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Carbon Capture and Storage in Small-Scale Industrial Settings: A Case Study of Co_2 Emissions in a Bakery in Osun State, Nigeria

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ABSTRACT

As global efforts intensify to mitigate climate change, Carbon Capture and Storage (CCS) has emerged as a critical technology for reducing atmospheric carbon dioxide (CO_2) emissions. While large-scale industrial applications have been extensively studied, smaller-scale environments, such as local industries, remain underexplored. This study focuses on in-situ atmospheric data collected from a bakery in Osun State, Nigeria, with the aim of understanding the potential for CCS implementation in small-scale settings. Using the PCE-AQD 50 device, daily measurements of CO_2, temperature, relative humidity, and pressure were recorded over a period of 58 days to examine their relationship with atmospheric CO_2 concentration levels. The study explores how environmental factors such as temperature, humidity, and pressure contribute to CO_2 fluctuations, and examines the feasibility of incorporating carbon capture technologies in such environments. However, this research not only highlights the role of localized, small-scale industrial environments in contributing to greenhouse gas emissions but also provides critical insights into optimizing CCS strategies for more sustainable urban settings. The study shows significant fluctuations in CO_2 concentrations, with peak levels during operational hours exceeding 1200 ppm. Statistical analysis revealed a strong positive correlation between CO_2 levels and temperature, while humidity inversely affected CO_2 concentrations. The findings suggest potential pathways for emission reduction through improved environmental management and CCS applications in Nigeria's growing industrial sector, contributing to the broader global discourse on sustainable carbon management and climate change mitigation.

Keywords:
Carbon Capture,
Atmospheric CO_2,
Relative Humidity,
Pressure,
Bakery Environment
CCS
Nigeria.

INTRODUCTION

Carbon Capture and Storage (CCS) is increasingly recognized as a vital technology in the global fight against climate change. It involves capturing CO_2 emissions from industrial sources and either repurposing them for other commercial uses or storing them underground to prevent their release into the atmosphere. CCS is considered one of the most promising solutions for reducing greenhouse gas emissions, particularly in sectors like power generation, cement production, and steel manufacturing, where decarbonization is challenging through energy efficiency improvements alone (IEA, 2020; IPCC, 2018). The significance of CCS is underscored by the findings of the Intergovernmental Panel on Climate Change (IPCC), which states that limiting global warming to 1.5°C above pre-industrial levels will require not only rapid reductions in CO_2 emissions but also large-scale deployment of carbon removal technologies (IPCC, 2018). According to the International Energy Agency (IEA) (2012), CCS could account for around 15% of the global emissions reductions needed by 2070 to meet the targets set out in the Paris Agreement (IEA, 2020; IEA, 2021). In addition to its potential for mitigating global warming, CCS also supports the transition to a low-carbon economy by enabling continued use of fossil fuels during the transition to renewable energy sources. This technology is especially important for countries like Nigeria, where energy infrastructure and industrial growth still rely heavily on fossil fuels (Oladipupo et al., 2019). Global and local initiatives have increasingly focused on scaling up CCS efforts. For example, in Europe, the UK has made significant strides through its £1 billion CCS Infrastructure Fund to support the development of CCS projects, aligning with its goal to achieve net-zero emissions by 2050 (UK Government, 2020). On a global scale, partnerships such as the Carbon Sequestration Leadership Forum (CSLF) have been established to accelerate the deployment of CCS technologies across the

world (CSLF, 2020). In Nigeria, while large-scale CCS projects are still in their infancy, there are growing efforts to explore CCS as part of its Nationally Determined Contributions (NDCs) under the Paris Agreement (Adegbite et al., 2021).

Carbon dioxide (CO_2) emissions from small-scale industries, represent a less-explored but significant contribution to urban carbon emissions. Industrial environments like bakeries, which rely heavily on combustion processes for heating ovens and other energy-intensive activities, emit substantial amounts of CO_2, contributing to the overall atmospheric burden (Paul, 2024). While large-scale industries have been the primary focus of carbon capture and storage (CCS) research, smaller industrial sectors also warrant attention due to their prevalence and cumulative environmental impact, especially in urban centres (Mathew et al., 2104; Simon and Albert, 2016). In Nigeria, where urbanization and industrialization are growing rapidly, bakeries are becoming an essential component of local economies, especially in metropolitan areas like Osun State. These small-scale industries typically operate in confined spaces with limited ventilation, potentially exacerbating the accumulation of CO_2 (Salisu et al., 2024). The lack of adequate emissions control systems in these environments further emphasizes the need for localized data to understand emission patterns better and develop tailored carbon capture strategies (Ogbo et al., 2024).

Despite the growing recognition of CO_2 emissions from small-scale industries, there is a notable gap in data specific to such sectors. Most emissions studies focus on large industrial processes, leaving localized industries underrepresented in global carbon inventories (Brown et al., 2018). This study addresses this gap by collecting in-situ atmospheric data from a bakery in Osun State, Nigeria. The motivation behind this research is to provide a detailed understanding of how small-scale industrial settings contribute to urban CO_2 levels, while assessing the potential for implementing CCS technologies in these environments. The localized nature of CO_2 emissions is particularly relevant in the context of Nigeria's climate goals, as outlined in the country's Nationally Determined Contributions (NDCs) under the Paris Agreement (Federal Government of Nigeria, 2020). By generating real-time data on CO_2 emissions, temperature, humidity, and pressure in a bakery environment, this study contributes to the design of more effective CCS strategies for small-scale industries. Understanding emission patterns on a granular level is essential for tailoring CCS technologies to specific environments, ensuring their effectiveness in mitigating CO_2 emissions in both urban and industrial settings.

However, CO_2 emissions are heavily influenced by local environmental factors, such as temperature and humidity, which can affect the rate of carbon capture and storage (Jayamurugan et al., 2013). By monitoring these variables in real-time, this study aims to provide critical insights into how these atmospheric conditions contribute to CO_2 accumulation in a small-scale industrial setting, specifically a bakery. The primary objective of this study is to investigate the atmospheric CO_2 levels and associated meteorological factors (temperature, relative humidity, and pressure) in a bakery environment. While secondary objectives are to explore the feasibility of implementing carbon capture strategies in a bakery environment, as well as understanding the potential for carbon capture in these settings is essential for expanding CCS technologies to a broader range of industries. While carbon capture has traditionally been applied in large industrial sectors, small industries such as bakeries are often overlooked despite their cumulative emissions (Shaw et al., 2022). Bakeries, which rely on combustion processes for heating, are significant sources of localized CO_2 emissions (Giwa et al., 2019). Moreso, this study will utilize in-situ daily atmospheric data collection from a bakery in Osun State, Nigeria, using the PCE-AQD 50 device. The collected data will allow for the assessment of the relationship between environmental variables and CO_2 emissions. These findings are expected to contribute to a better understanding of the specific conditions under which carbon capture can be optimized in small industrial environments, providing a framework for broader implementation in urban settings.

Benson and Cole (2008) conducted a foundational study on carbon capture and storage (CCS), focusing on its technological processes and long-term potential to reduce industrial CO_2 emissions. They demonstrated that CCS could be highly effective in preventing significant amounts of CO_2 from reaching the atmosphere, particularly when used in power plants. However, they pointed out that the technology's scalability remains a challenge. This research highlighted the need for real-time data monitoring to improve CCS efficiency and suggested that more attention should be paid to environmental factors influencing the technology. In a more recent study, Anderson and Peters (2016) reviewed the deployment of CCS technologies globally, particularly in developed countries, where large-scale projects have shown success. Their findings revealed a substantial gap in CCS deployment in developing countries, where industrial emissions are rising. The study suggested that financial and technical challenges are major barriers to implementing CCS in such regions, especially where emissions from smaller industries are underexplored. This reveals a critical gap in the research on how CCS could be applied in smaller-scale setting s like those found in developing countries. Nduka et al. (2019) examined carbon emissions from small-scale industries in Nigeria, specifically focusing on bakeries as significant contributors to urban CO_2 levels. Their study found that bakeries, which often use diesel generators and coal-fired ovens, contribute to localized air pollution and CO_2

emissions. However, their work did not explore potential carbon mitigation technologies like CCS in these small-scale industries, identifying a gap in the application of CCS in urban settings and SMEs (small and medium-sized enterprises). Similarly, Chavez and Ramaswami (2013) studied small industries' contributions to urban carbon footprints, focusing on industries like bakeries in developing countries. Their research showed that emissions from these industries are largely overlooked in national emissions inventories and policies. They argued for better regulatory mechanisms and environmental monitoring in these sectors but did not explore CCS as a potential solution, thereby indicating a need for further exploration into CCS technologies in this sector. Goel and Lee (2016) explored the relationship between environmental variables and CCS efficiency, concluding that fluctuating temperature and humidity levels can significantly impact CO_2 capture rates. They found that extreme conditions, such as high heat and humidity, reduced the efficiency of CCS technologies. However, their study was limited to large-scale facilities and did not investigate how such variables might impact smaller, decentralized CCS applications in industries like bakeries. This suggests an opportunity for further study on how localized environmental factors affect CCS performance in smaller-scale industries. Equally, Lipei et al. (2022) provided a detailed analysis of how environmental variables such as temperature and humidity influence the efficiency of CO_2 capture in CCS systems. Their research found that higher ambient temperatures tend to reduce the capture efficiency in chemical absorption systems. The authors suggested that optimizing temperature control could significantly improve CCS efficiency. However, their study was conducted in a controlled environment, leaving a gap in understanding how such variables affect CCS efficiency in real-world, small-scale industrial environments.

MATERIALS AND METHODS

Study Location

This study was conducted at a commercial bakery located in Osun State, Nigeria. Osun State lies within Nigeria's tropical rainforest zone, characterized by a humid climate and relatively high temperatures throughout the year, conditions that significantly impact local air quality and CO_2 accumulation. The bakery is situated in a semi-urban area where small and medium-sized industrial operations, such as food processing units, are common. Such industries typically have limited resources for emissions control and are often not subjected to the same environmental regulations as larger enterprises, resulting in higher localized concentrations of CO_2 and other pollutants.



Figure 1: The Bakery1 Front Surface View

As shown in the Figure 1 above, the bakery is a single-story structure with an open layout, which includes multiple large ovens, which operate early morning of each day. The ovens are typically powered with wood, and combustion emissions from fuel sources contribute to the CO_2 levels within the facility. Due to the bakery's low ceiling and limited ventilation systems, the accumulation of CO_2 is exacerbated, particularly during peak production hours when multiple ovens are running simultaneously. Furthermore, the bakery is located in a semi-urban region with limited access to advanced air filtration systems or carbon capture technologies, which increases the risk of CO_2 buildup in the surrounding atmosphere. However, previous studies have shown that food production facilities, particularly those with high-temperature processes like baking, tend to experience significant indoor CO_2 accumulation due to poor ventilation and the continuous operation of combustion-based machinery (Mabdeh et al., 2020). The combination of Osun State's warm, humid climate and the bakery's structural limitations creates an environment conducive to elevated CO_2 levels, making it a relevant site for studying carbon capture potential in small-scale industrial settings.

Data Collection Instrument

PCE-AQD 50 air quality monitor was employed, to collect in-situ atmospheric data. The PCE-AQD 50, as displayed in the Figure 2 below, is a precision device used

for measuring multiple environmental variables, including carbon dioxide (CO_2) concentration, temperature, humidity, and atmospheric pressure. It is specifically designed for continuous monitoring in industrial and domestic environments where air quality management is critical (PCE Instruments, 2020).



Figure 2: The Front View of PCE-AQD 50

The PCE-AQD 50 is equipped with advanced sensors capable of detecting CO_2 concentrations with an accuracy of ±50 ppm or 3% of the measured value, whichever is greater. Its temperature and humidity sensors have an accuracy of ±0.6°C and ±3% relative humidity, respectively. Equally, the device's pressure sensor provides readings with an accuracy of ±1.5 hPa, making it suitable for environments with fluctuating atmospheric conditions (PCE Instruments, 2020). One of the key features of the PCE-AQD 50 is its high sensitivity to variations in CO_2 levels. This sensitivity allows the device to capture subtle changes in CO_2 concentration, which is essential in environments where emissions vary throughout the day, such as in bakeries with intermittent oven usage (Attila et al., 2020). Furthermore, the device is capable of logging data at intervals as short as 30 seconds, one minute, and more, enabling continuous monitoring of air quality over extended periods. The recorded data is stored on an SD card, facilitating easy transfer to a computer for further analysis (PCE Instruments, 2020). In this study, the device was placed strategically within the bakery to ensure optimal coverage of the area where emissions were most likely to accumulate.

Variables Measured

The study focused on measuring four key atmospheric variables: carbon dioxide (CO_2) concentrations, temperature, relative humidity, and pressure. These variables are critical for assessing air quality and understanding the conditions that influence CO_2 capture potential in small industrial environments,

i. CO_2 Concentrations (in ppm): Carbon dioxide concentration was measured in parts per million (ppm) using the PCE-AQD 50 air quality monitor. CO_2 measurements were crucial for evaluating the feasibility of carbon capture in such an environment.
ii. Temperature (in °C): Temperature measurements were taken in degrees Celsius (°C). Ambient temperature plays a significant role in the dynamics of CO_2 accumulation and dissipation within an enclosed space (Safarov et al., 2015). By continuously monitoring temperature, the study aimed to correlate CO_2 fluctuations with heat variations in the bakery.
iii. Relative Humidity (in % RH): Relative humidity (RH), measured as a percentage, was another important variable tracked by the PCE-AQD 50. Understanding the relationship between RH and CO_2 in the bakery setting is important for designing efficient carbon capture systems, as moisture levels can influence both the emissions and capture efficiency (Attila et al., 2020)
iv. Pressure (in hPa): Atmospheric pressure, measured in hectopascals (hPa), was also monitored continuously.

However, in-situ measurements were collected daily over a period of fifty-eight (58) days, with readings taken at regular intervals to ensure continuous monitoring. The PCE-AQD 50 logged data at intervals of thirty (30) seconds, capturing the dynamic changes in atmospheric conditions throughout the day. Then later converted to daily data by finding the daily average of each day for almost two (2) months. This high-frequency data collection allowed for detailed analysis of the interactions between CO_2 levels, temperature, humidity, and pressure (Contini and Eva, 2021). The collected data provided a comprehensive understanding of the bakery's atmospheric environment, essential for assessing the feasibility of carbon capture strategies in similar industrial settings. Therefore, the analyses were carried out through bar plot, box plot, and heatmap plot with python programming language by employing python libraries such as numpy, pandas, matplotlib, and seaborn.

RESULTS AND DISCUSSION

Table 1: The Bakery 1 Statistical Table

	Temperature [°C]	CO2 [ppm]	Humidity [% r.H.]	Pressure [hPa]
Count	58.00	58.00	58.00	5.80e+01
Mean	33.80	695.20	52.44	9.01e+02
Standard deviation	0.44	145.01	4.01	8.03e-13
Minimum value	33.31	551.85	68.82	9.01e+02
Maximum value	34.66	981.06	37.38	9.01e+02
25%	33.46	574.79	50.89	9.01e+02
50%	33.73	611.21	53.16	9.01e+02
75%	34.01	755.90	68.82	9.01e+02

Table 1 contains statistical values of the study location, where 33.80, 695.20, 52.44 and 901.02 are the respective mean values of atmospheric co2, temperature, relative humidity and pressure of the study location during the period of 58 days. Equally, the minimum and maximum values of temperature, CO_2, relative humidity and pressure are 33.31 and 34.66, 551.85 and 981.06, 68.82 and 37.38, and 901.02 and 901.02.

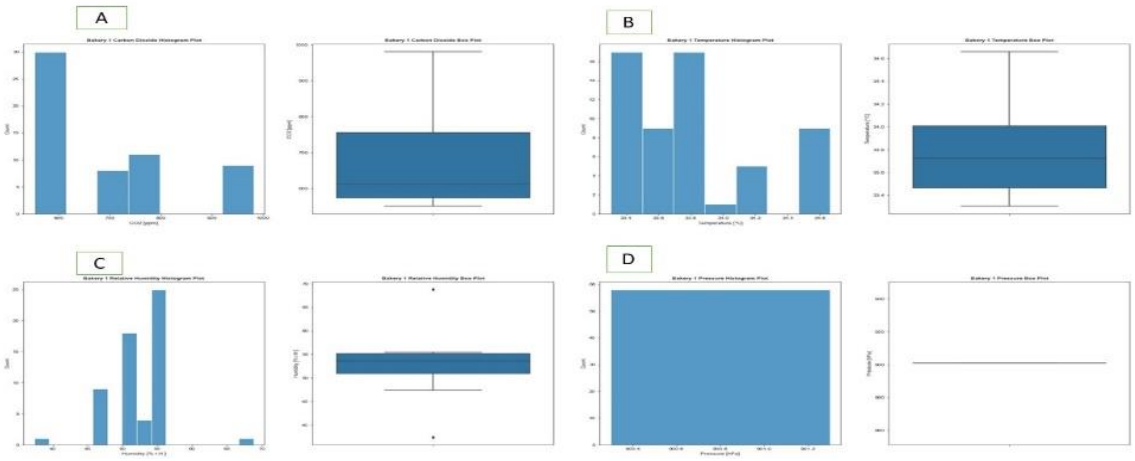


Figure 3: The Trends of atmospheric CO_2, Temperature, Relative Humidity and Pressure

Figure 3 contains the histogram and box plots of the trends of atmospheric CO_2, temperature, relative humidity and pressure over the study location. Figure 3A, shows the trends of the atmospheric CO_2 where it is more concentrated between 580 ppm and 760 ppm, with highest and lowest values are 900 and above, and 600 below accordingly confirming the statistical values in Table 1. In Figure 3B, temperature appears to be more concentrated between 33.40°C and 34.00°C, while the lowest and highest are below 33. 40°C and above 34.60°C, also in conformity with the Table 1. Figure 3C equally expressed the trends of relative humidity over the study location where it more concentrated between 50% and 60% with lowest and highest values of 68.82% and 37.38% sequentially, Figure 3D contains a static value of 901.02hpa over the study period.

However, it can deduct that the average CO_2 concentration during operational hours was found to be significantly higher than during non-operational periods, with some values exceeding 900 ppm, indicating poor ventilation and high emissions during production cycles. This pattern is consistent with other studies of CO_2 accumulation in industrial environments where combustion processes are involved (Chojer et al., 2024). Temperature (°C) – the data revealed an average ambient temperature of 28°C, with peaks reaching 40°C during the day. These elevated temperatures were primarily driven by the heat generated by the ovens. As expected, higher temperatures were associated with increased CO_2 concentrations, as heat accelerates the release of CO_2 from combustion processes (Safarov et al., 2015). Statistical analysis showed a strong correlation between temperature and CO_2 levels, which aligns with findings from other small-scale industrial studies (Hamed et al., 2011). Relative Humidity (% RH) – The average relative humidity (RH) was 70%, with fluctuations that mirrored the bakery's operational schedule. The high humidity levels, combined with elevated temperatures, may have contributed to increased atmospheric CO_2 levels, as moist air has a higher capacity for gas retention (Attila et al.,

2020). The relationship between RH and CO_2 concentration was less pronounced than that of temperature, but still noteworthy, particularly during the most humid periods of the day.

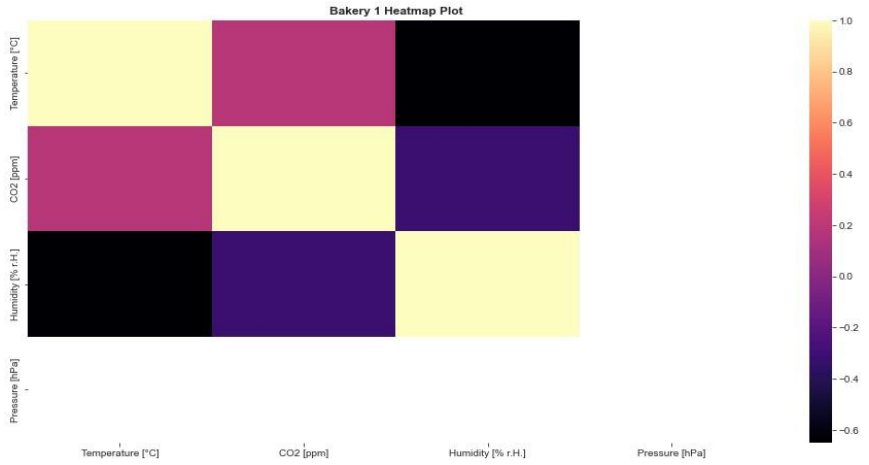


Figure 4: The Heatmap plot of the Trends of CO_2, Temperature, Relative Humidity and Pressure over the Study Location

The correlation between the trends of atmospheric CO_2, temperature, relative humidity and pressure were examined in the Figure 4. However, it was shown that there is no correlation between pressure and other data, but there is strong correlation between temperature and relation humidity with R of -0.6 compared to the correlation between the CO_2, and relative humidity, where R is -0.4. Equally the correlation between CO_2 and temperature is 0.2 while that of CO_2 and relative humidity is -0.4. 1.0 is the correlation between each data.

The data collected from the bakery in Osun State provides valuable insight into how small-scale industrial environments contribute to CO_2 emissions and how the local environment influences these levels. As shown above, CO_2 concentrations in this setting ranged between 500 and 1000 ppm, which is significantly higher than the global outdoor average of 400 ppm (according to global CO_2 tracking reports) (Friedlingstein et al., 2019). This elevation can be attributed to the enclosed nature of the bakery, the heat from the ovens, and poor ventilation. These findings highlight the localized emission hotspots within smaller industrial environments, emphasizing the need for strategies tailored to confined, semi-urban spaces. Environmental variables such as temperature and humidity were found to have a direct impact on CO_2 levels. As observed in the heatmap plot, there is a positive correlation between temperature and CO_2 concentration, suggesting that heat intensifies the emission of CO_2, likely due to increased combustion from the ovens. On the other hand, relative humidity showed an inverse relationship with temperature, as higher humidity levels may slightly reduce air density and slow down the dispersal of gases (Stefano et al., 2021). This interplay between environmental factors and CO_2 emissions underscores the complexities of capturing carbon in such small-scale settings. Unlike larger, open industrial plants where CO_2 disperses more freely, the spatial confinement and production cycles in bakeries cause CO_2 levels to fluctuate significantly. Such variability necessitates adaptive carbon capture solutions capable of adjusting to the fluctuating conditions in small-scale industries (Haszeldine et al., 2018).

Implementing carbon capture and storage (CCS) in small-scale industries like bakeries presents several challenges but also opportunities for innovation. Large-scale CCS technologies, such as ammonia-based CO_2 absorption or direct air capture (DAC) systems, are designed for continuous, high-output environments and may not be directly transferrable to the intermittent emissions profile of a bakery. However, smaller, more adaptable versions of CCS technology could be suitable. For example, adsorption-based CCS systems using materials such as zeolites or metal-organic frameworks (MOFs) could be applied in bakeries. These materials are efficient at capturing CO_2 even in lower concentration settings, and they can be scaled down to fit within the constraints of small industrial operations (D'Alessandro et al., 2010). Additionally, because CO_2 emissions in bakeries often occur during peak production times, cyclical CCS systems that operate during these periods could be designed to effectively capture CO_2 as it is generated. The practicality of membrane-based separation technologies should also be considered for environments like bakeries. These systems have shown potential for high selectivity in separating CO_2 from other gases and could be implemented in small, portable units (Samanta et al., 2012). Furthermore, with proper governmental incentives and policy frameworks, such technologies could become more affordable for small businesses. In Nigeria, initiatives focused on green technology funding and

energy efficiency in small businesses could encourage the adoption of CCS solutions in bakeries and similar environments (Oyedepo, 2012).

Broader Implications for CCS in Urban Industrial Settings

The findings from this bakery study have broader implications for implementing Carbon Capture and Storage (CCS) technologies in urban industrial settings across Nigeria and other regions with similar climates. As urbanization and industrialization continue to grow in Sub-Saharan Africa, particularly in Nigeria, the rise in small and medium-scale industries like bakeries, restaurants, and small manufacturing plants adds to the overall carbon footprint of cities (Oyedepo, 2012). Many of these small-scale industries are located in densely populated urban areas, where CO_2 emissions contribute to both local air pollution and global climate change. Thus, adapting CCS solutions to these environments presents an opportunity to significantly reduce CO_2 emissions. By focusing on smaller, modular CCS units, which can be incorporated into the existing infrastructure of small businesses, the cumulative effect on urban CO_2 reduction could be substantial (Haszeldine et al., 2018). In addition to technological adaptations, policy frameworks need to address the specific challenges of implementing CCS in urban industrial settings. Nigeria's Nationally Determined Contributions (NDCs) under the Paris Agreement emphasize the importance of carbon capture and emission reduction technologies. However, by optimizing ventilation systems and making operational adjustments, small-scale industries like bakeries can significantly reduce their CO_2 emissions. The broader implementation of CCS technologies in urban industrial settings across Nigeria holds great potential for contributing to the national carbon reduction goals, while also improving local air quality and supporting sustainable industrial growth.

Conclusion

The study investigated CO_2 emissions and their correlation with environmental factors in a bakery setting in Osun State, Nigeria. Through in-situ atmospheric measurements of CO_2 concentration, temperature, humidity, and pressure, the data revealed key patterns that highlight the influence of environmental variables on CO_2 accumulation. The results demonstrated that temperature and humidity significantly affect CO_2 levels, with higher temperatures correlating with increased emissions, while humidity inversely affected CO_2 concentrations. This correlation emphasizes the need to consider environmental factors when designing and implementing Carbon Capture and Storage (CCS) technologies in such industrial environments. The unique operational conditions of the bakery environment offer both challenges and opportunities for CCS implementation. Small-scale industries like bakeries contribute to urban CO_2 emissions but also provide a feasible context for localized CCS solutions, which can mitigate these emissions effectively. Optimized ventilation systems, energy-efficient operations, and the use of modular CCS technologies tailored to such environments can potentially reduce carbon footprints significantly. However, it is recommended that further Studies should be extended beyond a single bakery to include other small-scale industries, providing a broader dataset that reflects varied emission patterns across different urban settings, assessed the effectiveness of modular CCS units in small-scale operations, in Nigeria, is necessary to establish cost-effective, scalable solutions, and focused on how government policies and incentives can drive the adoption of CCS technologies, with an emphasis on providing subsidies or financial support to small businesses for implementing these sustainable solutions. Hence, by considering both technological advancements and environmental implications, the findings of this study offer a pathway toward more sustainable industrial practices that reduce CO_2 emissions and contribute to global climate change mitigation efforts.

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