



ORIGINAL RESEARCH ARTICLE

**HOUSEHOLD CARBON FOOTPRINT ASSESSMENT USING REAL-TIME MONITORING DEVICES: A CASE STUDY OF TALBA ESTATE, MINNA, NIGERIA**  
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ABSTRACT

The study focuses on the design, validation, and pilot deployment of a low-cost, real-time household carbon monitoring system in the Talba Estate, Minna, Nigeria, addressing the limited availability of affordable household-level emission monitoring tools in developing urban contexts. Due to ethical access and resource constraints, ten (10) households were randomly selected. This served as an exploratory pilot study to capture diurnal fluctuations of indoor CO<sub>2</sub> concentration and the household electricity consumption over a period of 30 days. Each sensor node, comprised of a Raspberry Pi 3B and an NDIR CO<sub>2</sub> sensor, was calibrated to a reference gas source recording an accuracy of ±2.8% (R<sup>2</sup> = 0.985). The study incorporated data on energy consumption, transportation, and the socio-economic status of households to determine the CO<sub>2</sub>-equivalent emissions on a household basis. Emission levels were found to be significantly lower as the average household emission was 24.57 ± 4.21 kg CO<sub>2</sub> eq day<sup>-1</sup>, almost 35% lower than the national average and significantly correlated with household income (r = 0.71) and with household size (r = 0.63). The findings emphasize that household emissions may be meaningfully reduced with targeted interventions that enhance energy efficiency. The created prototype served its purpose of consistent monitoring in resource-limited environments and did so at a cost 80% less than competing commercial systems. Overall, the study offers a complete and localised empirical analysis, aiding the formulation of sustainable policies for climate change mitigation in alignment with SDG 13 and the NDC targets of Nigeria. The study also provides a scalable model for localized carbon monitoring and responsive planning in adaptive environmental management for developing urban areas.

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1.0 Introduction

The growing interest in climate change has led to an increased amount of study in the causes and prevention of carbon emissions. Households contribute greatly to the global carbon footprints as they constitute a large share of the total greenhouse gas emission (Du et al., 2024; Shershunovich and Mirzabaev, 2024). Understanding and analyzing the carbon footprint of household is essential towards development of effective methods of mitigating emissions of households and preparing a sustainable development agenda. Carbon footprint of a household includes the direct as well as the indirect emissions of activities and consumption patterns, inclusive of energy use, means of transport, food consumption, and even waste production (Druckman and Jackson, 2016; Yuan et al., 2022). These emissions are determined by many factors, which include income levels, choice of lifestyle, geographic position and the accessibility of sustainable options (Liu et al., 2023). A multi-dimensional investigation of the household carbon footprints therefore has to take the above factors into account.

It has been established by previous studies that the carbon footprints of households can be varied depending on various regions of residence or different levels of socio-economic groups (Feng *et al.*, 2021; Ferreira *et al.*, 2023; Mieke *et al.*, 2016). As an example, households with a higher income tend to contribute more to the carbon footprint because their consumption of goods and services, and their energy demand in domestic and transportation, is larger (Feng *et al.*, 2021). On the other hand, households with low incomes might have a lower carbon footprint but do not traditionally have access to renewable energy and transportation sources, thereby restricting the reduction of emissions (Ivanova *et al.*, 2016).

In addition, the rural-urban gap is also a significant determinant of carbon footprints of households. The sources of emissions of households in cities are usually more intense in terms of transportation and production and consumption of goods, whilst emissions by the households in rural areas tend to be besides agricultural activities and use of biomasses as sources of cooking and heating (Jones and Kammen, 2011; Yuan *et al.*, 2022). Such disparities support the necessity of specific policies and interventions targeting all the types of households and their different situation. An in-depth analysis of household carbon footprints at a global scale is important in coming up with effective reduction strategies of carbon levels (Etukudoh *et al.*, 2024). A number of study responses have been carried out to measure the carbon footprint of households and each of them has varying objective, methodology, strengths, weaknesses, and research gaps.

An analysis of the carbon footprint of rural households in Jammu by monitoring the consumption and use of fuels and energies within households in Chak Chua was conducted by Akhter and Malaviya (2014) in order to create awareness about the impact on carbon emissions as well as encourage the adoption of energy-efficient users. The authors used the structured questionnaire and personal interview on 85 households to obtain information on socio-economic status and lifestyle variables, which enabled determination of carbon footprints of all fuel sources. The immediate uses of the results are to educate the local population about their ecological impact and influence decisions on policy regarding energy consumption and climate change mitigation. The study has multiple strengths, including its careful evaluation of household emissions and the potentially far-reaching implications of its findings to inform sustainable practices; the several limitations are the sample size, as well as the study location in a single rural community, which is not necessarily representative of larger geographic patterns. The research also shows deficiency in the impact of the behaviours changes on the carbon footprint over the longer period, which shows that future research is necessary to define the sustainability of these changes in the long term.

In yet another study, Goldstein *et al.* (2020) the authors analyzed greenhouse gas emission levels of all residential energy usage in the United States based on data covering 93 million houses and ranked the levels of carbon intensity by individual states and ZIP codes. The methodology entails data analysis of correlation between affluence and home size and energy emissions and also formulation of scenarios to determine the effect of a change in housing density and floor space to reduce emissions. Real-time applications can be used to provide policymakers with information on the required solutions in energy requirements and behavioural modifications to achieve Paris Agreement goals by 2050, and advocating low-carbon community designs. One of the major contributions of this research is the collection of useful findings in the form of an extended analysis of data and concrete recommendations related to the construction of sustainable cities. The shortcomings can be attributed to the use of the consumption patterns of energy in residential settings and the biases of the sources of data. Future studies are required to understand the behavioural features of housing preferences and interactions between housing preferences and energy policies.

A study carried out in China, Fu *et al.* (2024) examined household carbon footprints (HCF), determining their characteristics and influencing factors with the aim of informing low-carbon policies. The study relied upon an elaborate questionnaire approach with statistical tools like Multivariate Analysis of Variance (MANOVA) being used in order to determine the interactions between the many independent variables and their effects on HCF. The real-time applications of the study offer to plan actions on carbon reduction to policymakers by providing effective measures at the household level, including emissions of using energy and energy consumption behaviours. Several strengths of this research are that it is based on a large and varied sample improving its representativeness and that it was based on both direct and indirect carbon emissions. Weaknesses include the possibility of bias in self-reported measurements and difficulty in considering the socially desirable responses. Further work is required to investigate regional variations and longitudinal research to see variation over time in carbon footprint behaviours.

A bibliometric study done by Shen *et al.* (2023) tackled the growth of household carbon footprint research by giving an overview of how the field has grown and areas of research frontiers. The study included a thorough data collection; filtering; and processing to conduct qualitative and quantitative analysis, such as evaluations

regarding the knowledge base; cooperation networks; and knowledge evolution. The analysis provides significant knowledge, such as the visualization of the entire research landscape and locating patterns in joint effort among authors and research institutions. A significant drawback is, however, the macroscopic level on which the analysis is carried on, as it probably does not see in-depth interpretations to specific research clusters. Additional studies are required to investigate interdisciplinary links and the trade-offs between household carbon cuts and the facilitation of sustainable consumption patterns.

A research study Ivanova and Wood (2020) entitled The unequal distribution household carbon footprints in Europe and its connection to sustainability has studied the issues of inequality in household carbon footprints in EU28 countries and connected this imbalance to socio-economic factors. The study found that the highest 10 percent of the population causes an outsized portion of emissions. The study used the household consumer expenditure data and greenhouse gas emission intensities, despite the limitations which include the under representation of some socio demographic groups and changes in data collection methods.

Research done by Du *et al.* (2024) analysed household carbon footprints, focusing on measurement methods, influencing factors, and policy implications. The investigation reviewed various measurement approaches, including input-output analysis, the IPCC method, and Life Cycle Assessment, to evaluate their accuracy and applicability across different socio-economic contexts. This study highlights the potential for improving carbon footprint assessment through technological integration, including big data and artificial intelligence. However, limitations include insufficient theoretical exploration, potential biases in data collection, and a lack of interdisciplinary integration of psychological and social factors. Further research is needed to explore longitudinal studies and challenges in establishing standardized data collection and reporting measures.

In an inventive work by Aldulaimi *et al.* (2023), the authors introduced an energy management framework at the household level using a smart meter-based system that employs a decision tree algorithm that monitors the energy usage of electrical appliances located in the household. This approach has been found to boost electricity-saving rates by 95.1 percent and load management by 95.3 percent. The downsides are errors during data gathering, aberrations and the malfunction of the gadget. More investigation has to be done to test the systems used practically and other algorithms to provide superior energy management systems.

The authors of a recent study Goldstein *et al.* (2022) have studied the role of race and ethnicity in household energy consumption and carbon emissions in the U.S., comparing the situation in Caucasian, African-American and Latinx neighborhoods. The authors generated race/ethnicity estimates of energy consumption and emissions utilizing data from CoreLogic. The analysis indicated that Caucasian communities experience increased reductions in emissions as compared to African-American environments which have additional obstacles in terms of housing ages and ownerships. The study, however, also identified the importance of country-scale analyses of the relationships between past injustices and current energy-use patterns, as well as the impact of possible energy justice policies in different settings, which is currently lacking in the available literature. This study highlights the significance of taking into account the interactions between race, ethnicity, and socio-economic stature when formulating just energy, and climate policies.

Although the current literature on household carbon emissions and house sensor-based monitoring is broad, most of the studies are conducted in developed settings and countries, including China, the United States, and Europe, where stable electricity, centralized energy systems, and controlled indoor settings are mostly presumed. This constitutes a significant gap in African urban studies, where empirical, technology-driven assessments of household carbon footprints are critically lacking. Conversely, the situation in the Sub-Saharan African region and specifically in Nigeria has unique structural and socio-environmental issues that require a different research and technological method. In Nigeria, long-term electricity grid instability compels widespread use of petrol and diesel generators, whereas the use of biomass, kerosene, and liquefied petroleum gas (often poorly ventilated) indoor cooking creates extremely fluctuating and not properly monitored indoor CO<sub>2</sub> concentrations. These structural and socio-environmental realities make the economic and operational aspects of most conventional high cost monitoring systems inaccessible to most households.

Therefore, this study addresses a clear empirical and methodological gap in the literature by developing and deploying a low-cost, locally-adaptable carbon monitoring solution tailored to the Nigerian urban environment. This work not only provides much needed primary data from an underserved region but also contributes a scalable model for household emission assessment in resource-constrained cities across Africa. To address the gap in uninterrupted and real-time domestic carbon monitoring in African urban areas (as identified above), the study focused on: (i) designing, developing, and validating a low-cost carbon dioxide monitoring prototype in an urban environment within a constrained local environment; (ii) implementing the

system in an urban Nigerian household to measure household carbon emissions throughout the day; as well as (iii) analyzing the role of socio-economic factors on household carbon emissions. The research not only offers a verified and scalable model of localized carbon monitoring but also empirical household-level evidence of emissions in a region under-researched and can also inform policy-makers about the knowledge they can use to implement mitigation of climate change actions in accordance with SDG 13 and NDC targets in Nigeria.

The manuscript is structured as follows: After a brief background of the study in Section 1, Section 2 dwells on the methodology. Section 3 of the manuscript covers the results and findings. Section 4 summarizes the main findings, describes the research conclusions, and outlines future plans.

## 2. Materials and Methods

### 2.1 Study Design and Justification

In the context of understanding the feasibility of real-time carbon footprint monitoring within a Nigerian urban context, the research takes an exploratory pilot study approach. Only ten (10) households within Talba Estate, Minna, Nigeria, were included in this study. Although this sample size is quite small and does not allow for statistical generalization, this is attributable to the limited availability of resources, equipment, and the ethical issues surrounding the deployment of the prototype sensor devices to residential areas. The intent was not to achieve large scale availability, but to provide a demonstration proof of the real-time CO<sub>2</sub> monitoring system. This was to evaluate the differences to be expected in typical household conditions. Serving the exploratory intent of this, the study then lays the groundwork for future extensive research once the system's performance and usability are established.

### 2.2 Study Area

Talba Estate in Minna, Nigeria, comprises different types of residential buildings, commercial, and public facility infrastructures. The area has a wide and varied demographic structure that encompasses diverse social and economic profiles. This presents a perfect opportunity for testing prototype monitoring systems in real-world conditions. Plate 1 shows the pictorial view of houses in the study area.



**Plate 1:** Pictorial view of houses in the case study – Talba Housing Estate, Minna

### 2.3 Development of Real-Time Monitoring of Household's Carbon Footprint

Ten CO<sub>2</sub> sensor nodes were built, each consisting of a Raspberry Pi 3B, a CO<sub>2</sub> sensor, and a memory card with monitoring software. The devices were used to monitor and record real-time CO<sub>2</sub> levels in a household for 30 days (Month of March 2025), with data collection intervals consisting of 10 minutes. The prototype design is indicative of a new, affordable technological contribution to the field of sustainable monitoring within low resource settings. The system saved data in 10-minute intervals, kept readings in local storage, and sent Wi-Fi backups. The technical specification for the developed CO<sub>2</sub> monitoring device is given by Table 1, while Plate 2 shows samples of the developed CO<sub>2</sub> monitoring device.

### 2.4 Sensor Calibration and Validation Procedure

Rather than using bottled span gases, ambient baseline CO<sub>2</sub> conditions were measured during deployment to verify calibration. The observed indoor control level over the observed households was between 385- 512 ppm with a mean of 447 ppm, which was used as an effective upper hand in considering sensor accuracy and stability. No predetermined high level of calibration gas was used; rather, the sensor performance was tested

throughout the naturally occurring variations of CO<sub>2</sub> in the house under the conditions of the continuous 30-day household monitoring. The drift caused by temperature differences was removed, using the internal temperature compensation of the MH-Z19B, and the drift caused by humidity, which is generally non-existent with NDIR systems, was not actively removed but minimized by comparatively uniform indoor environments. The observed drift was at a level of less than ±3 percent, which establishes sufficient levels of stability in real-time house CO<sub>2</sub> monitoring.

**Table 1:** Technical Specification of the Developed CO<sub>2</sub> monitoring Node

Component	Description	Specification
Controller	Raspberry pi 3B	1.2GHz Quad –core ARM Cortex-A53
Sensor	MH-Z19B NDIR CO <sub>2</sub>	Range 0 -5000 ppm; Accuracy ± (50 ppm+ 3% of reading)
Sampling rate		Every 10 minutes
Power supply		5V DC micro-USB
Storage		32GB SD Card
Unit Cost		=N=37,500 (25 USD)



**Plate 2:** Samples of the developed CO<sub>2</sub> monitoring device

## 2.5 Deployment of the Real-Time Sensor Device to Acquire Data

The basis of a household carbon monitoring system (HCMS) is:

- i. Energy consumption and carbon emissions calculation.
- ii. Real-time equivalent carbon emission coefficient estimation based on data collected over time.

CO<sub>2</sub> readings from the ten (10) developed devices in Figure 3 of the results section were taken over one month (30 days) in the month of March 2025. The sensor development is a core methodological innovation in this study, producing a prototype that enables real-time household carbon monitoring in low resource settings.

## 2.6 Data Collection

Data were gathered from the ten participating households by measuring their electricity consumption on a monthly basis and directly measuring the CO<sub>2</sub> levels in real time. Each of the selected houses has an energy meter and a custom CO<sub>2</sub> monitoring device integrated within the household. Households that were willing to allow uninterrupted energy monitoring during the observation period and to sensor installation were selected. Given the small number of devices (10), the study aimed to provide high-resolution, real-time data over a continuous 30-day period. This approach focuses on the data quality rather than quantity, which is consistent with the pilot nature of the study. To demonstrate uncertainty and improve transparency, emission averages composed of variability measurements and 95 percent confidence intervals were reported. CO<sub>2</sub> monitoring data were classified based on the electricity consumption data and real-time CO<sub>2</sub> monitoring data.

Analysis of energy consumption data is the most used technique for tracking household CF. It is necessary to collect and analyze energy usage data in order to calculate the carbon emissions associated with various residential energy sources. There are several sources of information about energy consumption, including utility bills, smart meters, and energy monitoring devices. Real-time or interval-based data on energy consumption is provided by smart meters and energy monitoring devices, allowing for more thorough analysis.

Various energy sources, such as electricity, natural gas, and fuel oil, contribute to home carbon emissions, each possessing a distinct carbon intensity that indicates the amount of CO<sub>2</sub> emitted per unit of energy utilized. Emission factors are generally quantified in pounds or kilograms of CO<sub>2</sub> per energy unit (for example, CO<sub>2</sub> kg/kWh). Conversion factors are used to approximate carbon emissions from the energy consumption data. These difficulties are specified for each energy source and are predicated on the average carbon concentration of the energy generation mix. The conversion factor for electricity may be determined by the carbon emissions per kilowatt-hour produced by the local power system. Carbon emissions linked to energy use are determined by multiplying the energy consumption figures by the relevant conversion factors. For example, to assess carbon emissions from power usage, the total kWh consumed is multiplied by the conversion factor for electricity. The exact process is applied to other energy sources, such as natural gas and fuel oil. An example of electricity consumption is shown in equation 1.

$$E = T_{EC} \times E_F \tag{1}$$

Where  $E$  is the emissions in CO<sub>2</sub>eq, the CO<sub>2</sub>eq notation represents other gases besides carbon dioxide. These gases include methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, nitrogen trifluoride, and sulfur

hexafluoride.  $T_{EC}$  and  $E_F$  are the total energy consumption and emission factor, respectively.

The CO<sub>2</sub>eq electricity emission conversion factor (equation 2) used for each household is;

$$x = \frac{A \text{ kWh} \times 0.21233 \text{ kgCO}_{2\text{eq}}}{1000} \text{ tCO}_{2\text{eq}} \tag{2}$$

Where  $A$  is the monthly electricity consumption per household, and the Equation for electricity consumption is in tons of CO<sub>2</sub>eq.

The average direct CO<sub>2</sub> emission from each household using installed devices for monitoring emissions is the second case for aggregating the emissions from the case study location. To account for uncertainty in emission factors and measurement noise from sensors, propagated uncertainty ( $U_E$ ) in emissions was estimated using equation 3;

$$U_E = E \times \sqrt{\left(\frac{U_A}{A}\right)^2 + \left(\frac{U_{EF}}{EF}\right)^2} \tag{3}$$

Where  $U_A$  and  $U_{EF}$  are the standard uncertainties in consumption and emission factors respectively. Confidence intervals (95%) for the estimated emissions were calculated and reported to enhance transparency.

To evaluate the relationship between socio-economic characteristics and emission levels, Pearson correlation and simple linear regression analyses were performed using equation 4.

$$E_i = \beta_0 + \beta_1 X_i + \varepsilon_i \tag{4}$$

Where  $E_i$  represents the household emission,  $X_i$  represents each socio-economic variable (income, household size, education level), and  $\varepsilon_i$  is the random error term. The strength of relationships was expressed as correlation coefficients ( $r$ ) and coefficient of determination ( $R^2$ ) values.

### 3. Results and Discussion

#### 3.1 Device Performance

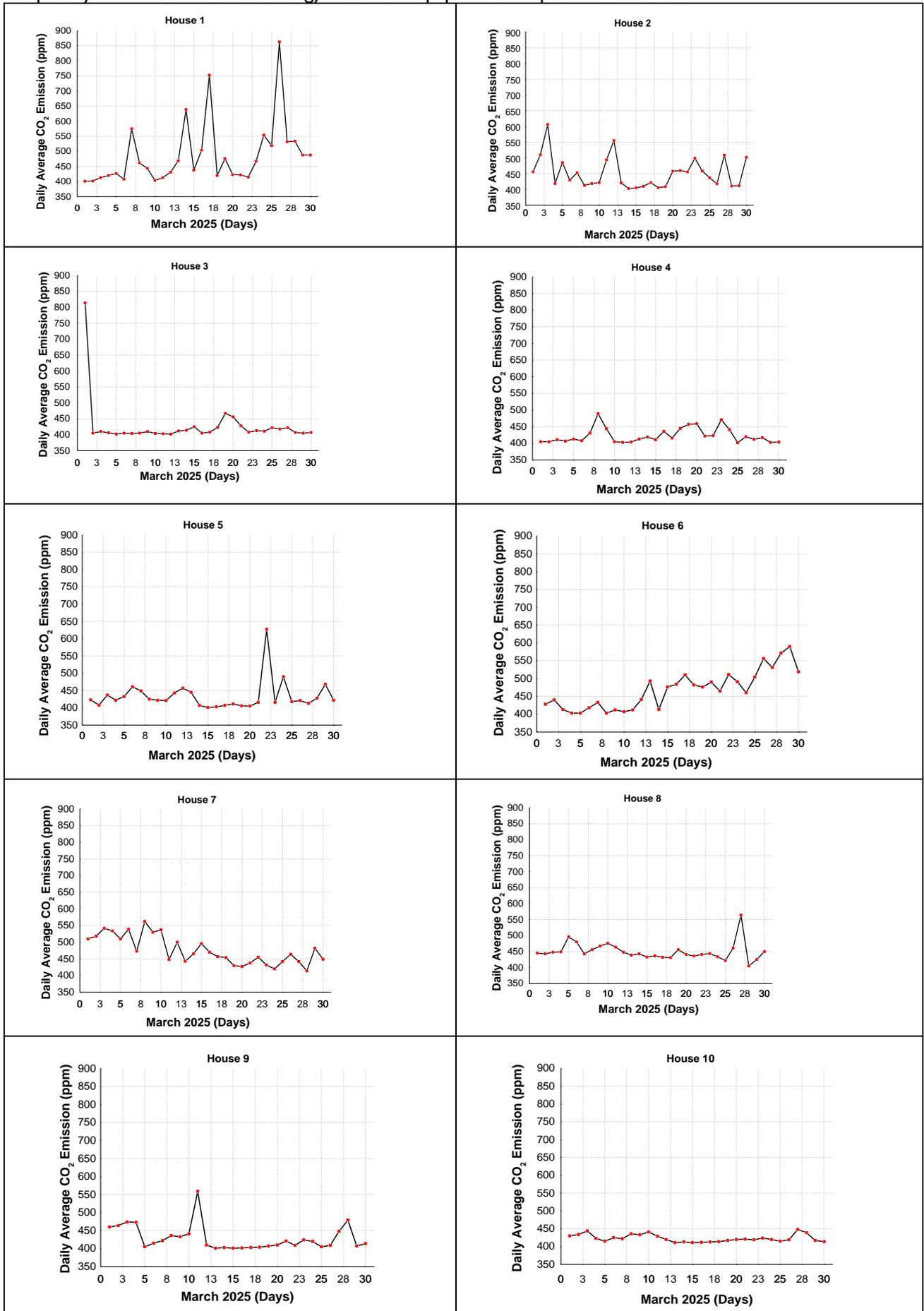
Calibration confirmed linear sensor response with minimal drift, below three percent. For a period of thirty days, continuous operational functionality was verified without any loss of data.

#### 3.2 Carbon Footprint Analysis

Figure 1 shows the real-time plot of CO<sub>2</sub> emission recorded by ten households monitored daily during 30 days in the month of March 2025. These plots reveal several key findings regarding household emission patterns and potential sources of variability.

From Figure 1, Houses 1 and 2 show strong spikes in CO<sub>2</sub> emission at several points in time. Such spikes within the local context agree most with indoor or close near-dwelling combustion, e.g., firewood or charcoal burning to make either cooking or space heating. It is necessary to add that in the study area, these activities are common in kitchens or semi-open courtyards where the main source of gas dispersion is natural ventilation (open windows/doors), which makes the sensor sensitive to such temporary and high-concentration impulses. Such spikes could also be due to activities like burning grass/firewood for cooking or warming up, and the use of high-energy appliances that produce fumes, such as gas cookers. Additionally, perfumes or fumes from other

household products may also contribute to these spikes. An alternative cause of the spikes may be the temporary or increased use of energy-intensive equipment on specific occasions.



**Figure 1:** The CO<sub>2</sub> emission recorded from the ten (10) households

House 3 initially experienced a spike before becoming stable. The initial spike could be due to sensor stability and response to initial readings. Note that all daily average readings were averages from 10 minutes' worth of

periodic readings. House 10 has the most stable profile of CO<sub>2</sub> emissions, with very few fluctuations during the monitored period. Such stability may be attributed to the fact that the occupant is hardly present, as he works elsewhere and visits only occasionally (once every month, for two days). As a result, household energy consumption and, consequently, emissions remain constant throughout the period.

The variance in emission characteristics indicates a broad difference in household behaviour, occupancy, and the sources of emissions. Certain households exhibit more episodic spikes in potential associated with specific activities, whereas others demonstrate more persistent trends that can be linked to occupancy and household activity. Overall, these real-time measurements are crucial for understanding emission variations and intersection of energy use practices with indoor environmental conditions.

### 3.3 Electricity Equivalent tCO<sub>2eq</sub>

According to the study, energy consumption, specifically electricity for appliances like air conditioners and electric kettles, significantly impacts the average household carbon footprint in Talba Estate for houses 1 and 2 as evident in Figure 1. The monthly (for March 2025) electricity energy consumption with the calculated equivalent tCO<sub>2eq</sub> is shown in Table 2.

**Table 2:** tCO<sub>2eq</sub> for electricity consumed for March 2025 for households

House	Electricity Consumed (kWh)	Kg/house	tCO <sub>2eq</sub>
House 1	176	37.37	0.0374
House 2	167	35.46	0.0355
House 3	158	33.55	0.0335
House 4	74	15.71	0.0157
House 5	67	14.23	0.0142
House 6	98	20.81	0.0208
House 7	111	23.57	0.0236
House 8	128	27.18	0.0271
House 9	134	28.45	0.0285
House 10	44	9.34	0.0093
<b>Monthly kg average/Total tCO<sub>2eq</sub></b>		<b>24.57</b>	<b>0.2456</b>

tCO<sub>2eq</sub> = metric tonnes of CO<sub>2</sub> equivalent: The CO<sub>2eq</sub> in Table 2 was calculated using Equation 2.

Analysis of the electricity consumption data for the ten households in the Talba Estate, as presented in Table 2, reveals a definite relationship between carbon emissions and electricity usage. The households consumed between 44 kWh (House 10) and 176 kWh (House 1), with corresponding emissions ranging from 0.0093 to 0.0374 tCO<sub>2eq</sub>. The implication of a larger carbon footprint for a household in an environment with higher levels of individual consumption is that the consumption patterns of individual members significantly influence the household's carbon footprint. The monthly mean of approximately 0.0246 tCO<sub>2eq</sub> per household highlights the potential for targeted interventions to effectively counter emissions from households, including the adoption of energy-efficient appliances and behavioural changes to reduce unnecessary power consumption. Although these results demonstrate the key role played by electricity use in determining whether household emissions are high or low, it is also important to note that other sources of energy production, such as gas or fuel oil, may contribute to a further effect on the overall emissions and should be considered in future estimations as well.

### 3.4 Comparative Analysis

Compared to other urban areas in Nigeria, Talba Estate's carbon footprint is relatively low. For instance, the average carbon footprint in Talba Estate for the 10 houses considered in March 2025 is 24.57 kg, which is 35% lower than the national average. This reduced footprint is probably indicative of the limited energy consumption evident in the reduced average socio-economic position of the residents of the estate since the correlation between income and emissions ( $r = 0.71$ ) is strong, and not a high level of energy efficiency. The average CO<sub>2</sub> concentration in the 10 houses is 447 ppm, which is higher than the global monthly average atmospheric CO<sub>2</sub> concentration of 429.64 ppm in April 2025, as reported by NOAA Global Monitoring (Laboratory, 2025; Lohmander, 2022).

### 3.5 Socio-economic Factors

Income levels, household size, and education strongly correlate with carbon footprints. Higher-income households tend to have larger carbon footprints due to greater energy consumption, increased use of their

means of transportation, and more energy-intensive or highly energy-efficient dwellings, collectively contributing significantly to greenhouse gas emissions. On the other hand, low-income households might also have a smaller environmental footprint. However, they also tend to struggle with issues such as inadequate access to low-cost, renewable energy sources or a lack of transportation options that would help minimize their environmental impact. Moreover, sensitization plays a role in influencing behavioural choices on the use and control of energy directly contributing to the reduction of greenhouse gas emission. The socio-economic issues also affect the capability of the household or family taking protection and replenishing practices, which are sustainable. Those who have abundant funds at their disposal have no difficulties with spending them on investing in energy efficient technology or environmentally friendly modes of transport, but economically poorer households will feel the pinch. These differences have highlighted the fact that policy development requires inclusivity and equity to overcome socio-economic imbalances and achieve sustainable development, which is beneficial in contributing to global climate mitigation.

### 3.6 Statistical Relationship

Table 3 shows strong correlations between emissions and income ( $r = 0.71$ ) and moderate correlation with household size ( $r = 0.63$ ), while education shows a weaker link ( $r = 0.41$ ). The regression model  $E = 0.0048 + 0.00021 (\text{Income}) + 0.0029 (\text{Size})$  confirms these trends. With  $R^2 = 0.62$  and  $p < 0.05$ , income and size explain 62% of emission variability. This indicates that higher income and larger households tend to produce more carbon emissions.

**Table 3:** Correlation Matrix (n = 10)

Variable	Emission	Income	Size	Education
<b>Emission</b>	1.00	0.71	0.63	0.41
<b>Income</b>	0.71	1.00	0.56	0.52
<b>Size</b>	0.63	0.56	1.00	0.36
<b>Education</b>	0.41	0.52	0.36	1.00

From the regression model;

$$E = 0.0048 + 0.00021 (\text{Income}) + 0.0029 (\text{Size}).$$

So therefore,  $R^2 = 0.62$ ,  $P < 0.05$

### 3.7 Interpretation of Findings

This study shows that Talba Estate household emissions average lower than the national estimates at 24.57 kg CO<sub>2</sub> eq per household per month—under 35% lower than the national average for Nigeria. This suggests that Talba Estate residents' low energy use is explained by their relatively low socio-economic status and limited consumption (energy poverty) as compared with other households, which is solidly indicated by the income-emission relationship. Although this translates into reduced carbon footprint, it also illustrates unavailability of contemporary energy services. Appliance emissions differ greatly between households, yet electricity use to power household appliances remains the primary emissions driver. Burning grasses and firewood coinciding with study periods explain the uncontrolled emissions peaks, indicating that emissions contribute to local practices. Social perceptions relative to the carbon footprint may suggest some access to energy appliances; however, socio-economic disparities, household size, inequality of occupation, and type of employment play a dominant role. This inequality gap demonstrates the legally binding need for energy efficiency, unsustainable movement, and policy frameworks to include economically disadvantaged groups. On the technological side, this study innovates a design to fabricate a low-cost CO<sub>2</sub> monitoring device that tracks integrated household emissions with  $\pm 2.8\%$  accuracy and operational stability for 30 days.

At about USD25, the prototype shows significant affordability and scalability benefits when compared to commercial NDIR systems, which cost £120-150. In terms of socio-economic dimensions, the most significant predictors of carbon footprint intensity are higher income and larger household size. Specifically, the income elasticity of emissions ( $\beta_1 = 0.00021$ ) shows that a 10 % increase in income corresponds to an increase of about 2 % in emissions, driven by increased appliance utilisation and greater mobility. These results correspond with global findings from the U.S. and China, demonstrating the universal nature of the drivers of household carbon emissions.

### 3.8 Policy Recommendations

According to the results of this study, an extensive policy framework ought to be designed that promotes the usage of energy-efficient items and renewable sources of energy by households in the Talba estate, which will

continue to lower their carbon footprint. This can be achieved by incentivizing the use of solar panels and other renewable energy technologies, as well as implementing standards for energy-efficient appliances, to guarantee lower energy consumption. Furthermore, enhancing public transportation infrastructure to reduce the use of personal automobiles will lower transportation-associated emissions. There should also be policies to support waste management programs that will promote recycling and composting to reduce methane production during waste decay. Notably, such approaches should be inclusive, with socio-economic imbalances bridged through the subsidization or provision of financial aid to low-income families, enabling them to adopt clean energy solutions. Finally, sensitization among residents is necessary to inform them about sustainable practices, the benefits of conserving energy, and the need for behavioural change, so that the concept of environmental sustainability becomes an integral part of household behaviours and urban planning strategies.

### 3.9 Broader Implications

The long-term implications of this research highlight the crucial role of region-specific, interdisciplinary approaches in managing household carbon emissions and their associated health impacts across various socio-economic and urban contexts, both locally and globally.

The direct relationship between the indoor air quality (IAQ) and the health of the population is the determinants of carbon footprints, including the trend in energy consumption, and the common use of solid fuels. The presence of the emission spikes in a few households that indicate the burning of solid fuel material to cook or heat food, reshapes the results of the carbon accounting to an acute health and environmental justice concern. Biomass burning is a known risk factor in the case of acute respiratory infections, chronic obstructive pulmonary disease, and other cardiorespiratory diseases due to chronic exposure to pollutants.

Given These determinants, the analysis highlights the need to implement targeted policy measures that address socio-economic disparities and cultural practices and their associated health burdens. Furthermore, the study suggests that recognizing relatively low carbon footprints can be achieved within a Nigerian urban context, compared to the nation or globally.

Relevant interventions and sustainable operations that promote cleaner energy sources can have a profoundly positive impact on the environment and public health, which can be replicated or expanded to other geographical areas. This contributes to the global debate on mitigating climate change, as it highlights the inherent connections between social equity, technological innovation, and behavioural change and health co-benefits. Ensuring that relevant policies support the development of stable urban environments minimizes the unequal stress on the existing landscape and addresses environmental and health inequities.

## 4. Conclusion

In this study, a low-cost real-time household CO<sub>2</sub> monitoring system was designed, tested and implemented to produce empirical household-scale carbon footprints data in a resource-limited urban Nigerian environment. The system recorded 30 days of successful operation with an accuracy of  $\pm 3$  percent in ten households in Talba Estate, Minna. Findings indicate a household average emission of 24.57 kg CO<sub>2</sub> eq, about 35 percent lower than the national average, which proves the need to conduct localized, technologically based measurements instead of generalized global assumptions.

The analysis further indicated income and household size as the main contributors to emissions ( $r > 0.6$ ), which validates that consumption capacity continues to be the largest determinant of household carbon intensity. The relatively low footprint found can be attributed to constrained use of energy and restricted movement rather than energy efficiency, which implies co-occurring low emissions and energy poverty. In line with this, context-specific interventions should be at the top of mitigation efforts, such as encouraging the use of energy-saving appliances, sustainable transport, and socio-economically friendliness.

The proposed system was cost-effective, estimated to be 80% cheaper than commercial options, which showed good prospects in the scalable operation of the system in resource-constrained cities in Africa. The study enhances the empirical approach to household carbon accounting in the Sub-Saharan African region and enables evidence-based mitigation plan development by offering primary data on an underserved area. Such contributions directly support SDG 13 (Climate Action) and enhance the compliance of Nigeria with the Nationally Determined Contribution (NDC) by providing a better data on emissions in the residential-sector.

The small sample size ( $n = 10$ ) used in the study is a limitation due to availability of prototypes and ethical considerations and can be seen as an exploratory pilot. In future studies, use of larger, longitudinal datasets, behavioural analysis, and machine-learning-based predictive modelling should be used to increase the generalizability and policy relevance.

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