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Assessing the impact of natural ventilation on indoor air quality and CO_2 concentration in residential apartments

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Abstract

This study investigates the impact of natural ventilation on indoor air quality (IAQ) and CO_2 concentration in residential buildings in Dhaka, Bangladesh, focusing on kitchen environments. Poor IAQ, particularly elevated CO_2 levels, poses significant health risks, including respiratory issues and cognitive impairments. In Dhaka, inadequate ventilation exacerbates these issues, especially in kitchens where cooking activities generate pollutants like CO_2 and particulate matter. The study aims to assess how variations in window size and ventilation influence CO_2 levels in kitchens and compare CO_2 concentrations before and after cooking. Additionally, it explores natural ventilation strategies to enhance IAQ in residential apartments. Using an experimental approach, CO_2 levels were monitored in various kitchens and living rooms over a one-week period, employing HOBO CO_2 sensors and temperature-humidity loggers. Cooking activities like grilling, frying, and boiling were analyzed to determine the effect on CO_2 concentrations. Results showed that CO_2 levels significantly increased during cooking, with kitchens exhibiting the highest concentrations. Notably, open windows contributed to lower CO_2 levels, particularly in living rooms and dining areas, emphasizing the role of natural ventilation. However, kitchens still experienced substantial CO_2 buildup, indicating the need for additional ventilation solutions. The study concludes that while open windows improve IAQ, enhanced ventilation systems and strategic airflow management are essential to reduce CO_2 levels and ensure healthier living environments in residential buildings.

Keywords: Indoor air quality; Carbon dioxide concentration; Kitchen; Residential apartments; Before cooking; After cooking

1. Introduction

In recent years, indoor air quality (IAQ) has emerged as a critical issue directly affecting the health and well-being of occupants. IAQ is influenced by the air quality (AQ) within and surrounding a building (Steinemann, Wargocki and Rismanchi, 2017). Globally, kitchens are recognized as one of the primary sources of indoor air pollution, largely due to indoor cooking (IC) activities that generate airborne contaminants such as particulate matter (PM), volatile organic compounds (VOCs), carbon dioxide (CO_2), and carbon monoxide (CO) (Gao et al., 2013; Stamatelopoulou, Asimakopoulos and Maggos, 2019; Cheung and Jim, 2019). These pollutants not only pose significant health risks but also exacerbate environmental concerns.

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IC is particularly detrimental due to the emission of intense oily fumes and gaseous constituents (Yassin, AlThaqeb and Al-Mutiri, 2012). Studies have highlighted the carcinogenic risks associated with frying, with VOC emissions varying depending on the type of cooking oil used (Zhang et al., 2019). Mabonga et al. (2021) emphasized the severe health issues caused by $PM_{2.5}$ exposure in households reliant on solid biomass fuels, reporting symptoms such as coughing, eye irritation and respiratory problems. Additionally, CO_2 and CO concentrations significantly increase during cooking (DC) compared to pre-cooking levels (Cheung et al., 2019), with fossil fuel combustion contributing to long-term adverse impacts on health, agriculture, and climate (Elahi et al., 2021; Elahi, Khalid and Tauni, 2022; Elahi et al., 2022). Consequently, transitioning to renewable energy sources is imperative to mitigate these effects.

The health risks associated with prolonged exposure to indoor pollutants are substantial. Fine and ultra-fine particulate matter, for example, has been linked to cardiovascular diseases, asthma, lung cancer, and premature death (Delfino, Sioutas and Malik, 2005; Timonen et al., 2006; Kennedy, 2007; Peng et al., 2017). Alarmingly, over 5.5 million deaths annually are attributed to respiratory diseases caused by air pollution (Hartman, Wheeler and Singh, 1997). These risks are amplified by the fact that humans spend approximately 60–90% of their lives indoors, where pollutant concentrations can be 2–5 times higher than outdoor levels (Guyot, Sherman and Walker, 2018; Lin et al., 2017; US EPA).

In Dhaka, Bangladesh, residential buildings face significant IAQ challenges as inadequate ventilation allows pollutants from cooking activities to accumulate, further worsening the city's already poor air quality. Dhaka has been ranked as the world's second most polluted city, making IAQ improvements essential to safeguard public health (UNB, 2023). The World Health Organization (WHO, 2021) reports that indoor air pollution accounts for 113,202 deaths annually in Bangladesh. Elevated CO_2 levels in kitchens have been linked to respiratory problems, impaired cognitive function, and sleep disturbances (Heal et al., 2012; Dherani et al., 2008; Kurmi et al., 2022).

Addressing IAQ concerns requires adequate ventilation, which helps remove stale air and introduce fresh outdoor air (Wei et al., 2017). Estimating ventilation rates per person (e.g., Q1; L/s/person) is critical, as it directly affects IAQ, occupant well-being, energy efficiency, and heat loss (Cao et al., 2017). This study investigates ventilation strategies in kitchens, focusing on improving IAQ and reducing health risks through sustainable and effective building design.

While indoor air quality depends on multiple factors beyond ventilation, guidelines such as those by the European Committee for Standardization (2006) and Gobierno de España (2007) use CO_2 measurements to estimate ventilation quality levels. These guidelines recommend that classroom CO_2 levels remain below 500 ppm above outdoor levels, corresponding to the IDA 2 category. However, infection risk thresholds cannot be universally fixed due to varying circumstances (Peng and Jimenez, 2021). For example, Harvard T.H. Chan School of Public Health suggests maintaining 5 air changes per hour (ACH) to reduce COVID-19 infection risks, leading to approximately 700 ppm CO_2 in typical classrooms (Joseph Allen et al., 2021).

The most common method for monitoring CO_2 levels involves using one analyzer per classroom (Toftum et al., 2015; Alonso et al., 2021; Vouriot et al., 2021; Zemitis et al., 2021; Turanjanin et al., 2014). Alternatively, some studies, such as Park et al. (2021) and Almeida et al. (2017), average results from multiple sensors. Vouriot et al. (2021) highlighted that placing multiple sensors within a space can reveal variations in CO_2 levels, offering valuable insights into differing risk levels within the room.

Effective building design plays a crucial role in enhancing the functionality of spaces, particularly in schools and residential buildings. A key aspect of this design is the strategic positioning and sizing of windows, as they significantly influence IAQ. Factors such as temperature and humidity also affect CO_2 levels, which are critical for maintaining a healthy indoor environment. Poor ventilation, coupled with indoor air pollution, can result in high pollutant concentrations. Elevated CO_2 levels can lead to respiratory issues, cognitive impairment, sleep disturbances, headaches, dizziness, and coughing (Heal et al., 2012; Dherani et al., 2008; Kurmi et al., 2022; WHO, 2021).

Designing windows for kitchens is a challenging task, as it requires balancing several factors, with natural airflow being a key consideration. Proper window design can significantly enhance natural ventilation, which is essential for reducing CO_2 levels and improving indoor air quality (IAQ). This raises critical research questions: (a) Are kitchens in residential buildings designed to meet the needs of occupants while neglecting IAQ, resulting in poor air quality? (b) Do kitchen designs effectively encourage natural ventilation and enhance IAQ?

This research highlights the crucial role of natural ventilation in improving indoor air quality, especially by reducing elevated CO_2 levels and boosting air quality in kitchens. Well-designed windows are vital for optimizing natural ventilation, which helps decrease CO_2 concentrations and improve overall IAQ in residential kitchens.

1.1. Aims and Objectives

To investigate the impact of natural ventilation on indoor air quality (IAQ) and CO_2 concentration in residential buildings in Dhaka, aiming to identify strategies for improving ventilation and creating a better indoor environment.

To explore how variations in window size and ventilation influence indoor air quality (IAQ), particularly CO_2 levels, in kitchens within Dhaka City.

To compare and analyze CO_2 concentration levels and temperature changes before and after cooking, focusing on the impact of different window opening sizes.

To examine the potential of natural ventilation strategies in reducing CO_2 levels and enhancing IAQ in residential apartments.

How does the design of natural openings influence indoor air quality (IAQ) and CO_2 levels in residential buildings in Dhaka City?

1.2. Literature review

Table 1 CO_2 Levels in Various Environments

Study (Year)	Source of CO_2	Methodology	Key Findings	Reference
Kumar et al. (2022)	Human respiration, building occupancy	Field measurements in 12 school buildings	CO_2 levels in classrooms exceeded 1000 ppm during peak occupancy, affecting comfort and concentration.	Kumar et al. (2022)
Nahar et al. (2016)	Human respiration, poor ventilation	Indoor air quality assessment in schools in Dhaka	CO_2 concentrations ≥600 ppm were linked to respiratory issues in 67% of schoolchildren.	Nahar et al. (2016)
García et al. (2019)	Human respiration, classroom design	Case study of school classrooms in Bogota	High CO_2 concentrations were found in classrooms with insufficient natural ventilation, negatively affecting students' cognitive performance.	García et al. (2019)
Willers et al. (2006)	Gas appliances in kitchens (schools with cafeterias)	Controlled experiments and monitoring in school kitchens	High CO_2 concentrations were observed in school kitchens with gas appliances, particularly in poorly ventilated cafeterias.	Willers et al. (2006)
Daisey et al. (2003)	Human respiration, building systems	Field measurements in office and school buildings	CO_2 levels >1000 ppm led to discomfort and loss of productivity in office environments.	Daisey et al. (2003)
Raouf et al. (2017)	Human respiration, ventilation systems	Monitoring in school buildings across Cairo	CO_2 concentrations were higher in schools with poor ventilation, contributing to student fatigue and discomfort.	Raouf et al. (2017)
Alshrefy et al. (2020)	Human respiration, HVAC systems	Field study in office buildings	Higher CO_2 levels in offices with centralized HVAC systems led to complaints of discomfort and concentration issues.	Alshrefy et al. (2020)
García et al. (2020)	Human respiration, ventilation	Case study in a school in Mexico City	CO_2 concentrations of 1200 ppm were found in classrooms with poor ventilation, affecting students' health and academic performance.	García et al. (2020)
Melo et al. (2020)	Human respiration, building occupancy	Field measurement in an office complex	High CO_2 levels in offices with high occupancy led to reduced work	Melo et al. (2020)

			efficiency and increased complaints about indoor air quality.	
Zaman et al. (2021)	Human respiration, overcrowding	Field measurement in classrooms in Dhaka	CO_2 concentrations in overcrowded classrooms ranged between 1200–1600 ppm, leading to discomfort and reduced cognitive performance in students.	Zaman et al. (2021)

2. Methodology

2.1. Sampling Site Description and Measurement Period

This study investigates the variability of CO_2 levels, indoor air temperature (T), and relative humidity (RH) in residential apartments located in the Wari area of Dhaka. Four separate sampling campaigns were conducted in each apartment, lasting for one week (working days only, from Sunday morning to Thursday evening). The first campaign was conducted during the summer season, between May and July 2023.

The study adopts an experimental-comparative approach. Dhaka, the capital city of Bangladesh, is situated in a tropical climate zone, characterized by hot, wet, and humid conditions. According to the 2023 meteorological data from the city's weather station and global climate sources, Dhaka experiences a tropical wet and dry climate, as classified by the Köppen climate system. The city has distinct seasonal variations, with an average annual temperature of 25°C (77°F), fluctuating between 18°C (64°F) in January and 29°C (84°F) in August. The monsoon season, which lasts from May to September, accounts for nearly 80% of the total annual rainfall, which averages 1,854 millimeters (73 inches).

This study specifically focuses on naturally ventilated residential apartments in the Wari residential area of Dhaka. Air enters and exits these apartments through doors, windows, cracks, and other openings, ensuring natural ventilation. The selected apartments vary in terms of age, construction, and size. A summary of the key parameters for each selected apartment is provided in Table 2.and figure 1

2.2. Measuring Instruments

CO_2 concentration levels were measured every 10 minutes using the HOBO Carbon Dioxide/Temperature/Relative Humidity Data Logger, which has a precision of 50 ppm and a measurement range of 0-5000 ppm for indoor CO_2 concentrations. Temperature and humidity levels were measured using the Testo 445 device, with the following specifications:

- Temperature Range: 0 °C to 50°C (32 °F to 122°F)
- Accuracy: ±0.21 °C from 0°C to 50 °C (±0.38 °F from 32 °F to 122 °F)
- Resolution: 0.024 °C at 25 °C (0.04°F at 77°F)
- Drift: <0.1 °C per year (<0.18 °F per year)

To ensure the accuracy of measurements, the equipment was calibrated at the beginning of each session. The CO_2 sampling device was positioned approximately one meter above the floor, away from doors and windows, to minimize disturbances from air currents and ensure precise measurements of the indoor air quality.

2.3. Sample Collections and Analysis

This study evaluated three common cooking methods used in Bangladeshi households: grilling, frying, and boiling. The selected dishes represent typical local cooking styles, and included: (1) grilled fish and meat, (2) fried eggs and vegetable fritters, and (3) boiled lentil soup. All ingredients and condiments were purchased from local markets, and the weights of the ingredients ranged from 190g to 260g.

- **Grilling**: Fish and various meats were selected for grilling.
- **Frying**: Four eggs were used to prepare fried eggs, and vegetable fritters were made using a deep pan with 500 ml of oil.
- **Boiling**: A common lentil soup was prepared with traditional ingredients.

Cooking was carried out using pans of similar size, except for the frying of frozen food, which required a larger, deeper pan. Cooking times were capped at 15 minutes to prevent overcooking. Background air quality measurements were taken in both the living room and kitchen for 15 minutes before cooking. The specific cooking times for each process were as follows: grilling meat (3 minutes), grilling fish (13 minutes), frying eggs (4 minutes), frying vegetable fritters (6 minutes), boiling soup (6 minutes), followed by a decay period. All measurements were completed over 30 minutes, including the cooking duration.

The kitchen was equipped with a two-burner fixed exhaust hood, which was turned off during the study to simulate typical kitchen ventilation. Air quality sampling was conducted both before and after cooking. The measurements were taken at two locations: the kitchen and the living room, with sampling points set at a height of 1.5 meters. In most cases, the kitchen was directly connected to the living room. While some buildings had doors separating the two areas, these doors were kept open during the cooking process to allow air circulation.

Figure 1 Observed kitchen (source: authors 2024)

Table 2 The specification of 4 residential apartments

Residential Building (#)	Building Type	Floor Area (m^2)	Volume (m^3)	Number of Rooms	Number of Occupants	Kitchen Ventilation System	Kitchen (K) and Living Room (L) Shape Area (m^2)
1	APT	70	165.2	3	4	Natural Ventilation	18.6
2	APT	72	173.2	3	5	Natural Ventilation	22.8
3	APT	68	233	3	4	Natural Ventilation	21.4
4	APT	74	154.8	3	4	Natural Ventilation	26.2

3. Results and Discussion

The table 2 figure 2 shows that kitchens have varying levels of CO_2 concentrations before and during cooking. Kitchen 4 exhibits the highest CO_2 levels, with 1500 ppm before cooking and a significant rise to 2560 ppm during cooking, averaging 2030 ppm. Kitchen 3 also records elevated CO_2 levels. This indicates a potential link between kitchen size, cooking habits, and ventilation efficiency. Kitchens with higher CO_2 levels may suffer from inadequate ventilation, larger cooking areas, or specific cooking activities that contribute to greater CO_2 accumulation. The differences between kitchens highlight the influence of factors such as ventilation quality, kitchen layout, and the number of cooking appliances on CO_2 buildup during cooking. Kitchens with less effective ventilation or larger spaces may experience more pronounced increases in CO_2 levels. Living rooms show the smallest increase in CO_2 levels compared to kitchens and dining rooms. For instance, in Living 1, CO_2 rises from 1340 ppm before cooking to 1750 ppm during cooking, a relatively smaller change. This suggests that living rooms are less affected by cooking emissions, likely due to their distance from the kitchen and better airflow. Improved ventilation or open spaces in living rooms may help disperse CO_2, preventing significant accumulation. The minimal increase in CO_2 levels in living rooms underscores the importance of room layout and airflow. Since living rooms are not directly exposed to cooking activities and often feature larger windows or open designs, they are less susceptible to high CO_2 concentrations compared to kitchens, where pollutants are primarily generated.

The table 4 and figure 3 data shows that CO_2 levels increase across all spaces during cooking, as expected, due to the emissions generated by cooking activities. However, with open windows, the overall CO_2 concentrations are notably lower compared to scenarios where windows remain closed. This highlights the effectiveness of natural ventilation in mitigating CO_2 buildup, especially in dining and living spaces, which are farther from the cooking source. For example, in Dining 1, CO_2 levels during cooking reach 1610 ppm with open windows, compared to 1780 ppm when windows are closed. Similarly, in Living 1, CO_2 levels rise to 1670 ppm during cooking with open windows but remain significantly lower than the kitchen.

Kitchens consistently record the highest CO_2 concentrations, both before and during cooking, due to their proximity to the source of emissions. For instance, in Kitchen 4, CO_2 levels increase from 1100 ppm before cooking to 2121 ppm during cooking, averaging 1610.5 ppm. Despite the presence of open windows, this significant rise suggests that emissions in kitchens are concentrated and require additional ventilation solutions to maintain healthier air quality. In contrast, living rooms show the smallest increases in CO_2 levels, benefiting the most from open windows and better airflow, as they are further from the kitchen and have fewer direct cooking emissions. This underscores the importance of strategic ventilation and airflow management to control CO_2 levels in residential spaces.

Table 3 Average CO_2 concentration ppm for each measured class.100% closed window

CO_2	Before cooking close window	During Cooking close window	Average
kitchen 1	1167	2250	1808.5
Dining 1	1355	1780	1567.5
Living 1	1340	1750	1545
kitchen 2	1476	2378	1927
Dining 2	1420	2221	1820.5
Living 2	1418	2150	1784
kitchen 3	1465	2400	1932.5
Dining 3	1195	2276	1835.5
Living 3	1405	2244	1824.5
kitchen 4	1500	2560	2030
Dining 4	1155	2255	1855
Living 4	1423	2210	1816.5

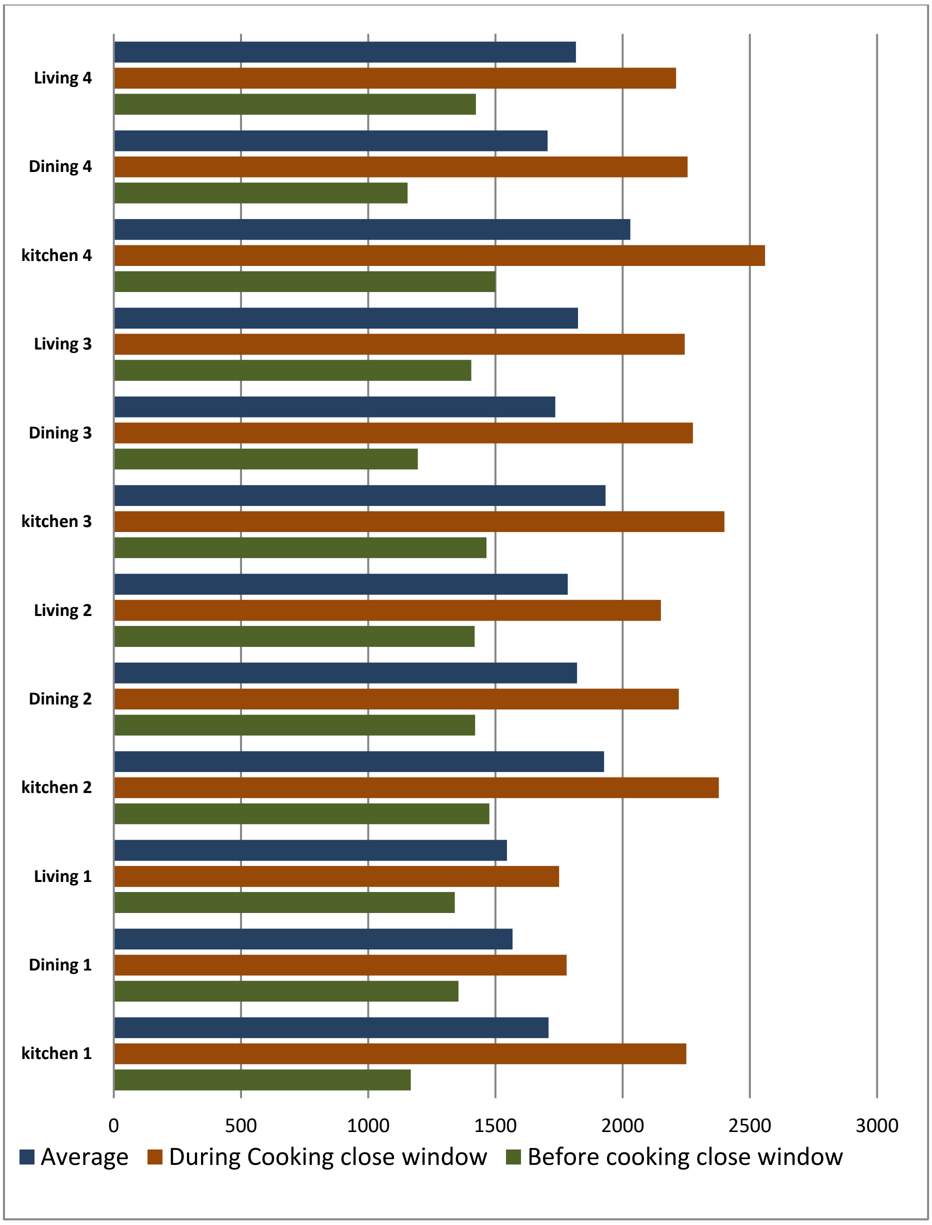

Figure 2 Average CO_2 concentration ppm for each measured kitchen 100% closed window

Table 4 Average CO_2 concentration ppm for each measured kitchen 50% closed window

CO_2	Before cooking open window	During Cooking Open window	Average
kitchen 1	1167	1965	1566
Dining 1	1155	1610	1382.5
Living 1	1040	1670	1355
kitchen 2	976	2110	1543
Dininng 2	1120	1675	1397.5
Living 2	1018	1798	1408
kitchen 3	1165	1994	1579.5

Dininng 3	995	1540	1267.5
Living 3	1105	1490	1297.5
kitchen 4	1100	2121	1610.5
Dining 4	1255	1567	1411
Living 4	1123	1421	1272

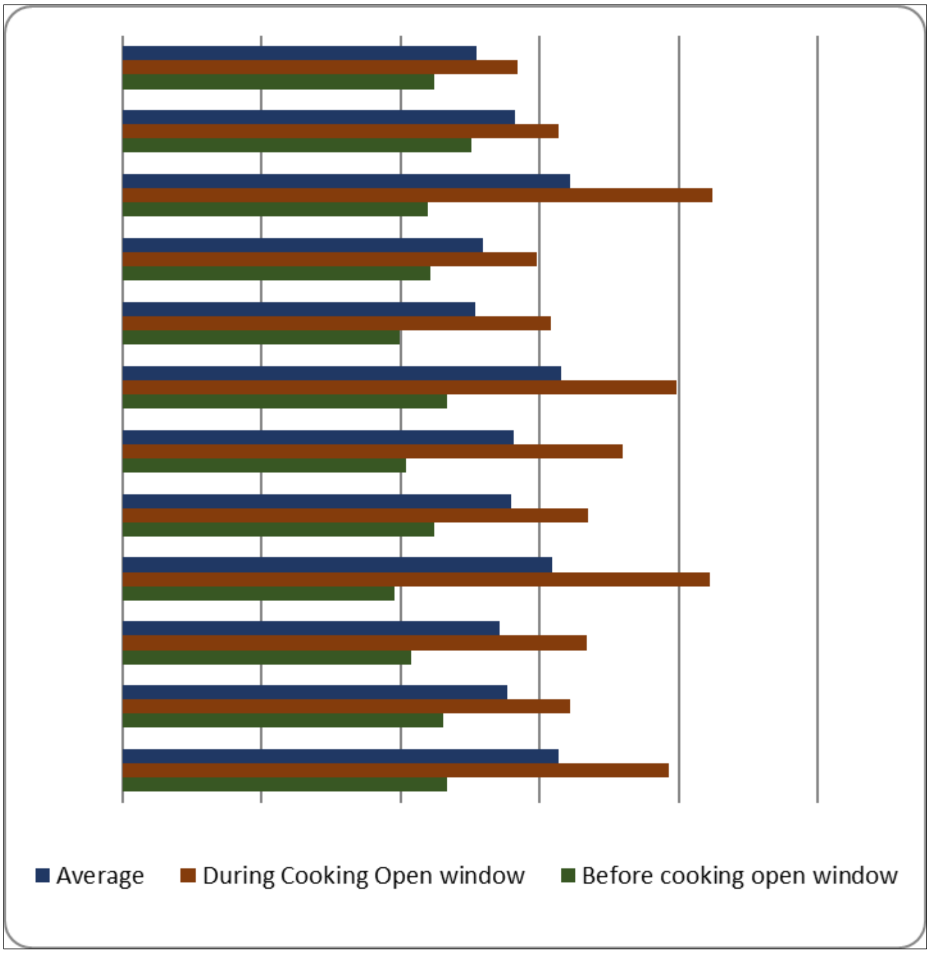

Figure 3 Average CO_2 concentration ppm for each measured kitchen 50% closed window

4. Conclusion

The findings reveal that CO_2 levels significantly increase across all spaces during cooking, regardless of whether windows are open or closed. Kitchens consistently exhibit the highest concentrations, given their proximity to the source of emissions. However, when windows are open, CO_2 levels are notably lower compared to when windows remain closed, highlighting the effectiveness of natural ventilation. For example, in scenarios with open windows, CO_2 levels in Kitchen 4 rise from 1100 ppm before cooking to 2121 ppm during cooking compared to 1500 ppm to 2560 ppm in closed-window scenarios. This indicates that open windows play a significant role in reducing CO_2 accumulation during cooking activities.

The impact of open windows is particularly evident in living rooms and dining spaces, which experience smaller increases in CO_2 levels compared to kitchens. In Living 1, CO_2 levels during cooking rise to 1670 ppm with open windows, compared to 1750 ppm with closed windows, further emphasizing the benefit of ventilation. These findings underscore the importance of implementing effective ventilation strategies, particularly in kitchens where emissions are concentrated. Open windows, while beneficial, may still be insufficient in managing high CO_2 levels in spaces with inadequate airflow or larger cooking areas, necessitating the need for improved ventilation systems and strategic airflow management to enhance indoor air quality.

Compliance with ethical standards

Disclosure of conflict of interest

The author(s) declare that there are no competing interests.

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