cooking, the lowest average CO_2 concentrations were observed for homes using electric + LPG (531 ± 216 ppm), while the highest average CO_2 concentrations were found for those using kerosene (784 ± 340 ppm). These results substantiate the benefits of using clean fuels (such as NG + LPG), instead of fuels like kerosene [69]. Although all the cooking fuels were fossil-fuel based, using clean fuels reduced CO_2 exposure during cooking.

Fig. 3c groups homes according to kitchen volume (m^3), with 20 and 32 kitchens falling into small (4–15 m^3) and medium (16–45 m^3) size, respectively, with average CO_2 concentrations being 673 ± 330 and 745 ± 297 ppm, respectively, during cooking. This observation indicates that larger volume (up to 45 m^3) has not been associated with lower CO_2 concentrations where other factors such as cooking type, fuel and duration might be more influential on the CO_2 concentrations. However, the remaining eight kitchens had large volumes (46–120 m^3), showing 28% and 20% less CO_2 concentrations than those of medium and small sized kitchens, respectively. These differences indicate that large-volume kitchens (>45 m^3) might have contributed to lowering CO_2 concentrations during cooking. Hence, allocating larger surface area or higher ceilings to increase the volume of kitchens should be considered during the design of new homes.

Occupancy is another evident factor contributing to CO_2 concentrations during cooking (Fig. 3d). Kitchens with more than two occupants during cooking sessions had 7% higher average CO_2 concentrations than kitchens with one occupant, confirming that CO_2 concentrations increased with the occupancy [70]. These results suggest avoiding passive occupancy during cooking to avoid further addition to CO_2 concentrations.

Grouping CO_2 concentrations according to regions (Fig. 3e) and cities (Fig. 3f) provides evidence on the similarities of cultural habits among various international cuisines. The average in-kitchen CO_2 concentrations during cooking followed the decreasing trend: Middle Eastern homes (779 ± 277 ppm), South American homes (741 ± 279 ppm), African homes (697 ± 346 ppm) and Asian homes (597 ± 236 ppm). For instance, Middle Eastern homes carried out substantial boiling for long periods (up to 3 h/d) (Fig. 3g and Table 2). Specifically, the highest average CO_2 concentrations were in SUL (881 ± 277 ppm), followed by DAR (869 ± 433 ppm) and SAO (785 ± 260 ppm). SUL homes had small kitchens and frequent boiling (>50% of the time) for long durations. SAO homes also carried out boiling for >40% of the time, while DAR homes used charcoal for cooking (Fig. 3g and Table 2), as plausible causes for high CO_2 concentrations. Conversely, lowest CO_2 concentrations were observed in BLZ (507 ± 146 ppm), NKG (566 ± 175 ppm) and CHE (568 ± 159 ppm). Most BLZ kitchens were sized within the 46–120 m^3 range, while NKG and CHE kitchens used cleaner fuels (NG and LPG, respectively) for cooking. It was also noted that CO_2 emissions during cooking were slightly lower than the weekly average in ADD and AKR (Fig. 3f). Field researchers reported that home occupants in these two cities ensured better ventilation (resulting in lower CO_2 concentrations) during cooking by opening doors and windows versus keeping them shut throughout the day. Also, occupancies were higher during the day, while charcoal was used for cooking, which might have contributed to higher weekly CO_2 concentrations. Overall, analysing kitchen CO_2 emissions based on region and city suggests favourable behaviours and conditions that can be adopted elsewhere.

Fig. 3g shows the percentage of time within the week spent on each type of cooking: frying, boiling/steaming, grilling, reheating and oven-baking for each home. No consistent trend relating to cooking types against the average CO_2 concentrations were observed. However, the CO_2 concentrations were high for some homes with frequent frying and vice versa. Likewise, homes having frequent boiling appeared to link with the high CO_2 concentrations compared with others involving less boiling.

The above discussion suggests that high in-kitchen CO_2 concentrations are favoured by low ventilation (NV_d), polluting fuels (e.g., kerosene), higher occupancy and smaller kitchen volumes, while cooking type showed no apparent trend as some homes that carried out frying and those doing boiling on a frequent basis were associated with high CO_2. To further understand the impact extent of the controllable factors (such as ventilation conditions and occupancy) on the IAQ, we carried out detailed analysis of the individual features with respect to further air quality indicators (such as thermal comfort, ventilation rates, ACH (air change rate per hour) and hazard ratios) to ultimately provide homeowners with actionable advice to improve their in-kitchen air quality.

3.2. Frequency distribution

The kernel density distribution plots help understand the CO_2 concentration peak frequencies and their spread, based on ventilation, volume of kitchens, cooking fuel, occupancy, type of food cooking and city-wise difference (Fig. 4a–e). These density plots are a smoothed form of histograms that depict the distribution of data using the density function to estimate a continuous curve.

Fig. 4a shows the density plot of overall and cooking averaged CO_2 concentrations in the left and right columns, respectively, based on ventilation type. The bimodal shape of the density distribution curves was similar in both plots but narrowed and peaked at different concentration ranges. For example, the concentration peaks over the cooking period were at ~400, 500 and 510 ppm for NV_d, NV_{dw} and DV_{mn}, respectively. For the weekly average, the peak density curves for DV_{mn} were the sharpest and tallest (ranging between 450 and 800 ppm), indicating a less frequent occurrence of high concentrations. For NV_{dw}, a wider peak was observed for 480–900 ppm CO_2. Whereas for NV_d, the peaks were the broadest and shortest (with slow buildup, diminishing between 400 and 100 ppm), suggesting a more frequent occurrence over a broader concentration range (Fig. 4a).

During cooking, NV_{dw} showed a higher and broader peak (400–1100 ppm), followed by DV_{mn} of 400–1000 ppm and NV_d (Fig. 4a). The weekly and cooking periods averaged for both DV_{mn} and NVdw exhibited more frequent CO_2 concentrations within 400–1000 ppm. The above discussion suggests that DV_{mn} is more effective in reducing the frequency of high CO_2 concentrations than natural ventilation during cooking.

Fig. 4b shows the density of CO_2 concentrations for various fuels used during cooking. A significant difference in the distribution of

CO_2 concentrations among the fuel types was observed. Charcoal showed the highest peak frequency in the lower CO_2 concentrations range (400–480 ppm), followed by electric + NG (480–520 ppm) for the weekly average (Fig. 4b). The CO_2 concentration distribution for cooking periods within the 400–1500 ppm range shows different peaks for various fuel types (Fig. 4b). During cooking, electric + NG (BLZ5) had the highest peak (450–520 ppm), followed by charcoal (BLZ4) and charcoal + electric (ADD1-5, and BLZ1-3) with lower frequency peak (410–550 ppm). The result suggests the probability of having lower CO_2 concentrations in those kitchens is higher than other kitchens using other fuel types (Fig. 4b). In addition, homes that used fuels, such as LPG (SAO, CHE and SUL) or NG

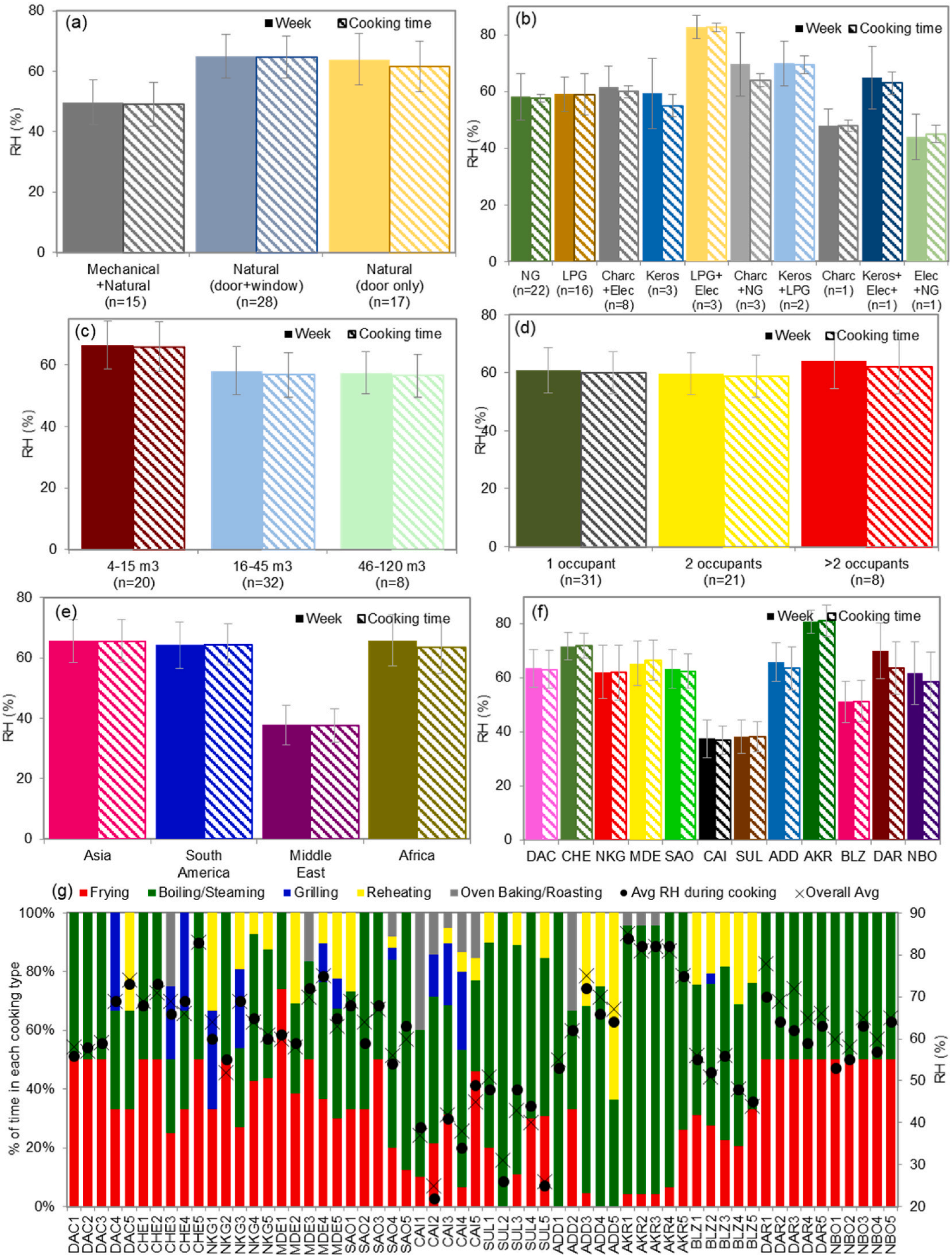

Fig. 5. The weekly and cooking session averaged relative humidity (RH in %) in contrast with the diverse kitchen conditions: (a) ventilation, (b) cooking fuel, (c) volume of kitchens, (d) kitchen occupancy, (e) region and (f) city. Sub-figure (g) shows the % of time spent within the week for each cooking type against the RH (%) (during cooking) for each of the investigated homes. The x-axis indicates different types of grouping and *n* refers to the number of kitchens per group.

(DAC, NKG, MDE and CAI) exhibited lower frequency (broader peaks) in the higher CO_2 concentration range (420–1300 ppm) (Fig. 4b). Interestingly, LPG and kerosene evinced wider distributions, arising from their non-clean fuel attribute.

Fig. 4c illustrates a density plot and weekly CO_2 distributions for the three kitchen volume categories. Large-sized kitchens exhibit a narrow density function tail in the lower concentration range (400–560 ppm), indicating a higher probability of low CO_2 concentrations (Fig. 4c). Whereas small and medium-volume kitchens show a smaller peak with a wider CO_2 range (410–1200 ppm), with or without cooking (Fig. 4c). The density plot patterns are similar for both scenarios (Fig. 4c), i.e., the impact of kitchen volume is not

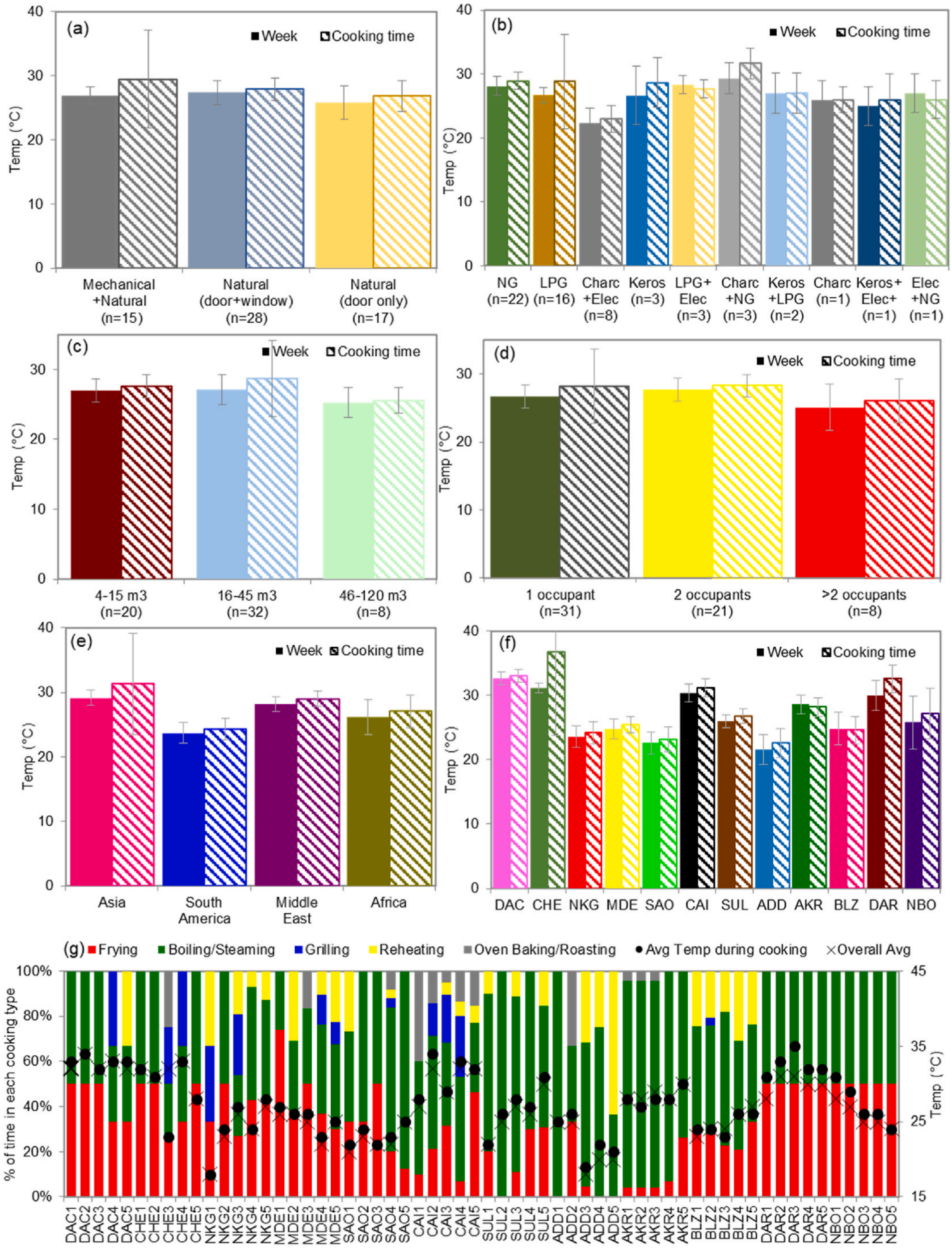

Fig. 6. The weekly and cooking session averaged temperature (°C) in contrast with the diverse kitchen conditions: (a) ventilation, (b) cooking fuel, (c) volume of kitchens, (d) kitchen occupancy, (e) region and (f) city. Sub-figure (g) shows the % of time spent within the week for each cooking type against the average temperature (°C) for each of the investigated homes. The x-axis indicates different types of grouping and *n* refer to the number of kitchens per group.

affected by the difference in cooking time. These findings substantiate earlier observations that kitchens with larger surface area or higher heights could help to reduce CO_2 emissions.

Fig. 4d shows the influence of kitchen occupancy on weekly CO_2 concentrations with and without cooking. For the overall average, kitchens with >2 and two occupants showed higher probability of CO_2 concentrations (400–1200 ppm) than those with one occupant (high peak with low CO_2 range, 400–550 ppm). During cooking, the highest density peak was for >2 occupants, followed by two and one occupants (Fig. 4d). Thus, a direct relationship exists between CO_2 concentrations and the number of kitchen occupants.

Further, the weekly and cooking average CO_2 concentration distribution for all homes were grouped by city together (Fig. 4e) and separately (Fig. S8). For the weekly average, CAI, BLZ, ADD and AKR showed the highest peak frequency with lower CO_2 ranges (420–520 ppm), while SUL, SAO and NKG showed the lowest peak (Fig. 4e). During cooking, BLZ characterises the highest, sharp peak with a narrow range of CO_2 ~400–520 ppm. BLZ, AKR DAR, and NBO exhibited the highest peak, while SUL and SAO evinced the lowest (Fig. 4e). The cities with high density peaks also showed a narrow CO_2 range. For example, BLZ exhibits the highest but narrow CO_2 range ~420–520 ppm. Furthermore, cities with higher CO_2 concentration probability during cooking included South American (SAO), Middle-eastern (SUL) and Asian (DAC) homes. They exhibited a stretched tail on the right of the density function. Hence, we conclude that cities with high density peaks (sharp) have relatively lower CO_2 concentrations (420–520 ppm), while those with a lower density peak and wide range have higher CO_2 concentrations (420–1200 ppm), consistent with the findings in Section 3.1.

Fig. S9 illustrates CO_2 frequency distribution in all homes at different range groups. The frequency variations differ for each city. Asian homes show CO_2 concentrations in the first three ranges (350–500, 500–700 and 700–900 ppm). Similarly, South American homes show different variations: MDE shows two main CO_2 ranges (350–500 and 500–700 ppm) and two little bars (700–900 and 900–1100 ppm); SAO shows four clear bars in four CO_2 ranges (350–500, 500–700, 700–900 and 900–1100 ppm). Furthermore, homes in Middle-eastern cities show different profiles. CAI is similar to Asian homes, while SUL is similar to African homes (e.g., ADD). These results indicate that CO_2 concentrations vary for each home (Section 3.1). Conversely, African homes exhibit various patterns. For instance, ADD shows a bar peak in all CO_2 ranges for all five homes (Fig. S9). AKR and BLZ have a similar profile, with the bar peaks in the same CO_2 ranges (350–500 and 500–700 ppm). DAR and NBO suggest different profiles, indicating that they are influenced by differences in CO_2 concentrations. In addition, the first two CO_2 ranges (350–500 and 500–700 ppm) were the most common among all cities. The first range (350–500 ppm) was the highest peak in all cities, except SAO, ADD and NBO (Fig. S9). This result is consistent with the findings reported in Section 3.1, showing that 46 out of 60 homes had weekly average CO_2 concentrations within 400–800 ppm.

3.3. Thermal comfort

Since cooking is a primary activity in most homes, especially for women and young adults, people often spend 2–3 h daily in their kitchens [71], wherein their CO_2 exposure is increased by 22.2% (Section 3.1). The weekly cooking duration in our study ranged from 5.1 (SAO) to 22 h (AKR) (Section 2.1; Table 2). Therefore, a thermally comfortable kitchen environment is crucial for the residents' health.

The recommended indoor thermal comfort range for RH and temperature is 40–60% and 21–23 °C, respectively [72]. Table S7 lists the descriptive data of in-kitchen RH and air temperatures. The overall average RH across all homes was 61 ± 7.8%; it was 60 ± 8% during cooking (Fig. S10). Most kitchens were warm (>25 °C), probably because the monitoring took place during the spring/summer. The overall temperature across the homes was 27 ± 2 °C, albeit 28 ± 2 °C during cooking sessions (Fig. S11).

Furthermore, we examined the average RH and temperature during cooking based on the ventilation type (Figs. 5a and 6a), fuel type (Figs. 5b and 6b), kitchen volume (Figs. 5c and 6c), kitchen occupancy (Figs. 5d and 6d), region (Figs. 5e and 6e) and city (Figs. 5f and 6f). The RH was high (60–80%) in DAC, AKR, DAR, ADD, SAO and NBO (Fig. 5f) due to lack of mechanical ventilation, small-volume kitchens, and cooking type (Fig. S10). This observation indicated that homes in those cities (RH) did not comply with the ASHRAE guidelines for thermal comfort [72]. The RH was relatively low (<40%) in SUL and CAI, attributable to the use of mechanical and natural (open windows) ventilation modes in these cities (Fig. S10). In contrast, the average air temperature was <26.8 °C in all the studied kitchens (Fig. S11), which could be ascribed to seasonal effects, occupant' body heat and occupants' disposition to natural ventilation. During cooking, we found that 55 (due to high RH) and 50 (due to high temperature) kitchens did not comply with the ASHRAE standard for thermal comfort (RH >40%, temperature >23 °C). During cooking, the highest RH average was found for Africa (58–81%), followed by Asia (62–72%), South America (62–66%), and the Middle East region (37–38%) (Fig. 5e). The highest temperature average was found for Asia (24–33 °C), followed by the Middle East (27–31 °C), Africa (23–32 °C), and South-America region (23–25 °C) (Fig. 6e). Overall, 87% of the kitchens did not comply with the ASHRAE guidelines.

Regarding the influence of ventilation type, NV_{dw} induced the highest average RH of 65 ± 7%, followed by NV_d of 64 ± 8%, while DV_{mn} gave the lowest level of 49 ± 7% (Fig. 5a). Hence, DV_{mn} helped reduce the humidity in the kitchens and consequently ensured thermal comfort of the kitchen occupants. These results are consistent with those reported elsewhere [71], wherein mechanical and natural ventilation helped in reducing in-kitchen RH by 10–40%. During cooking, the RH levels were similar to the weekly variations, i.e., 49 ± 7, 65 ± 7 and 62 ± 8% for the DV_{mn}, NV_{dw} and NV_d, respectively. Considering the ventilation effect on temperature (Fig. 6a), the average temperatures were 29 ± 7, 28 ± 2 and 27 ± 2 °C for DV_{mn}, NV_{dw} and NV_d, respectively. Generally, the ventilation types did not impact the in-kitchen temperature significantly (Fig. 6a). Therefore, inadequate ventilation and elevated temperature must have caused thermal discomfort of the residents in homes that relied solely on natural ventilation, because all the kitchens in this category did not comply with the ASHRAE guidelines [72].

Furthermore, the in-kitchen RH were grouped according to cooking fuel type. 44–82% of the kitchens using electric + charcoal showed the lowest average RH (44 ± 8%), while those using LPG exhibited the highest (82 ± 4%). The average RH levels during cooking were similar to the weekly average values. In addition, the variations in the RH were similar among other fuel types, indicating that fuel types do not influence in-kitchen RH significantly. Moreover, the in-kitchen temperature range grouped by fuel type was 25–29 °C (Fig. 6b). Charcoal + NG and kerosene + electric showed the highest and lowest values of 29 ± 2 and 25 ± 3 °C, respectively. In addition, the air temperatures during cooking sessions were relatively higher than weekly average, likely due to the heat generated by various cooking devices [73].

The average RH reduces as the kitchen size increases (Fig. 5c): small-, medium- and large-sized kitchens exhibited average RH of 66 ± 8%, 58 ± 8% and 57 ± 7%, respectively. Similarly, the average RH while cooking in the small, medium and large-sized kitchens was 66 ± 8, 57 ± 7 and 56 ± 7%, respectively. Fig. 6c shows that medium- and small-volume kitchens had the same average temperature of 27 ± 2 °C, while that of the large-volume kitchens was lower (25 ± 2 °C). In addition, the temperature was higher during cooking (26–29 °C) than the overall weekly average (25–27 °C). Regarding occupancy, the average RH levels did not vary appreciably with occupancy (Fig. 5d): 61 ± 8, 60 ± 7 and 64 ± 9% for one, two and >2 occupants, respectively, while those of weekly temperatures were 27 ± 2, 28 ± 2 and 25 ± 3 °C (Fig. 6d). The overall average temperature during cooking (28 ± 3 °C) was higher than the weekly average (26 ± 2 °C).

Figs. 5g and 6g illustrate the average RH and temperature levels during cooking and the time (weekly) spent on each cooking type (i.e., frying, boiling/steaming, grilling, reheating and oven baking). The average RH levels were the highest for homes that engaged more in boiling/steaming. For example, AKR homes evidenced the highest RH (81%), having spent 88% of their weekly cooking time on boiling/steaming, which has been reported to produce high RH [74]. Fig. 6g informs that DAC and DAR homes exhibited the highest

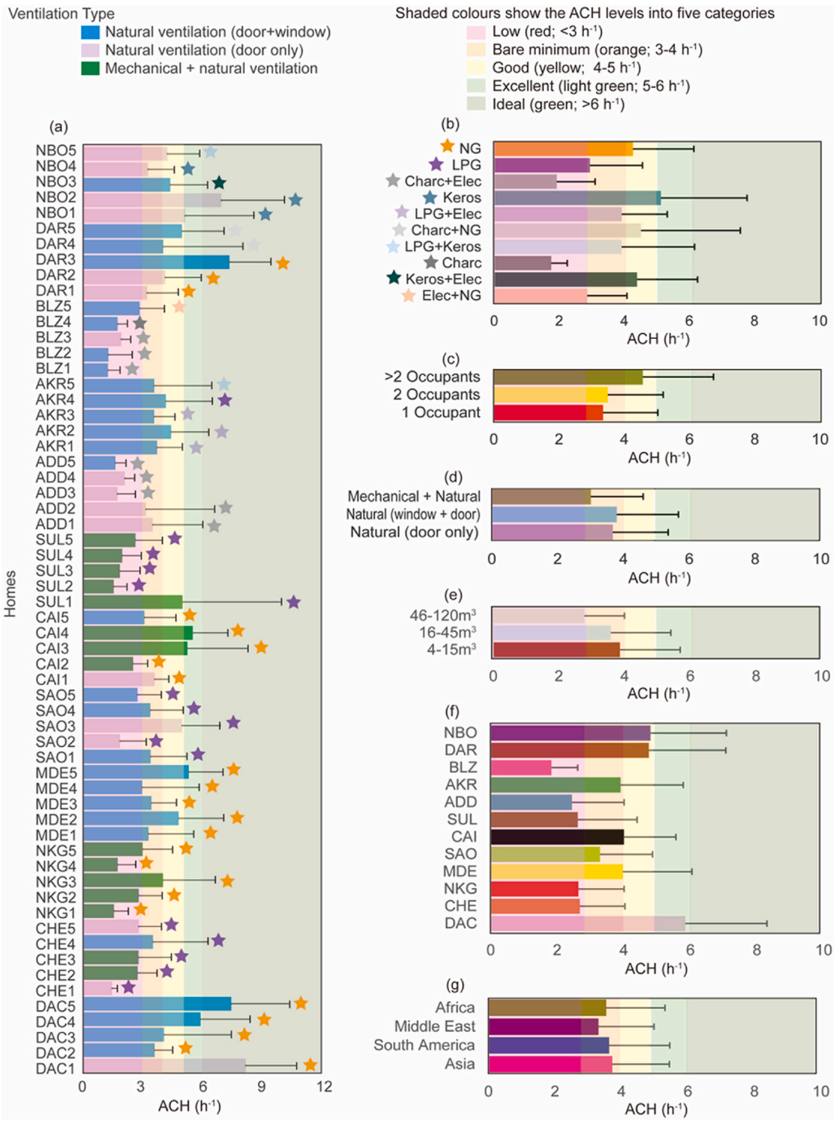

Fig. 7. The weekly averaged ACH (h^{-1}) in contrast with the diverse kitchen conditions: (a) comparison of ACH (h^{-1}) estimated in all kitchens, (b) cooking fuel used, (c) occupancy, (d) ventilation type, (e) kitchen volume, (f) country, (g) region. The shadings indicate 5 ACH levels based on a 5-step guide by Allen et al. [76]. The star colour denotes the type of cooking fuel. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

temperatures (30–33 °C) from spending 50% each of their cooking period on frying and boiling/steaming. Therefore, the higher temperatures in DAC and DAR may be attributed to frying [75]. Conversely, SAO and ADD homes had the lowest temperature (22–23 °C), ascribed to spending 62% of their cooking sessions on boiling/steaming, with 8% and 30% on frying, respectively (Fig. 6g).

Fig. S12 presents the scatterplots among CO_2 and RH and temperature. A very weak correlation exists between CO_2 with RH (R^2 <0.01, Fig. S12a) and temperature (R^2 <0.01, Fig. S12b) for weekly average and during cooking. The relatively non-existent relationship between CO_2 and RH or temperature could be attributed to the low water solubility and inherent greenhouse potential of CO_2, respectively. More so, the weak correlations suggest a variation in their respective in-kitchen sources. In addition, CO_2 concentration variation is depicted based on the RH (Fig. S12c) and temperature (Fig. S12d) in all homes, respectively. Different bubble colours show different RH levels and temperatures in each home. For example, SUL and CAI homes had RH <40%, while AKR and CHE homes showed higher RH values. These findings indicate that ventilation, kitchen volume and cooking type impacted the RH levels the most. DV_{mn} significantly reduced the RH in the kitchens. The average RH was relatively high (60–80%) in some cities due to unavailability of mechanical ventilation, unlike in SUL and CAI (RH<40%) where mechanical ventilation was enabled. Also, small-volume kitchens had relatively higher RH than medium- and large-volume kitchens. We also observed that boiling/steaming increased the RH significantly. Generally, the average temperature during cooking was relatively higher than the weekly averages. We also found that 87% of all the kitchens did not comply with the ASHRAE guidelines. Therefore, DV_{mn}, effective convective inflow of outdoor air, and a relatively large kitchen are essential to achieve a thermally comfortable kitchen during cooking.

3.4. Ventilation

3.4.1. ACH

The weekly average ACH during cooking, derived using the method explained in Section 2.5, was 3.56 ± 1.75 h^{-1}, ranging between 8.19 ± 2.55 (DAC1) and 1.27 ± 0.61 h^{-1} (BLZ1) (Fig. 7a). Individually, the majority of kitchens in the same city showed a similar ACH range (Fig. 7a), despite a diversity of kitchen ventilation conditions and cooking habits. For example, half of the kitchens within each city had a similar ACH as the standard deviation from the average values was below 1.80 h^{-1}: CHE = 2.68 ± 1.35, NKG = 2.64 ± 1.37, SAO = 3.29 ± 1.58, SUL = 2.61 ± 1.79, ADD = 2.44 ± 1.57 and BLZ = 1.28 ± 0.80 h^{-1} (Table S5). Among these cities, BLZ kitchens indicated the lowest and the closest range of ACH. According to the five ranges (low, bare minimum, good, excellent and ideal) of ACH discussed in Section 2.5 [76], nearly half of the kitchens had low or bare minimum values (<4 h^{-1}) (Fig. 7a). In addition, NBO2 (6.95 ± 3.18 h^{-1}), DAC1 (8.19 ± 2.55 h^{-1}), DAC5 (7.46 ± 2.93 h^{-1}) and DAR3 (7.36 ± 2.08 h^{-1}) had ideal average ACH values (>6 h^{-1}). Of these four kitchens, all were naturally ventilated (two NV_d and two NV_{dw}) with lower overall and lower average CO_2 concentrations during cooking except DAR3 which was higher than 1000 ppm (Fig. 2). Tariq et al. [77] and Hwang [78] found similar results in DAC residential houses as well. Hence, according to the current and previous studies, we opine that effective natural ventilation of housing design in these countries should be prioritised.

Table S5 shows the average ACH values according to several factors e.g. ventilation and fuel types, occupancy, kitchen volume, city and region. To avoid ambiguity, we clarify that the maximum and minimum values stated hereafter are related to these factors; they are not the same as the maximum and minimum values according to ACH in individual homes described earlier in this section. As for the regions, Asia and the Middle-East showed the highest (3.72 ± 1.72 h^{-1}) and lowest (3.31 ± 1.67 h^{-1}) average ACH (Fig. 7g). As for countries in different regions, DAC in Asia (5.85 ± 2 h^{-1}) recorded the highest ACH. Lower ACH cities included SUL in the Middle East (2.61 ± 2 h^{-1}) (Fig. 7f). Elsewhere, Pinto et al. [79] found considerable variability in ACH across countries or regions, consistent with our findings. Overall, it reflects the variations in ACH between countries or regions and provides advice to policy makers and designers to consider in their local situation.

According to ventilation types, the average ACH was highest for NV_{dw}, followed by NV_d and DV_{mn} (Fig. 7d), showing bare minimum performance (3-4 h^{-1}) with the average ACH of 3.79 ± 1.88, 3.67 ± 1.68, 3.01 ± 1.60 h^{-1}, respectively. This result indicates that NV_{dw} within the studied kitchens resulted in 0.78 ± 0.28 h^{-1} higher ACH values than DV_{mn} during the week. Moreover, ACH for NV_d was 0.66 ± 0.08 h^{-1} greater than that for DV_{mn}. The result of our study could be attributed to limited exhaust air volume and irregular cleaning of the exhaust fans of the mechanical systems in the studied low-income kitchens. This finding is consistent with previous studies. For instance, Howard-Reed et al. [57] and Wallace et al. [80] reported that opening the windows and doors resulted in the highest ACH. Earlier, Iwashita [81] and Boyd et al. [82] found that 87% and 60% of the total ACH was attributed to opening the windows and doors, respectively. Also, Kvisgaard and Collet [83] estimated that 16 Danish households had an average of 63% of ACH caused by opened doors and windows. As stated in the previous section, the lowest weekly average CO_2 concentration was ascribed to NV_{dw}, followed by DV_{mn}, and NV_d. Hence, according to CO_2 and ACH, we recommend cooking with NV_{dw}. However, this finding will also be discussed with ventilation rate and hazard ratios further.

In terms of fuel used, kerosene shows excellent average ACH performance (5.12 ± 2.65 h^{-1}), followed by charcoal + NG which resulted in good performance (4.51 ± 2.65 h^{-1}), followed by kerosene + electric (4.39 ± 3.05 h^{-1}), and NG (4.26 ± 1.86 h^{-1}) (Fig. 7b). However, kerosene and charcoal are considered more CO_2-emitting fuels than others, hence, they are not recommended for use despite showing appropriate performance. This observation is further supported by the findings in Section 3.4.2. Therefore, NG is the clean fuel recommended for in-kitchen cooking [84].

Based on occupancy, homes with >2 occupants in the kitchen during cooking showed excellent average ACH performance (4.57 ± 2.16 h^{-1}), while 1 and 2 occupants lead to worse ACH performance (3.35 ± 1.68 and 3.49 ± 1.70 h^{-1}, respectively) (Fig. 7c). Based on these results, we cannot draw a relationship between occupancy and ACH because the ACH values are similar. In addition, there are still limitations to these results, because various factors like the difference between indoor and outdoor temperatures, wind direction, wind speed, building permeability and occupant behaviour, which have significant effects on the ACH [57,85], were excluded from this study.

In addition, grouping kitchens in terms of volume revealed that smaller-volume kitchens (4–15 m^3) had higher average ACH levels (3.85 ± 1.84 h^{-1}), followed by medium-size kitchens (16–45 m^3) with 3.58 ± 1.83 h^{-1}. However, the average ACH of larger kitchens (46–120 m^3) was a bit lower than both (2.78 ± 1.21 h^{-1}). Therefore, higher ACH performances were observed in smaller kitchens (Fig. 7e) due to more convective air circulations therein, occupancy effects and the cooking habits. Regarding weekly CO_2 concentrations, the trend was larger-volume < small-volume < medium volume kitchens. Based solely on this deduction, we would suggest cooking in small-volume kitchens. However, considering the ventilation rate and hazard ratio are imperative toward making conclusive recommendations as well.

We conclude that the kitchen size, ventilation conditions, fuel type are the significant factors influencing ACH in low-income kitchens. Appropriate weekly ACH and CO_2 concentrations were observed in small-volume kitchens that used NV_{dw} while cooking with NG. Nabinger and Persily [86] found that the temperature variation in the indoor and outdoor air affects ACH. We were unable to control this factor in the current study because of the wide variability in geographical location and climatic conditions of the 12 countries involved.

3.4.2. Ventilation rates

Numerous studies exist on the relationships among indoor ventilation rates and CO_2 concentrations and human health [22,23,66,87,88], but lacks studies involving in-kitchen conditions of low-income homes. We derived the weekly ventilation rates per person in

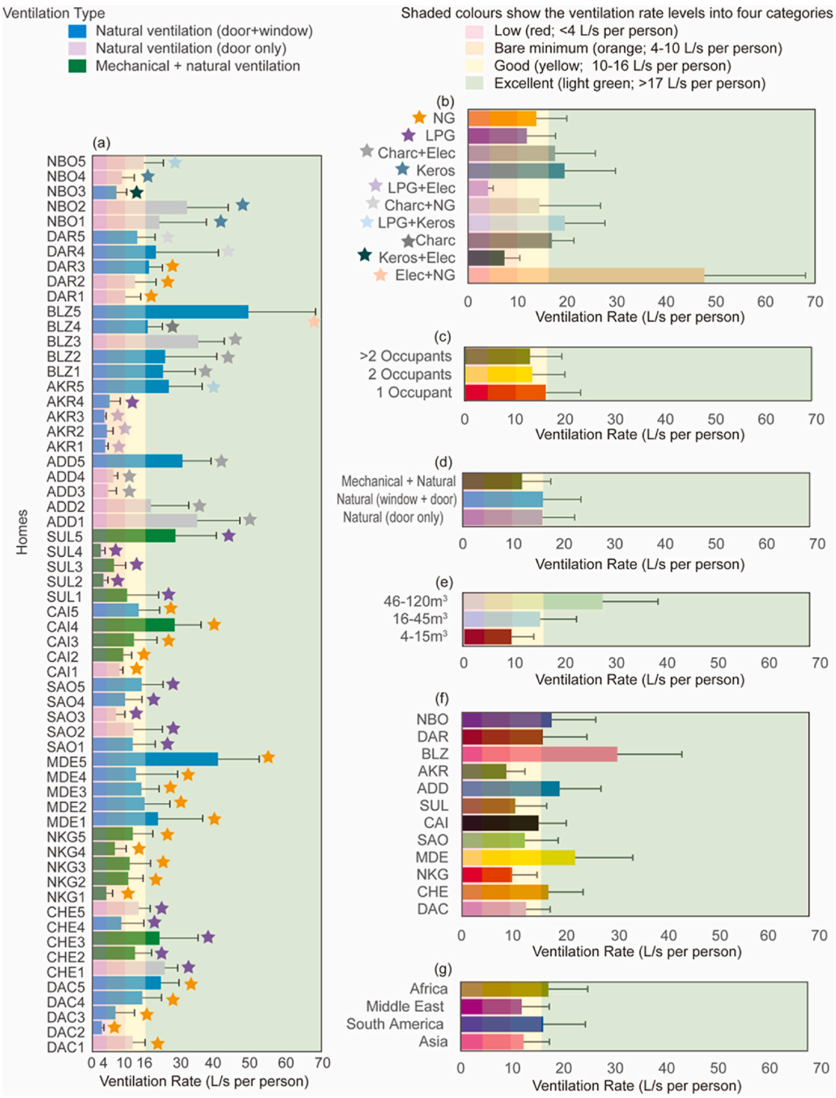

Fig. 8. The weekly averaged ventilation rates (L/s per person) in contrast with the diverse kitchen conditions: (a) comparison of ventilation rates per person estimated in all kitchens, (b) cooking fuel used, (c) occupancy, (d) ventilation type, (e) kitchen volume, (f) country, (g) region. The shadings indicate ventilation rate levels based on EN 15251 European Standard [61]. The star colour indicates the type of cooking fuel. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

all the kitchens studied, following the method described in Section 2.5.2. According to the four classes (low, bare minimum, good, excellent) of ventilation rates discussed therein (based on European Standard EN 15251), one-third of the kitchens showed excellent ventilation rates (>17 L/s/person) (Fig. 8a), eleven, six and three of which adopted NV_{dw}, NV_d and DV_{mn}, respectively. The average ventilation rate of the kitchens was 14.8 ± 6.7 L/s/person. BLZ5 experienced the highest ventilation rates (47.7 ± 20.4 L/s/person), while the lowest in SUL4 (2.6 ± 1.3 L/s/person) (Table S6). The standard deviation for BLZ5 was high, showing a large variability due to its excessive kitchen volume (120 m^3) with NV_{dw}. Fig. S7 presents the corresponding box plots for individual kitchens.

The variations in ventilation rates for each kitchen were studied in relation to ventilation conditions, cooking fuel used, occupancy, kitchen volume, country and region (Fig. 8). To avoid ambiguity about the values quantified here, it is necessary to clarify that the maximum or minimum values described hereafter relate only to these variables, i.e., they are not the same as those described in the previous paragraph, which were based on each studied kitchen. In terms of regions, Africa presented the maximum average ventilation rate of 17.0 ± 7.7 L/s/person, with a minimum average of 11.8 ± 5.4 L/s/person in the Middle East (Fig. 8g). This difference occurred because many African homes recorded higher in-kitchen ventilation rates, such as 21.6 ± 9.8, 22.2 ± 15.7, 32.4 ± 7.8, 16.9 ± 4.5, 47.7 ± 20.4, 32.1 ± 13.0, 17.9 ± 11.6 and 27.5 ± 8.8 L/s/person in BLZ1, BLZ2, BLZ3, BLZ4, BLZ5, ADD1, ADD2 and ADD5, respectively. Lower ventilation rate in Asian and Middle Eastern homes e.g., DAC2, DAC3, NKG1, NKG4, CAI1, CAI2, SUL2, SUL3 and

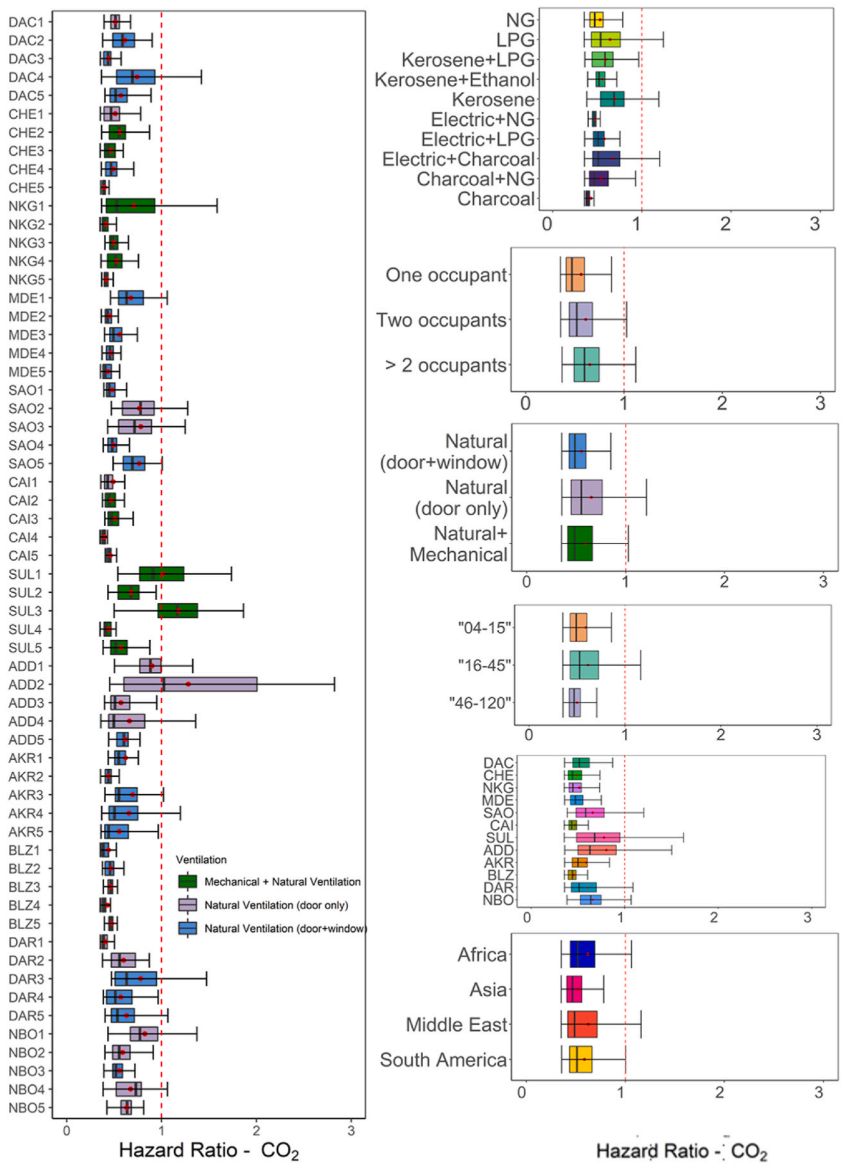

Fig. 9. Box plots illustrating Hazard Ratio (HR) for CO_2 (left) for each of the investigated homes by types of ventilation. The HR was estimated for CO_2 concentration average of 1000 ppm and 2.5 h exposure time [67]. On the right, the box plots represent the HR values by region. The figure on the right presents the HR values in contrast with the diverse kitchen conditions: ventilation types, volume of kitchens, cooking fuel and kitchen occupancy. The ratio (1.0) is indicated by the red dashed line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

SUL4 was 2.9 ± 0.7, 7.0 ± 5.8, 4.3 ± 1.9, 6.8 ± 3.4, 8.3 ± 0.9, 9.4 ± 2.6, 3.4 ± 1.4, 6.6 ± 3.6 and 2.6 ± 1.3 L/s/person, respectively (Fig. 8a). Generally, it reflects the variability of ventilation rates between countries or regions and provides useful information to them.

According to EN 15251 European Standard, natural as well as mechanical ventilation highly influenced the ventilation rates of the studied kitchens because all the ventilation types achieved >10 L/s/person. Specifically, both natural ventilation systems (NV_d and NV_{dw}) achieved a similar average ventilation rate (15.7 ± 6.3 and 15.8 ± 7.5 L/s/person, respectively), whereas DV_{mn} recorded 11.7 ± 5.7 L/s/person (Fig. 8d), indicating that natural ventilation had ~4 L/s per person greater ventilation rate than DV_{mn}. Mak and Yik [89] found that the window area should be at least 23.33% of the kitchen floor area to achieve a suitable ventilation rate which is consistent with our findings. Mechanical ventilation can solely produce a cleaner breathing zone with upward make-up air supply (UPMS) or downward make-up air supply (DWMS) from the cooks' position [90]. Based on the weekly CO_2 concentrations aforementioned, the lowest was shown in NV_{dw}, followed by DV_{mn} and NV_d. Therefore, NV_{dw} is preferentially recommended. However, the findings will be discussed with ACH and hazard ratio for comprehensive advice.

As for the fuel used, kitchens using electric + NG (47.7 ± 20.4 L/s/person), charcoal (16.9 ± 4.5 L/s/person), kerosene (19.5 ± 10.3 L/s/person), kerosene + LPG (19.5 ± 8.1 L/s/person) and charcoal + electric (17.6 ± 8.1 L/s/person) presented excellent ventilation rates (>17 L/s/person). These conditions were followed by kitchens using charcoal + NG (14.4 ± 12.3 L/s/person), NG (13.8 ± 6.1 L/s/person) and LPG (11.8 ± 5.8 L/s/person), exhibiting good performances (>10 L/s/person) (Fig. 8b). Conversely, LPG + electric (4.0 ± 1.1 L/s/person) showed low ventilation rates (<4 L/s/person). Hence, kerosene and charcoal are considered polluting fuels, and are hereby not recommended for in-kitchen cooking [84]. Rather, electric + NG are recommended.

Moreover, the more the in-kitchen occupants during cooking, the less was the ventilation rate. One-occupant kitchens reflected 16.1 ± 6.9 L/s/person, while two and more occupants evinced lower and similar (13.4 ± 6.5 and 13.0 ± 6.4 L/s/person, respectively) values (Fig. 8c). However, because the occupancy had few relationships with ACH analysis, it is necessary to consider other influencing parameters simultaneously to achieve the best in-kitchen ventilation condition.

Furthermore, the ventilation rate improved with kitchen volume, i.e., large-, medium- and small-sized kitchens exhibited high, good and bare-minimum ventilation rates of 27.3 ± 10.9, 15.0 ± 7.1 and 9.4 ± 4.4 L/s/person, respectively. And as discussed earlier, the lowest CO_2 concentration was shown in large volume, followed by small- and medium volume. According to these factors, we suggest cooking in large sized kitchens. However, in terms of the aforementioned ACH suggestion which suggests cooking in small ones, we will compare the results to provide comprehensive conclusions in the end. Moreover, ventilation rate also depends on the air-tightness of the external walls [91], especially the windows which were not considered in the current study.

3.5. Health risk assessment for CO_2

Based on the methods described in Section 2.6, the exposure risk was assessed using HR for CO_2 concentration. Fig. 9 presents a box plot of the HR for CO_2 concentrations. We presented the HR values of all categories including ventilation type, cooking fuel, kitchen volume, kitchen occupancy, region and city (Fig. 9). The Middle Eastern kitchens exhibited the worst HR with a 90th percentile (P90) value of 1.1, informing that 10% of the data from this region had HR >1. Elsewhere, Africa, South America and Asia showed P90 values of 0.9, 0.9 and 0.7, respectively. Specifically, the HR values ranged from 0.35 (SUL4, CAI4, NKG2, BLZ4, CHE3) and 0.54 (SUL1) to 3.0 in Africa (in ADD2), 2.4 in the Middle East (SUL1), 2.0 in Asia (NKG1) and 1.8 in South America (SAO3). Table S8 summarises the statistics of CO_2 HR by region.

Published literature on estimated HR in open literature are scarce. For example, Datta et al. [92] estimated HR for working people and students in non-residential buildings. The authors found that the HR values ranged between 0.9 and 5.3 based on 1111 ppm CO_2 reference value. Of late, Moreno-Rangel et al. [40] assessed the HR for CO_2 in homes of Mexico City, Mexico. They found that HR was <1 for annually 85.9% in the bedroom while 90.1% in the living room of the Passivhaus Dwelling. However, HR was >1 for 42.9% and 97.5% of the time in the bedroom and living room of the Standard Dwelling, respectively. In another study conducted in residential kitchens in Alexandria, Egypt, HR for CO_2 using 1000 ppm reference concentration fell between 0.43-0.69 and 0.73–1.1 in kitchens with and without exhaust fans, respectively [44]. According to a study carried out in temporary shelters in Africa, HR for CO_2 ranged from 0.60 to 3.6 at a camp in Djibouti and from 1.4 to >5 ata camp in Ethiopia [46]. These results highlight the effect of poor ventilation, overcrowding (usually ≤25 inhabitants) and in-shelter cooking with a coal stove on human health.

Based on ventilation type, the P90 for HR followed the trend of 1.0, 0.95 and 0.80 for NV_d, DV_{mn} and NV_{dw}, respectively (Table S9). This sequence shows that opening the doors and windows simultaneously during cooking aids convective cross-ventilation, favourable for human health.

As for the number of kitchen occupants, the P90 was <1 for all occupancy groups. The median values highlight the following trend: worse (0.60) for kitchens with >2 occupants, followed by those with two occupants (0.52) and one occupant (0.47) (Table S10). In terms of the kitchen volume, the group of medium-volume kitchens showed the worst conditions (0.53), followed by small- (0.49) and large- (0.47) volume kitchens (Table S11). Based on fuel type (Table S12), the worst condition was evinced by electric + charcoal (P90 of 1.1), followed by LPG (P90 of 1.0), then kerosene (P90 of 0.97).

We observed that at least 25% of total kitchens had P90 value >1, indicating that the reference value was exceeded during 10% of the in-kitchen monitoring period. Therefore, the occupants should limit their residence time in the kitchen while cooking. Since exposure to high CO_2 concentrations interrupts cognitive development, in-kitchen residence of children during cooking should also be minimised.

4. Conclusions and recommendations

This is a first global study assessment of CO_2 exposure, ventilation and thermal comfort conditions in 60 low-income home kitchens across twelve cities in four regions (Asia, South America, Middle-East and Africa). To develop a globally comparable dataset, CO_2, temperature, and relative humidity (RH) were measured using a uniform approach and a similar set of equipment.

The following conclusions were drawn:

- The average CO_2 concentration during cooking was the highest for natural ventilation (door only, NV_d) at 711 ± 302 ppm, followed by 690 ± 319 ppm (natural: door + window, NV_{dw}), and 677 ± 219 ppm (dual, DV_{mn}). These values highlight the importance of enhanced ventilation through doors, windows and extraction fans in the kitchen during cooking to reduce indoor CO_2 concentrations. Also, kitchens using cleaner fuels (such as LPG and electric cookers) had 32.2% less CO_2 levels during cooking than those using kerosene. Larger kitchens (>45 m^3) provided better ventilation and lowered the CO_2 levels by 28% compared to smaller kitchens (16–45 m^3). Moreover, kitchens with >2 occupants during cooking had 7% higher average CO_2 concentrations than those with one occupant, informing that CO_2 levels are directly influenced by the occupant density.
- Cooking with charcoal and electric + NG exhibited higher CO_2 concentrations (~400–520 ppm) than other fuels. Some cities (CAI, BLZ, ADD and AKR) showed smaller tail (sharp peaks) with a relatively lower CO_2 concentration (420–520 ppm), compared with others (SUL, SAO and NKG) showing wider tails in higher concentrations (420–1200 ppm).
- The RH levels were most significantly influenced by ventilation, kitchen capacity and cooking type. DV_{mn} significantly lowered the RH and consequently increased thermal comfort of the kitchen occupants during cooking. The unavailability of mechanical ventilation in several cities resulted in high RH (60–80%). Exceptions were SUL and CAI, where mechanical ventilation was used, but the RH was relatively low (<40%). RH values also increased as boiling/steaming took place. About 87% of total kitchens did not comply with the ASHRAE standard (RH >40%, temperature >23 °C) for thermal comfort.
- The highest ACH and ventilation rate were obtained by NV_{dw} (3.8 ± 1.9 h^{-1}; 15.8 ± 7.5 L/s/person), followed by NV_d (3.7 ± 1.7 h^{-1}; 15.7 ± 6.3 L/s/person) and DV_{mn} (3.0 ± 1.6 h^{-1}; 11.7 ± 5.7 L/s/person). Compared with medium- and small-volume kitchens, larger ones (46–120 m^3) showed 22% and 28% lower ACH, and 82% and 190% higher ventilation rate. We found that 57% of total kitchens met the minimum requirement of ACH (≥3 h^{-1}) and ventilation rate (≥4 L/s/person).
- At least, 25% of the homes showed HR P90 >1, indicating that 10% of the data exceeded the reference value during this study. Hence, prolonged cooking hours in the kitchen poses health risks to individuals such as children, who may experience cognitive impairment.

Below are easy-to-implement recommendations built on the scientific findings of this study, to be considered by home occupants, homeowners and building designers:

- **Large-volume kitchens (>45 m^3) were found to be associated with ~28% lower CO_2 concentrations during cooking compared with small-volume kitchens.** The effect of kitchen volume on CO_2 concentrations and ventilation rates was clearly evident, as was also the case for reduced PM exposure [38]. Therefore, considerations to increase the volume of kitchens via their ceiling height and/or floor area in newly built homes or those under renovation or reconstruction, is recommended to builders and local councils, when feasible.
- **DV_{mn} was associated with favourable thermal comfort conditions.** The use of extraction fans during cooking while ensuring that both windows and doors were open reduced the average RH by 20–40% in some kitchens. Therefore, improving the in-kitchen ventilation through available means would enhance the thermal comfort of occupants whilst also ventilating the cooking emissions.
- **Keep passive occupancy to a minimum during cooking.** The average CO_2 exposure concentrations in kitchens with >2 occupants during cooking sessions were 7% higher than those with one occupant, indicating a direct relation between occupancy and CO_2 concentrations. Thus, to avoid the risks associated with high CO_2 levels (and aerosol exposure; [38]), passive occupancy during cooking, especially by infants and children who are not engaged in the cooking, should be discouraged.
- **Use cleaner fuels and electric cookers.** Cooking using LPG + electric indicated 32.2% less CO_2 than kerosene, which was associated with the highest CO_2 concentration. Since biomass-based fuels also emit co-pollutants e. g. $PM_{2.5}$ [38], green fuels and cookers such as solar-based e-cooking should be promoted and polluting fuels such as charcoal and kerosene should be avoided where and when possible.
- **Installing indoor CO_2 monitoring devices in kitchens is recommended to alert occupants when CO_2 exceeds 1000 ppm.** Affordable CO_2 monitors are available in the market that display the concentrations in a colour coded traffic light system to indicate when a corrective action is needed by the occupants. These corrective actions such as opening doors and windows, turning on extraction fans during cooking, reducing passive occupancy and investigating the source of high CO_2 if the concentrations are persistently high. Indoor CO_2 concentrations should be progressively reduced given their potentially negative effect on human health, particularly on vulnerable populations such as elderly, children and those with compromising health conditions.

This study created the first CO_2 exposure global dataset of low-income home kitchens in twelve cities across the globe. The in-kitchen hazard ratio and ventilation rates were also assessed in all investigated homes. We investigated the variation of CO_2 concentrations during cooking in reference to several factors such as the type of food, the kitchen size, the type of fuel used and the ventilation condition. For example, significant reductions in CO_2 concentrations were found as a result of improvement in fume extraction and use of mechanical ventilation. However, there were some limitations to this research because various factors, such as the difference between indoor and outdoor temperatures, infiltration of CO_2 originating from outdoor sources, wind direction, wind speed, building permeability, and occupant behaviour, were excluded. Nevertheless, this study recommends effective measures to improve in-kitchen air quality as well as preserve the occupant's health in low-income homes. Also, it provides useful guidelines and guidance to homeowners, home occupants and building designers to consider adequate ventilation in kitchens of newly built or renovated homes while considering feasibility constraints. The focus of this work was to understand the in-kitchen CO_2 exposure and ventilation conditions across the kitchens. Therefore, in-kitchen CO monitoring was beyond the scope of current work. Further studies are needed to measure similar indoor parameters (such as CO and NOx) for longer periods and across a range of kitchens for building a comprehensive global database in order to develop a holistic assessment for a diverse range of low-income homes.

Author statement

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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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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