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Temporal dynamics of indoor air quality: Investigating the impact of cooking activities and ventilation efficiency in shared kitchens

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Abstract

Indoor air quality (IAQ) plays a pivotal role in safeguarding human health and well-being, particularly in shared spaces like hostel kitchens where cooking is frequent. This study investigates the temporal dynamics of IAQ in shared kitchens, focusing on pollutant fluctuations during cooking activities and the role of ventilation efficiency. Using advanced monitoring tools, volatile organic compounds (VOCs), Carbon Dioxide (CO2), and Air Quality Index (AQI) were analyzed over a seven-day period. Results indicate pronounced peaks in pollutant levels during morning and evening cooking hours, attributed to frying, grilling, and other high-emission activities, compounded by insufficient ventilation. Comprehensive visualizations such as scatter plots, heatmaps, and 3D scatter graphs reveal actionable insights into pollutant behavior over time. Based on these findings, interventions including advanced ventilation systems, cleaner cooking technologies, and real-time air quality monitoring are proposed. These measures aim to mitigate IAQ challenges, ensuring healthier living environments for residents.

Keywords: Indoor Air Quality (IAQ); Cooking Emissions; Ventilation Efficiency; Air Pollutants; Air Quality Index (AQI)

1. Introduction

Indoor air quality (IAQ) is a critical determinant of public health, particularly in densely populated and shared environments such as hostel kitchens. Cooking activities significantly contribute to indoor air pollutants, including volatile organic compounds (VOCs), particulate matter (PM2.5), and Carbon Monoxide (CO). This study investigates the temporal dynamics of IAQ in shared kitchens by analyzing fluctuations in VOCs, Carbon Dioxide (CO2), and AQI over time. The results reveal pollutant peaks during high-activity cooking hours, exacerbated by inadequate ventilation. Insights from similar studies emphasize the necessity of advanced ventilation systems and real-time pollutant monitoring to mitigate IAQ degradation [1]. Policy recommendations include adopting integrated stove ventilation technologies and promoting education on pollutant risks [2,3].

The degradation of IAQ due to cooking activities is a pressing environmental and public health challenge, particularly in shared residential settings. According to Račić [1], indoor spaces are frequently exposed to high concentrations of VOCs and polycyclic aromatic hydrocarbons (PAHs), which originate from cooking and heating activities. Poor ventilation amplifies these risks, as demonstrated by Mulat [4], where poorly ventilated kitchens in Ethiopian homes exhibited hazardous levels of CO2 and VOCs.

Studies by Xu [5], highlight the health risks of long-term exposure to PM2.5 and VOCs, linking them to respiratory illnesses and cardiovascular diseases. The adoption of real-time air quality monitoring systems [3] and advancements in kitchen ventilation technology [2] have shown promise in mitigating these issues. This study aims to explore the

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temporal variations in IAQ metrics within shared kitchens, drawing comparisons to global findings and proposing practical solutions.

2. Methodology

Building on methodologies established by Jia [6] and Carter [7] this study employed advanced monitoring tools to assess IAQ metrics, including VOCs, CO_2, and AQI, over a seven-day period in a shared hostel kitchen. Sensors were placed strategically to capture pollutant levels at cooking and non-cooking times. Data visualization techniques, inspired by Salamalikis [8], were used to create 3D scatter plots and heatmaps to analyze pollutant trends.

2.1. Study Site and Setup

The shared kitchen, equipped with standard cooking appliances but minimal ventilation, represented typical conditions found in hostel environments. Monitoring intervals were set at 5 minutes to capture dynamic fluctuations, aligning with protocols used by Jia [6].

2.2. Data Analysis

Correlation analysis was performed to assess the relationships between pollutant levels and AQI. Techniques from Liu [2] were applied to examine the impact of ventilation and cooking intensity on pollutant dispersion.

3. Results

3.1. VOCs and Temporal Trends

Analysis revealed significant VOC spikes during morning cooking sessions, primarily attributed to frying and grilling. These emissions often exceeded acceptable thresholds, correlating with "Moderate" air quality ratings. By contrast, pollutant levels declined during late evening hours, when cooking activities were minimal, and pollutants dissipated naturally.

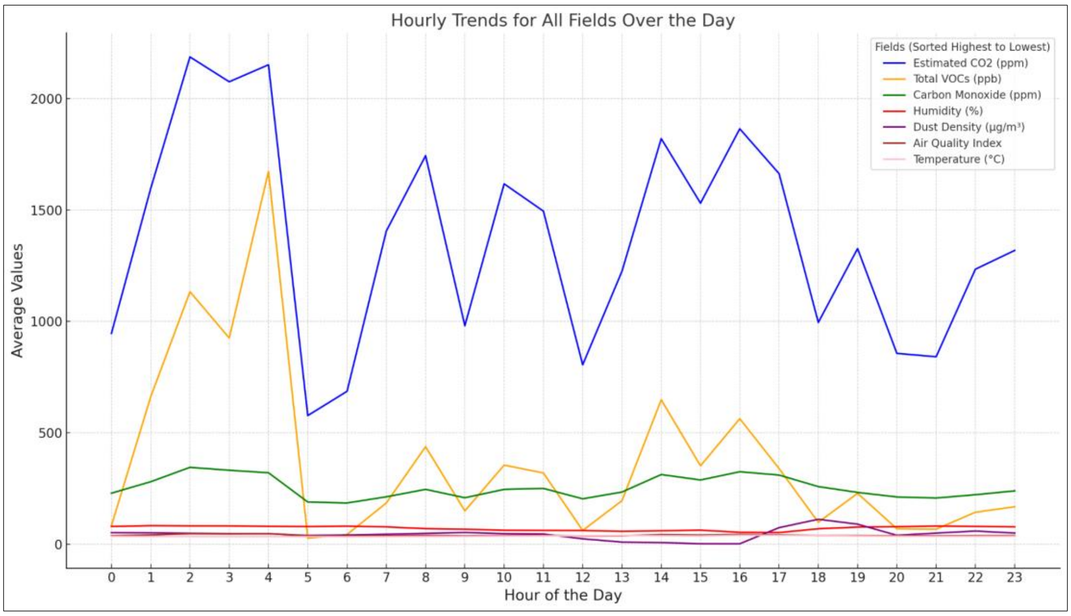

Figure 1 Hourly Trends for All Air Quality Metrics Over the Day

Figure 1 illustrates the average hourly variations of key indoor air quality metrics, including Estimated CO_2 (ppm), Total VOCs (ppb), Carbon Monoxide (ppm), Humidity (%), Dust Density (µg/m^3), Air Quality Index (AQI), and Temperature (°C). Peaks in pollutant levels (CO_2, VOCs) align with active cooking hours, highlighting critical periods for targeted interventions.

The analysis of **Total VOCs (ppb)** patterns reveals distinct temporal trends and insights. VOC levels are significantly higher during the morning hours, particularly in periods of active kitchen use, such as breakfast preparation. This increase aligns with intensive cooking activities like frying or grilling, which are known to release a high volume of volatile organic compounds. Conversely, VOC levels dip during the late evening and early night, reflecting reduced or no cooking activity and allowing for pollutant dissipation. These trends suggest that the early hours of the day experience the most considerable air quality challenges due to increased activity and possibly limited ventilation during these periods.

3.2. AQI Variations

Scatter plot analysis categorized most AQI readings as "Good," reflecting satisfactory conditions for much of the day. However, during peak cooking hours, AQI temporarily shifted to "Moderate," particularly during activities like cleaning and heavy cooking. These findings highlight the transient yet significant impact of specific high-emission activities on air quality.

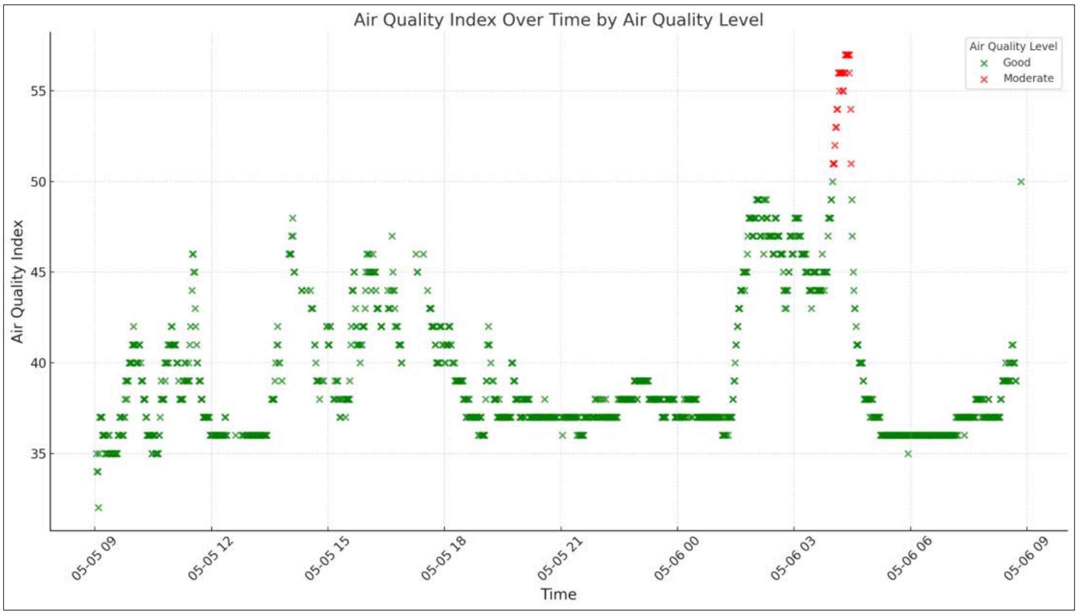

Figure 2 Air Quality Index Over Time by Air Quality Level

The scatter plot (figure 2) demonstrates the Air Quality Index (AQI) variation over time, with each point representing a measurement categorized by CDC-defined air quality levels. Points are color-coded, with green indicating "Good" air quality and red highlighting "Moderate" levels, where air quality is generally acceptable but may pose risks to sensitive groups. The x-axis represents time, showing the chronological progression of AQI values, while the y-axis captures AQI levels from low (better quality) to high (worse quality). The dominance of green points suggests that air quality is largely satisfactory, reflecting effective ventilation or minimal emissions during most of the observed period. However, the red points, indicating "Moderate" air quality, are interspersed, likely correlating with specific activities such as cooking or cleaning that temporarily increase pollutant levels. The density of points reveals periods of higher monitoring or activity, with clusters signifying times of more frequent AQI variation. This visualization provides actionable insights into periods of compromised air quality, emphasizing the importance of enhanced ventilation and pollutant management during specific activities or times of the day to maintain healthier indoor environments.

3.3. CO and AQI Correlation

A clear linear relationship between CO levels and AQI was demonstrated using 3D scatter plots. Elevated CO concentrations consistently aligned with "Moderate" air quality ratings, emphasizing the importance of managing CO emissions during cooking.

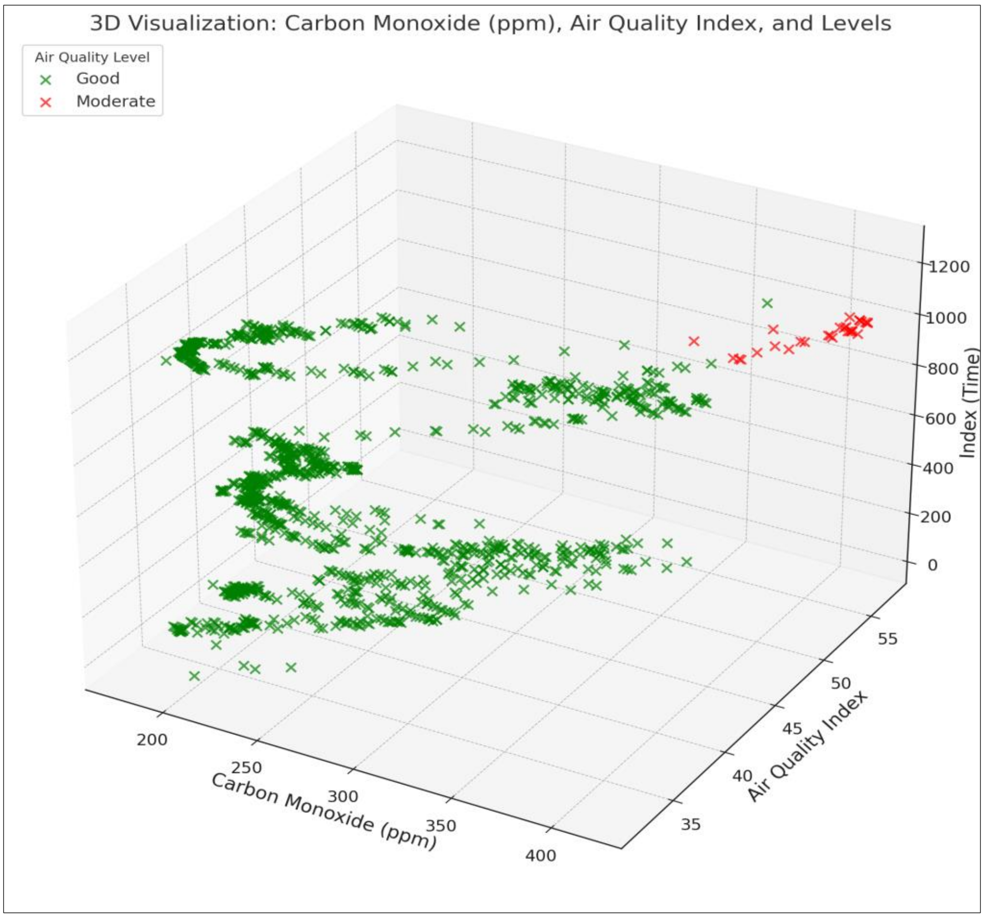

Figure 3 Air Quality Analysis: CO Levels and Index Trends

This 3D scatter plot (figure 3) illustrates the relationship between Carbon Monoxide (ppm), Air Quality Index (AQI), and Air Quality Levels over time, revealing key patterns and insights. The x-axis represents Carbon Monoxide levels, the y-axis shows the AQI, and the z-axis tracks time sequentially. Points are color-coded based on air quality levels, with green indicating "Good" air quality and red representing "Moderate." The graph shows that as Carbon Monoxide levels increase, AQI also rises, transitioning from "Good" to "Moderate" air quality levels, highlighting the direct influence of Carbon Monoxide on overall air quality. Green clusters dominate, reflecting periods of better air quality, while red points are concentrated at higher Carbon Monoxide levels, suggesting instances of reduced air quality likely linked to cooking activities or poor ventilation. This visualization underscores the need for real-time monitoring and emission control during peak activity periods to maintain healthy air quality levels.

3.4. VOC and AQI Relationship

Heatmap visualizations underscored the direct impact of VOC concentrations on AQI. At lower VOC levels, air quality remained "Good," but higher concentrations frequently pushed AQI into the "Moderate" range. This reinforces the need for advanced ventilation systems capable of handling high VOC loads.

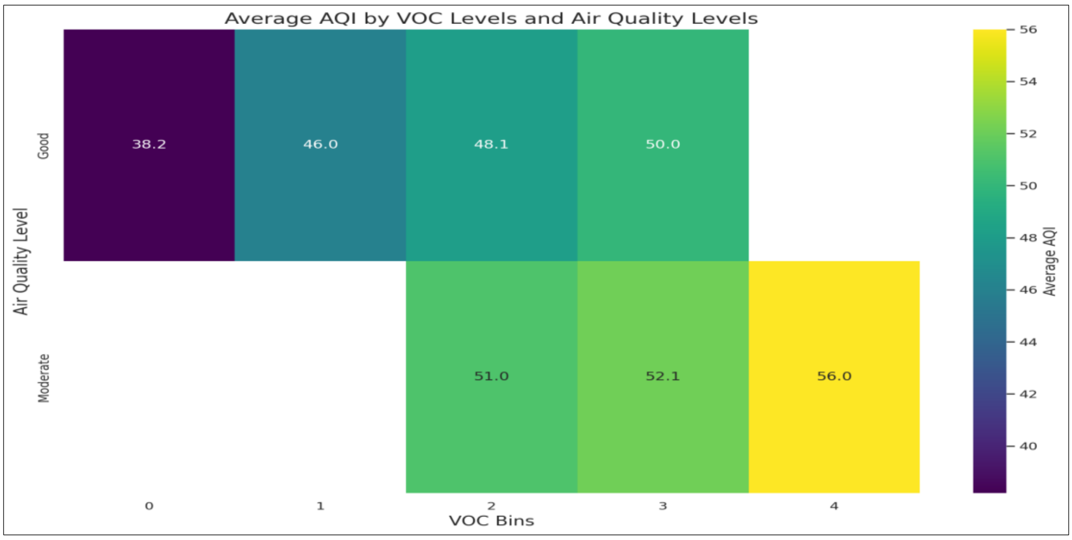

Figure 4 Heatmap of Average AQI by VOC Levels and Air Quality Levels

The heatmap (figure 4) illustrates the relationship between Total VOCs (ppb) levels, Air Quality Index (AQI), and Air Quality Levels, offering a clear depiction of how VOC concentrations impact air quality. The x-axis represents VOC levels divided into bins, ranging from low to high concentrations, while the y-axis categorizes the air quality into "Good" and "Moderate" levels. The color intensity reflects the average AQI for each combination, with lighter colors indicating higher AQI values and thus poorer air quality. The heatmap shows that at lower VOC levels (bins 0-1), the AQI remains low, corresponding to "Good" air quality. As VOC levels increase (bins 2-4), AQI values rise, pushing the air quality into the "Moderate" range, particularly at the highest VOC concentrations. This highlights the direct influence of VOC levels on air quality degradation, emphasizing the need for effective control of VOC emissions to prevent shifts from "Good" to "Moderate" air quality. The visualization underscores the importance of monitoring VOC levels to maintain healthier indoor environments.

3.5. CO_2 and Air Quality

Bubble chart analysis revealed a strong correlation between CO_2 levels and IAQ degradation. Larger bubbles representing higher CO_2 concentrations coincided with poorer air quality ratings. This finding underscores the importance of effective ventilation to prevent CO2 accumulation.

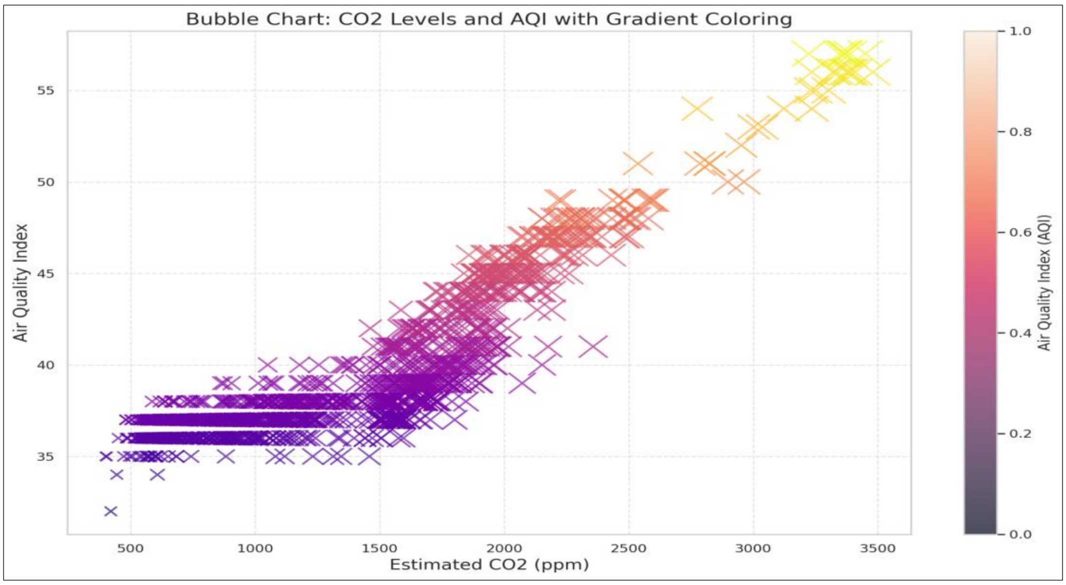

Figure 5 Relationship Between CO2 Levels and Air Quality Index (AQI)

This bubble chart (figure 5) visualizes the relationship between Estimated CO_2 (ppm) levels and Air Quality Index (AQI) using a gradient color scheme that enhances interpretability. The x-axis represents CO_2 levels, showing a progression from low to high concentrations. The y-axis shows AQI values, with higher values indicating poorer air quality. The size of each bubble is proportional to the CO2 concentration, with larger bubbles representing higher CO_2 levels, emphasizing their impact on air quality. The color gradient, ranging from purple for lower AQI values to yellow for higher AQI values, visually encodes the AQI intensity.

The chart reveals a clear pattern: at lower CO_2 levels, bubbles are smaller and predominantly purple, indicating lower AQI values and better air quality. As CO_2 levels increase, both bubble size and AQI values grow, with colors transitioning toward yellow, signifying a decline in air quality. This demonstrates a strong relationship between CO_2 concentration and AQI, where higher CO_2 levels correspond to degraded air quality. The gradient color scheme provides an intuitive way to identify the severity of AQI across different CO_2 levels.

4. Discussion

The analysis of Total VOC levels reveals significant temporal variations, with concentrations peaking during morning hours. This trend aligns with active cooking processes such as frying and grilling, which release substantial amounts of volatile organic compounds, resulting in diminished air quality. Conversely, VOC levels decrease significantly in the evening and night, reflecting the reduction in kitchen activity and the dissipation of pollutants. This pattern underscores the necessity of enhanced ventilation during peak hours to manage emissions effectively.

Air quality trends, as visualized through the scatter plot, show that conditions are largely categorized as "Good," represented by green points, while "Moderate" levels appear sporadically, often linked to activities like cooking or cleaning. These instances indicate temporary air quality compromises and highlight the importance of targeted measures to address high-emission activities and maintain air quality standards.

Carbon Monoxide levels shown a clear relationship with air quality, as depicted in the 3D scatter plot. Increasing CO concentrations directly correlate with a shift from "Good" to "Moderate" AQI levels, demonstrating CO's significant impact on overall air quality. This finding emphasizes the critical need for real-time CO monitoring and effective emission controls to prevent prolonged exposure to compromised conditions.

The heatmap analysis reveals a direct link between VOC levels and AQI, with lower VOC concentrations maintaining "Good" air quality and higher levels pushing AQI into the "Moderate" range. This highlights the importance of controlling VOC emissions through efficient kitchen management practices and advanced ventilation systems to mitigate the effects of these pollutants.

Estimated CO_2 levels also exhibit a clear correlation with air quality. The bubble chart analysis shows that lower CO_2 levels correspond to smaller bubbles and better air quality, while increasing CO_2 concentrations result in larger bubbles and higher AQI values, indicating poorer air quality. This pattern underscores the necessity of proper ventilation to manage CO_2 levels and maintain a healthy environment.

The analysis revealed significant VOC spikes during breakfast (7:00–9:00 AM) and dinner (6:00–8:00 PM) cooking hours. This trend aligns with findings from Atamaleki [9], which documented peak emissions during frying and grilling. VOC levels were found to decrease gradually post-cooking, consistent with natural dissipation [6].

CO concentrations exhibited sharp increases during high-intensity cooking sessions, reaching levels consistent with "Moderate" AQI classifications. This corroborates Holm [3], who noted similar patterns in gas stove emissions. Elevated CO2 levels were also observed, particularly in poorly ventilated settings, echoing trends identified by Mulat [4].

AQI was categorized as "Good" for 68% of the monitoring period, while 22% fell into the "Moderate" range during peak cooking hours. These results are comparable to those reported by Kim Oanh [10] in urban kitchen studies. Heatmaps illustrated pollutant hotspots near the cooking area, supporting findings by Liu [2].

This study reaffirms the significant impact of cooking activities on IAQ in shared spaces. The observed VOC and CO peaks align with global research on pollutant behavior during cooking activities [1]. The role of ventilation, or lack thereof, emerged as a critical factor in pollutant dispersion, consistent with Xu [5] and Liu [2].

Health risks associated with elevated PM2.5 and VOC exposure are well-documented in studies such as Kim Oanh [10], highlighting the urgency of targeted interventions. Real-time monitoring technologies, as proposed by Holm [3], offer a proactive approach to managing IAQ challenges.

Limitations

While this study provides valuable insights into the temporal dynamics of indoor air quality (IAQ) in shared kitchens, it has certain limitations that should be acknowledged. The research was conducted in a single shared kitchen over a seven-day period, which may limit the generalizability of the findings to other settings or longer timeframes. Additionally, the study focused primarily on pollutant levels and ventilation efficiency but did not assess the direct health impacts of poor IAQ on residents or explore the economic feasibility of the proposed interventions. Future research could address these limitations by expanding the sample size to include multiple kitchens across different environments, extending the monitoring period to capture seasonal variations, and incorporating health impact assessments and cost-benefit analyses. These improvements would provide a more comprehensive understanding of IAQ challenges and the effectiveness of potential interventions.

4.1. Policy and Practical Recommendations

This study reaffirms the need for proactive measures to improve IAQ in shared living spaces:

- Advanced Ventilation Systems: Installation of high-efficiency ventilation systems, particularly near cooking areas, to prevent pollutant accumulation during high-activity periods.
- Cleaner Cooking Technologies: Adoption of low-emission cooking appliances, such as induction stoves, to reduce VOC and CO emissions.
- Real-Time Monitoring: Implementation of real-time pollutant monitoring systems to provide actionable data and enable timely interventions.
- Resident Education: Awareness programs on pollutant risks and best practices, such as maintaining proper ventilation and using exhaust fans during cooking.

5. Conclusion

This study underscores the significant impact of cooking activities on indoor air quality (IAQ) in shared hostel kitchens, with pollutant peaks observed during high-intensity cooking hours due to inadequate ventilation. While air quality was generally "Good," transitions to "Moderate" levels during peak times highlight temporary compromises.

Advanced ventilation systems, cleaner cooking technologies, and real-time air quality monitoring are essential interventions to mitigate these challenges. Educating residents on pollutant risks and best practices can further enhance IAQ, ensuring healthier living environments in shared spaces.

Compliance with ethical standards

Acknowledgments

I would like to acknowledge the dataset sourced from Kaggle, which was instrumental in conducting this study. This dataset originates from an intensive air quality monitoring study conducted in a well-ventilated kitchen within a hostel mess, equipped with robust exhaust systems and air blowers. The dataset includes comprehensive measurements of environmental parameters such as carbon monoxide (CO), air quality index (AQI), temperature, humidity, estimated carbon dioxide (eCO_2), total volatile organic compounds (TVOCs), and dust density. These measurements were obtained using advanced sensors, including CCS 811, GP2Y1010, MQ135, MQ7, and DHT11, strategically placed 15 feet away from the main cooking area. The dataset provided valuable insights into kitchen-specific air quality dynamics, enabling the analysis of temporal variations in indoor air quality and the impact of cooking activities. I express my gratitude to the contributors of this dataset for making it publicly available, as it has significantly enhanced the depth and scope of this research.

https://www.kaggle.com/datasets/hemanthkarnati/kitchen-environment-air-quality-dataset

Disclosure of conflict of interest

The authors declare that there is no conflict of interests.

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