Emissions from fuel combustion by stoves in residential kitchens in São Paulo - Brazil

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Abstract. This study investigates greenhouse gas (GHG) emissions and indoor air quality associated with residential cooking practices in São Paulo, Brazil. Measurements were conducted in 30 households, focusing on kitchens using natural gas (NG) or liquefied petroleum gas (LPG) stoves. A measurement protocol was developed to assess emissions of carbon dioxide (CO_2), methane (CH_4), and nitrogen oxides (NOx) under different operational conditions. Emission rates and factors were calculated using mass balance approaches, considering kitchen volume, air exchange rates, and gas concentrations. The results show different behavior for the type of fuel, especially for methane, which has a significant response to the use of NG, unlike LPG. It was also possible to observe a difference between the temporal variability cycles, as the burners responded quickly to the increase in concentration, while the oven showed a delayed increase observed in the environment. There was a high variability in the concentrations in the different residences, which may be associated with factors such as the age of the stove, model, leak and internal influence. The emission factors obtained were three times higher than the IPCC considering only the ~~close~~ consistent values, but when considering the outliers it is up to 10 times higher for CH_4 in the case of NG. For CO_2 the factor obtained was lower than the IPCC. The findings highlight the importance of considering fuel type in evaluating GHG emissions from residential cooking and the need for robust data on residential emissions in Brazil.

1 Introduction

Carbon dioxide (CO_2), methane (CH_4), and nitrogen oxides (NOx) are emitted during fossil fuel combustion, material production (e.g., steel, cement, plastics), and food cultivation. CO_2 and CH_4 are major greenhouse gases, significantly contributing to global warming (IPCC, 2022b). NO_2 primarily affects health and is a key precursor of tropospheric ozone (IPCC, 2022a; WHO, 2021). Additionally, these gases impact the atmospheric radiation budget (IPCC, 2022a).

Indoor ambients, such as kitchen, can have their air quality significantly affected by concentrations of compounds such as NO_2, CO_2 and CH_4. These gases can have different impacts on human health depending on their concentration, the time of exposure, and on climate conditions. NO_2, a pollutant known for its health effects, can cause irritation to the lungs, eyes and throat in high concentrations during short-term exposure, while respiratory effects can be severe in the long term (WHO, 2021). CO_2 and CH_4, although not strongly associated with health risks, can cause fatigue and possible mental confusion in confined environments and in high concentrations (OSHA, 2021; NIOSH, 2022). In the case of CH_4, in cases of cumulative risk, there is also an explosive risk (NIOSH, 2022).

According to the World Meteorological Organization (WMO) Greenhouse Gas Bulletin (No. 20 – October 28, 2024), the global average CO_2 concentration increased from 417.9 ppm, in 2022, to 420.0 ppm in 2023. Methane (CH_4) levels also exhibited a significant increase, going from 1923 ppb to 1934 ppb, between 2022 and 2023 (WMO, 2024). The WMO reports that this persistent increase reflects the ongoing impact of human activities. Anthropogenic sources contribute approximately 4.7 billion tonnes of CO_2 annually (WMO, 2024).

As a signatory of the United Nations Framework Convention on Climate Change (UNFCCC), Brazil is comitted to submitting its National Inventories of Greenhouse Gas (GHG) Emissions. In its most recent National Inventory published in 2020 with base year up to 2016, Brazil has been committed to the implementation of the "2006 IPCC Guidelines for National Inventories of Greenhouse Gas Emissions", being organized into five sectors: Energy; Industrial Processes And Use Of Products (IPPU); Agricultural; Land Use, Land Use Change And Forests (LULUCF) and Waste. However, Brazil reports Agriculture and LULUCF separately due to their significant impact on the country's emissions, whereas the IPCC groups them under the Agriculture, Forestry, and Other Land Use (AFOLU) sector (MCTI, 2020; IPCC, 2019).

The latest National Inventory contemplated in the Fourth National Communication presents the GHG emissions of Brazil from 1990 to 2016. In 2016, Brazil's emissions totaled 1,467 Tg CO_2e, with CO_2 being the most emitted GHG. The Agriculture sector contributed 33.2% of total emissions, the Energy sector 28.9% and the LULUCF sector with 27.1%. IPPU and Waste contributed smaller portions of emissions, representing 6.4% and 4.5%, respectively (MCTI, 2020).

In 2016, the state of São Paulo's energy sector was responsible for 59% of GHG emissions, around 90 Mt CO_2e. These emissions are mainly fed by transport (vehicular emissions) - National Inventory of Greenhouse Gas Emissions, Brazil, 2022 (SEEG, 2024). The city of São Paulo follows in the same direction as the state of São Paulo, with the largest emissions from the energy sector, 11 Mt CO_2e in 2023. In this sector, the biggest emitter in the city is transport, followed by air and residential sectors (classified as IPCC Category 1A4b in the national inventory) (SEEG, 2024).

According to SEEG (2024) estimates, 2,296 Mt of CO_2e were emitted in 2023, distributed as follows: Deforestation (46%), Agriculture (28%), Power Generation (18%), Waste (4%) and Industrial Processes (4%). Analyzing only the energy sector, we have the following breakdown: Transport (53.3%), Industry (16.2%), Fuel Production (13.2%), Residential (6.4%) and Others (11.2%). The impact of the residential sector on greenhouse gas emissions is approximately 1.2%.

The information in the Brazilian Energy Balance summary report for 2020 highlights the diverse sources of energy consumption in residential settings across the country, emphasizing the dominance of electricity at 46%, throughout the entirety of the household premises. However, the reliance on other fuels like firewood (26.6%), Liquefied Petroleum Gas (LPG) (24.4%) and Natural Gas (NG) at 1.5% varies significantly by region (EPE, 2020).

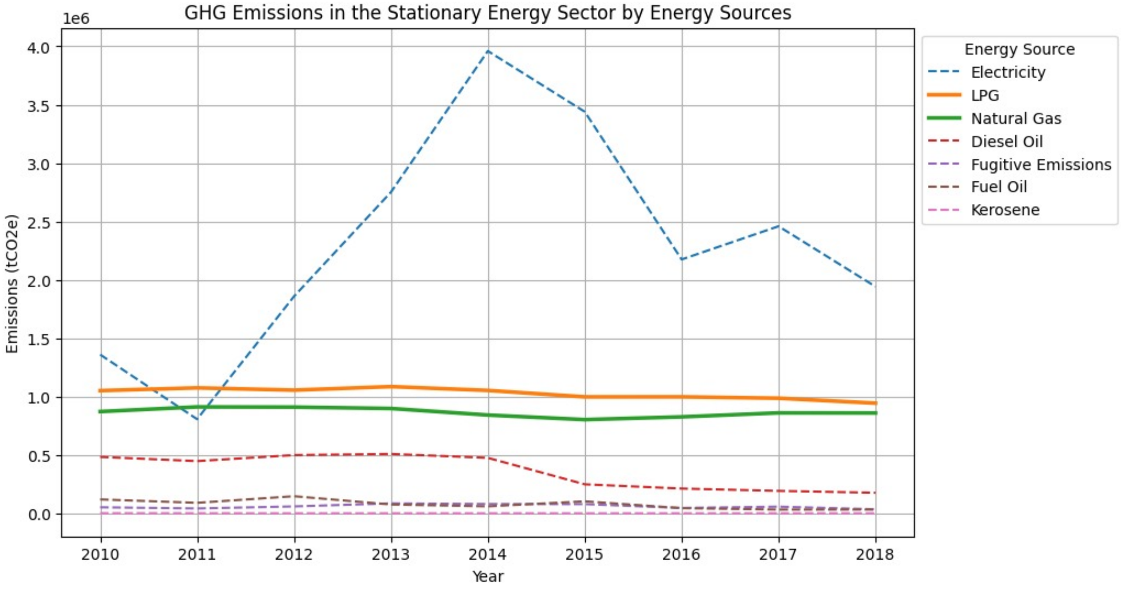

Figure 1. GHG emissions for energy sources (Based on Anthropogenic Emissions and Removals of Greenhouse Gases Inventory in the São Paulo Municipality 2010 – 2018). Source: SVMA (2022).

In the Southern Region, colder climates and traditional practices lead to higher firewood usage, while the North and Northeast Regions show a tendency towards solid fuels due to economic constraints. LPG, although accounting for a smaller percentage of total energy consumption, plays a crucial role, especially as the primary cooking fuel with over 70% of its use in households. This demonstrates how regional characteristics and economic factors shape energy preferences in Brazilian households (Gioda, 2019).

The Anthropogenic Emissions and Removals of Greenhouse Gases Inventory in the São Paulo Municipality presented GHG emissions, between 2010 and 2018, from stationary energy sources, including electricity, LPG, natural gas, diesel oil, fugitive emissions, fuel oil, and kerosene (SVMA, 2022). Figure 1 shows electricity emerging as the dominant source, with a notable spike in 2014, due to increased reliance on thermal power plants during a drought, significantly impacting residential emissions. LPG and natural gas show stable trends, reflecting their consistent use in cooking and heating, particularly in the residential sector. Diesel oil, fuel oil, and kerosene contribute minimally but remain relevant for specific applications in rural or less urbanized areas. Fugitive emissions, primarily from natural gas distribution, add a steady but smaller share. The residential sector is a significant contributor to these emissions, driven by its reliance on electricity, LPG, and natural gas (SVMA, 2022).

Studies, including the one conducted by Cameron et al. (2022) using the MESSAGE-Access model, emphasize the benefits of induction stoves. These stoves are not only efficient in reducing GHG emissions, but also improve health outcomes by minimizing indoor air pollution. However, they emphasize that this transition depends on reliable electricity and adequate infrastructure, especially in developing regions where energy systems are still evolving (Cameron et al., 2022).

Lebel et al. (2022) estimated total emissions of 28 Gg CH_4/year (28,000 tonnes) from residential sources in the United States, which exceeds the estimates provided by the U.S. EPA. Their detailed breakdown revealed that burners emit 2.7 Gg CH_4/year (2,700 tonnes) during steady-state-on conditions and 1.1 Gg CH_4/year (1,100 tonnes) from on/off pulses, while 21.2 Gg CH_4/year (21,200 tonnes) is attributed to steady-state-off emissions from stoves, indicating substantial leakage even when appliances are not in active use (Lebel et al., 2022). Complementary findings by Merrin and Francisco (2019) estimated 2.7 Gg CH_4/year (2,700 tonnes) from burner use, aligning closely with Lebel et al. (2022), but also reported emissions of 3.3 Gg CH_4/year from stoves (3,300 tonnes) and 5.0 Gg CH_4/year from ovens (5,000 tonnes), suggesting that multiple components of cooking systems contribute significantly to overall methane release (Merrin and Francisco, 2019). Similarly, Fischer et al. (2018) identified 1.6 Gg CH_4/year (1,600 tonnes) from general cooking equipment in California alone, reinforcing the relevance of regional assessments (Fischer et al., 2018).

Globally, the residential sector contributes less to GHG emissions than larger sectors such as transport and industry, but it is important to understand its influence on these emissions to address the challenges related to climate change and health (IPCC, 2022a; WRI, 2024). ~~Thus, given the lack of indoor data on both concentration and emissions, this research aims~~

The objective of this research is to gather data on cooking fuel usage in Brazilian kitchens, focusing on the two most commonly used sources: liquefied petroleum gas and natural gas. ~~Considering to analyze~~ The study seeks to evaluate the emissions of CO_2, CH_4, and NOx, ~~emitted by~~ resulting from the use of gas stoves in ~~cities~~urban areas, and to analyze the associated indoor air quality, expanding the analysis of data on indoor concentrations and emissions, which is limited.

2 Materials and Method

2.1 Denifition of sample object components

Measurements were carried out in the kitchens of Brazilian homes, more specifically in the city of São Paulo. This study focused on different types of stoves and specifically analyzed natural gas or LPG-powered stoves, most of which have 2 to 6 individual cooking elements (burners). These burners were the main objects of analysis due to their direct impact on energy consumption and emissions associated with their use.

In addition, two types of kitchens were evaluated during the sampling process: open and closed concepts. Open concept kitchens are integrated with other areas of the house, such as living or dining rooms, without physical partitions between spaces (Fig. 2a); in this case, it was necessary to put a plastic seal. In contrast, closed concept kitchens are entirely separated from other areas by walls and doors, providing a more enclosed environment (Fig. 2b).

2.2 Region of study and distribution of residence

The city of São Paulo is known as the most populous city in Brazil, according to the 2022 census, the population of São Paulo is 11,451,999 people, and adding with the cities of the metropolitan region of São Paulo comes to around 20 million inhabitants (IBGE, 2025). Most of the volunteer residences for the study were located in the city of São Paulo, with additional

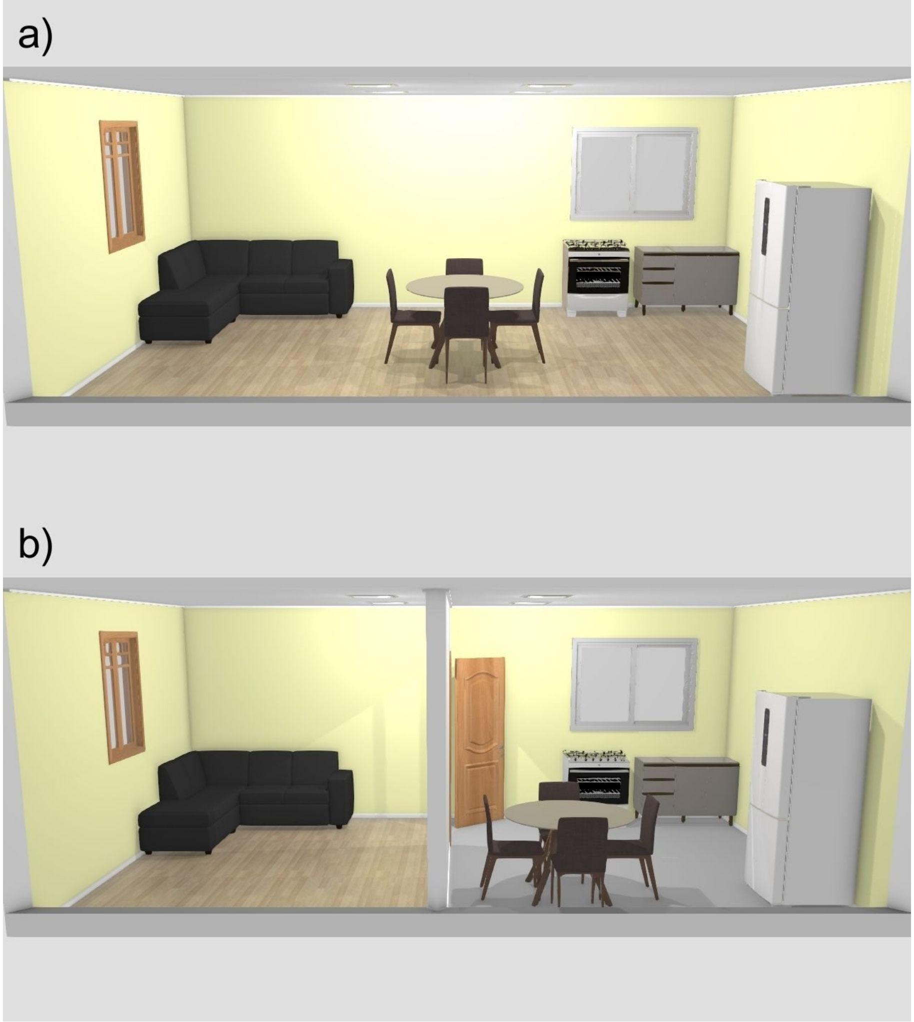

Figure 2. Types of kitchen concepts. **(a)** Open concept kitchen design. **(b)** Closet concept kitchen design.

samples from neighboring cities in the metropolitan region, as shown in the map of participant residences (Figure 3). The map highlights the Metropolitan Area of São Paulo (MASP), with the city of São Paulo marked in red. The triangles represent the distribution of volunteer residences, indicating that most data collection occurred within the city of São Paulo.

The participating residences included apartments and houses, reflecting the variety of housing in São Paulo. 60% of the samples were collected in apartments, while 40% were in houses, which usually had larger kitchens. Approximately 67% of the kitchens were closed concept, while 33% were open concept, requiring sealing with plastic, and the samples of cooking fuels were from Natural Gas (NG), approximately 67% and Liquefied Petroleum Gas (LPG) was approximately 33%.

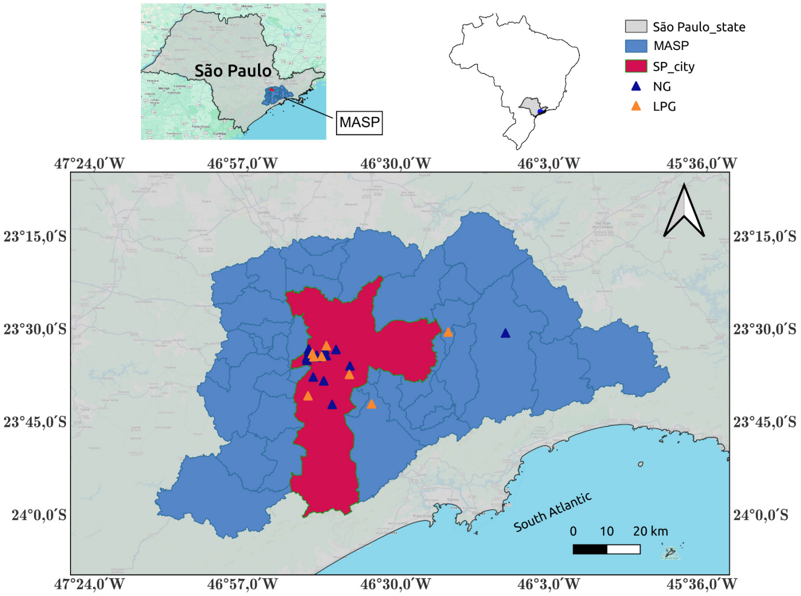

Figure 3. Map of the São Paulo state with highlights of the São Paulo (SP) city and the spatial distribution of residences. Source: Own author, map generated in QGIS 3.22 – QGIS Geographic Information System with shapefile São Paulo City from the Brazilian Institute of Geography and Statistics (IBGE).

2.3 Measurement protocol

Measurement Protocol for Evaluating Greenhouse Gas (GHG) Emissions in Brazilian Households was developed based on international studies and tailored to local conditions. The methodology applied follows a series of steps to ensure the accuracy and reliability of the data collected and aims to verify the emissions from the use of natural gas in the cooking process. The measurements were carried out in kitchens of volunteer residences in the city of São Paulo and region, in total the experiment was conducted in 30 properties. The key stages of the protocol with full description is in the Supplementary Material Section.

~~The cycles and~~ The experimental modules were organized based on the methodological framework proposed by Lebel et al. (2022), with adaptations made to accommodate the specific context of Brazilian households. The nomenclature and respective cycle durations of each module ~~used in the experiments~~ are detailed in Table 1~~, along with the specific modules assigned to each cycle. The cycle durations were adapted from the study conducted by Lebel et al. (2022) and tailored to the context of Brazilian residences. Preliminary tests conducted prior to the measurements identified patterns that influenced the timing~~. These durations were refined through preliminary tests conducted before data collection, which identified behavioral and operational patterns influencing the temporal configuration of each module (Lebel et al., 2022). ~~For example, the "Inject Gas" module was performed over a period of 4 minutes at the beginning of the measurements. This duration was selected based on~~

Table 1. Module, cycles, and time of each module performed in the residences.

Module	Cycle	Time	Module	Cycle	Time	Module	Cycle	Time	Module	Cycle	Time
Back	1	2 min	Back	2	2 min	Back	3	2 min	Back	4	2 min
Inj_gas	1	4 min	St_OFF	2	2 min	St_OFF	3	2 min	St_ON	4	5 min
St_OFF	1	2 min	St_ON	2	5 min	St_ON	3	5 min			
St_ON	1	5 min	Off	2	2 min	Off	3	2 min			
Off	1	2 min	On	2	1 min	On	3	1 min			
On	1	1 min	Off	2	2 min	Off	3	2 min			
Off	1	2 min	On	2	1 min	On	3	1 min			
On	1	1 min	Off	2	2 min						
Off	1	2 min	On	2	1 min						
On	1	1 min									

~~observations that CO_2 concentration values stabilized within this timeframe, allowing for accurate calibration and air exchange rate assessment.~~

In the "~~State~~ STATE ON" module, a duration of ~~5 minutes was determined to be sufficient for CO_2 and CH_4 concentrations to stabilize~~ five minutes was established as adequate for the stabilization of CO_2 and CH_4 concentrations while the burner ~~was active. For~~ remained active. In the "ON" and "OFF" modules, distinct gas ~~behavior patterns~~ emission dynamics were observed: a rapid increase in ~~gas~~ concentrations during the "ON" phase, followed by a gradual decay during the "OFF" phase. These changes were effectively captured within 1 minute for the "ON" module and 2 minutes for the "OFF" module.

~~The modules were distributed across four distinct cycles to evaluate emissions from different sources and scenarios. Cycle 1 focused on the larger burner, Cycle 2 on the smaller burner, Cycle 3 on the oven, and Cycle 4 on the overall kitchen environment.~~

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Figure 4 illustrates the sequence and duration of each module applied during the first measurement cycle. The process begins with environmental ventilation, followed by a 2-minute background stabilization phase (“Back”). Next, a 4-minute CO_2 injection is performed (“Inject Gas”), after which the cycle proceeds through the ST_OFF and ST_ON modules. During the ST_OFF phase, the burner remains off, allowing gas concentrations to return toward baseline levels over 2 minutes. In contrast, the ST_ON phase involves igniting the burner under typical cooking conditions, with emissions monitored for five minutes to ensure stabilization of CO_2 and CH_4 concentrations. Finally, the ON and OFF phases are alternated to capture transient emission dynamics, lasting one and two minutes, respectively. The injected gas (in Inject Gas step) was used to ensure accurate

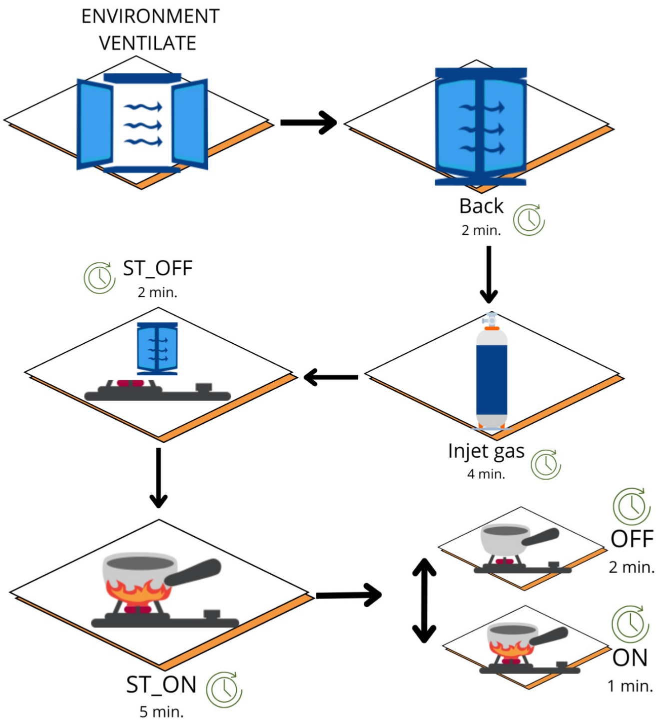

Figure 4. Sequence and durations of the measurement protocol applied to cycle 1. The ON/OFF phases were repeated three times within each cycle, followed by a ventilation phase to reset the environment.

CO_2 concentration values for assessing the enclosed environment and the air exchange rate. Additional methodological details are provided in the Sections 1 and 4 in the Supplementary Material.

2.4 Equipments

Nitric oxide (NO), nitrogen dioxide (NO_2), and total nitrogen oxides (NOx) were continuously analyzed by the Serinus 40 analyzer, which employs gas-phase chemiluminescence detection for continuous analysis, with a measurement support of ± 0 to 20 ppm. Approved by the ~~US~~ U.S. EPA as a reference method and certified by the TUV (Technischer Überwachungsverein) according to EN (European Norms), the instrument consists of a pneumatic system, a converter from NO_2 to NO, a reaction cell, a measuring cell (PMT), an ozone generator and a PCA controller (Ecotech Inc., 2020; U.S. EPA, 2017).

Chemiluminescence occurs by the emission of light from an activated species of NO_2^*, formed by the reaction between NO and O_3 in an evacuated chamber (Ecotech Inc., 2020).

Methane (CH_4) and carbon dioxide (CO_2) were measured by the Microportable Greenhouse Gas Analyzer (MGGA), that employs the Integrated Cavity Output Spectroscopy (OA-ICOS) technique, configured to acquire samples of the greenhouse gases, including water vapor, reaching an accuracy of < 0.9 ppb (1 second) for CH_4 and < 350 ppb for CO_2 (1 second) (ABB Inc., 2022). The MGGA has measurement rates ranging from 0.01 to 10 Hz and supports CH_4 concentrations of 0.01 to 100 ppm and CO_2 concentrations of 10 to 20,000 ppm, respectively. The analyzer's optical system consists of two lasers, with specific wavelengths for the detection of CH_4 and H_2Ov (Laser A) and CO_2 (Laser B), respectively (ABB Inc., 2022).

Furthermore, some auxiliary materials were used, such as fans, plastic for sealing the open kitchen, a tripod for fixing the equipment tubes, a CO_2 cylinder, and an auxiliary pump.

2.5 Emission ~~rate estimation methodology~~Estimation Methodology

Accurate measurement of gas concentrations over time enables the determination of the instantaneous emission rate of gas "i". This methodology was applied to different operational modes of stoves, such as the use of individual burners, and the average emission rate was calculated as showed in the Equation 1, based on IPCC (2006).

$$E_i e_i = V_0 \frac{\Delta C_i}{\Delta t}\left[\frac{dC_i}{dt} + \lambda\left(C_i C_i - C_{i,b}\right)\frac{p}{RT}\right] V_0 \frac{pM_i}{RT} \tag{1}$$

~~where:~~

~~- $C_{i,b}$ is the gas background concentration;~~

~~- V_0 is the kitchen volume (m^3);~~

~~- λ is the air exchange rate (ACH), in min^{-1};~~

~~- p is the ambient pressure;~~

~~- R is the ideal gas constant;~~

~~- T is the ambient temperature.~~

This method accounts for the environment's volume, baseline and measured concentrations, and the air exchange rate, providing detailed insights into emissions. Therefore, the following description will be provided for each part of the equation (Equations 2.5 to 2.5).

$Part1 \rightarrow \frac{dC_i}{dt}$

Emissions were calculated for all cycles and homes during the stove stabilization (St_ON). The concentration change rates over time are determined by subtracting the final time concentration from the initial time, divided by the change over time. Rates are given for each gas and one for each cycle.

$$Part2 \rightarrow (C_i - C_{i,b})$$

Where, concentration (Ci) is the average ppm concentration of the St_ON event, and background concentration (Ci,b) is the average ppm concentration of the Back event.

$$Part3 \rightarrow \lambda$$

The ~~environment's volume (in liters) is based on the physical dimensions of the space being measured. The~~ air exchange (λ) rate was determined after ventilating the kitchen and ensuring concentrations similar to ~~those of the~~ external environment. ~~A controlled release of CH_4 was then carried out, and the decay rate of the concentration was monitored, enabling the precise calculation of the ACH. This step was essential to validate the measurements and assess the degree of isolation in the environment.~~ After the first St_ON (stove stabilization) the decay rate was calculated by exponential adjustment of the decrease in CO_2 concentration. More details about this methodology is in the Section 4 of the Supplementary Materials.

$$Part4 \rightarrow V_0 \frac{pM_i}{RT}$$

Equation 2.5 were used for the conversion from ppm to mg/l. The Volume (V0) was estimated by calculating the volume of the environment (in liters) based on the physical dimensions of the space of measurement. The atmospheric average pressure (p) in the study region is 101,600 Pa (INMET, 2023). Others factor used were universal gas constant (R) of 8.314 J/(mol.K), molar mass (Mi) of 16 g/mol for methane, 44 g/mol for carbon dioxide, and 46 g/mol for nitrogen dioxide, and temperature (T; Kelvin) at the environmental station in the city of São Paulo (CETESB, 2025).

2.5.1 Emission factor calculations

The emission factor FE_i for gas "i" was calculated using Equation 2 (IPCC, 2006).

$$FE_i = \underline{E_i/q_{GN}.LHV}\frac{E_i}{(q \times LHV)} \qquad (2)$$

~~where:~~

~~- M_i is the molecular weight of gas "i";~~

~~- LHV is the lower heating value of natural gas and glp;~~

~~- q is the~~ Where the average gas consumed ~~based~~ (q) was based on 0.25 m^3/h (Petrobras, 2022)~~.~~, and the lower heating value (LHV), was based on values for Brazil, which is 45 MJ/kg for NG (ANP, 2010), and 46 MJ/kg for LPG (ANP, 2020). The complete characteristics are in Tables S2 and S3 in Section 5 of Suplementary Materials.

3 Results

3.1 Normalized concentration

The concentrations of the gases analyzed (CH_4, CO_2, and NOx) were normalized, making it possible to evaluate the influence of each gas on the others and their behavior in relation to the conditions maintained at the time of measurement, as they had different magnitudes. This normalization was done through the standardization method (z-score), which transforms the data so it has a mean of zero and a standard deviation equal to one. The equation based in this method is described in the Section 3 of the Supplementary Material.

The normalized concentration profiles illustrate the temporal variability differences between two household examples: SP_CASA02 (Fig. 5a), which uses liquefied petroleum gas (LPG), and SP_CASA03 (Fig. 5b), which uses natural gas (NG) for CH_4, CO_2, and NOx. In the LPG case, CO_2 and NOx concentrations increase upon stove ignition (St_ON), except during Cycle 4 (ambient conditions). It is important to notice that, in both examples of Figure 5, the houses had closet concept kitchens, in other words, it was not necessary sealing with plastic.

Methane (CH_4) concentrations remained stable for most of the period in SP_CASA02 but showed variability from Cycle 3 onwards, suggesting an external influence unrelated to the LPG source.

Measurements on the large and small burners (cycle 1 and cycle 2) caused immediate responses in all compounds, which means that turning on the burner results in an increase in gas concentrations. Figures 5a and 5b presents time series examples from House SP_CASA02, which utilizes LPG for cooking, and House SP_CASA03, which uses NG.

In the case of NG (SP_CASA03), all gases displayed an increase upon stove ignition (St_ON), except in Cycle 4. In Cycle 3 (oven use), the response appeared delayed but resulted in higher CH_4 concentrations. This behavior was observed in other households using NG, although no consistent pattern was identified across all samples, meaning it did not occur universally. Such delays, particularly in ovens, may be associated with leaks, a topic that warrants further investigation.

3.2 Concentrations by cycles: CH_4, CO_2, NO and NO_2

The concentrations variability in CH_4 (Fig. 6a) and CO_2 (Fig. 6b) is evident across the monitored homes. CH_4 shows the highest values in natural gas (NG) homes, with considerable variability and several outliers, while homes using liquefied petroleum gas (LPG) display relatively stable CH_4 levels. The CO_2 concentration exhibits the greatest variability, particularly

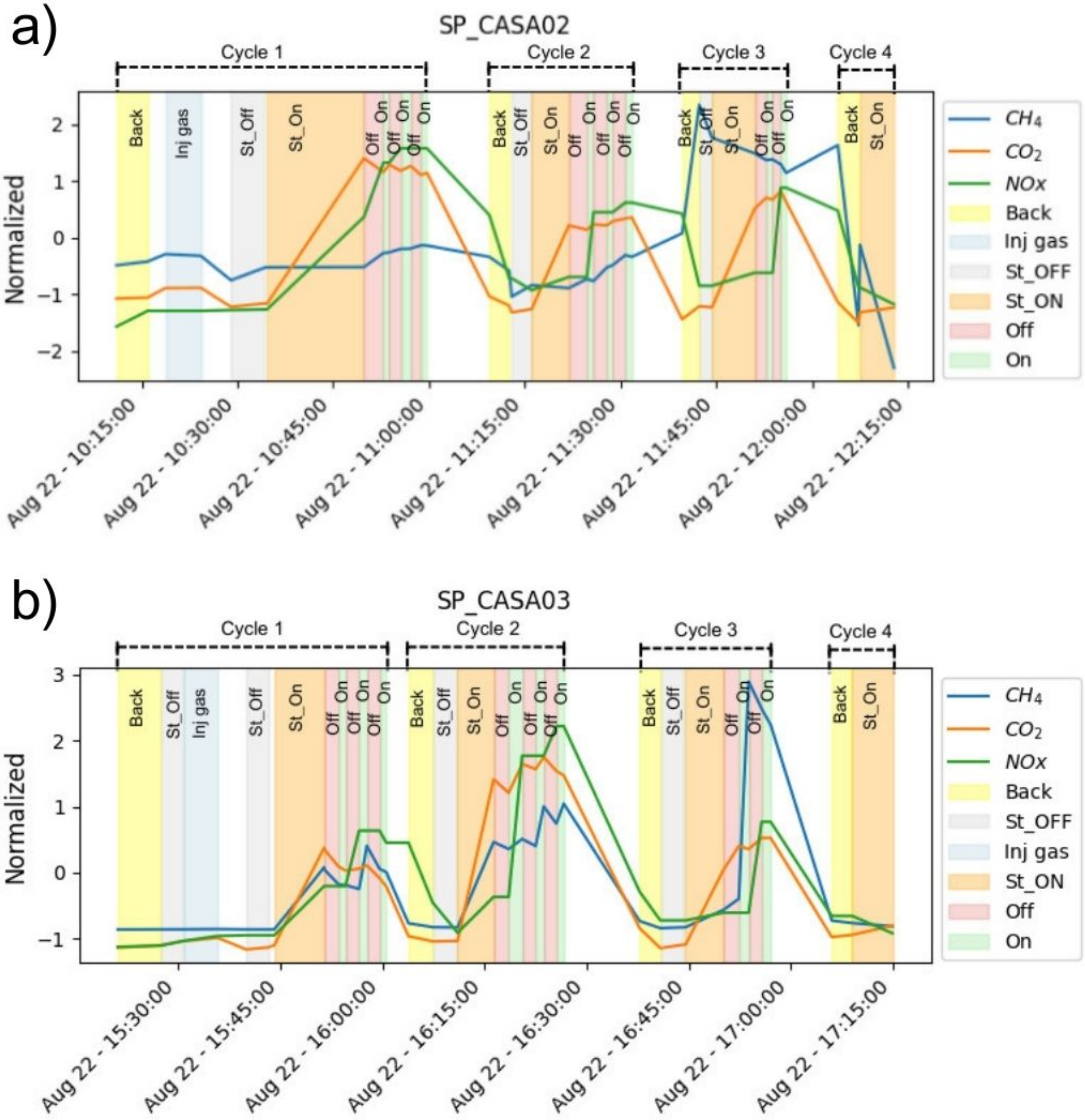

Figure 5. Temporal variability of the normalized concentrations of CH_4, CO_2 and NOx. **(a)** House using Liquefied Petroleum Gas (SP_CASA02). **(b)** House using Natural Gas (SP_CASA03).

in Cycle 2, in some cases where concentrations often exceed health effect limits. LPG homes show elevated CO_2 levels in both burner cycles (Cycle 1 and Cycle 2).

Figures 7a and 7b presents the NO and NO_2 concentration data for households using natural gas (NG) and liquefied petroleum gas (LPG). NO concentrations show significant variability in both distribution and median values. Although the medians for NG are generally higher than those for LPG in most cycles, along with the presence of outliers, it was not possible

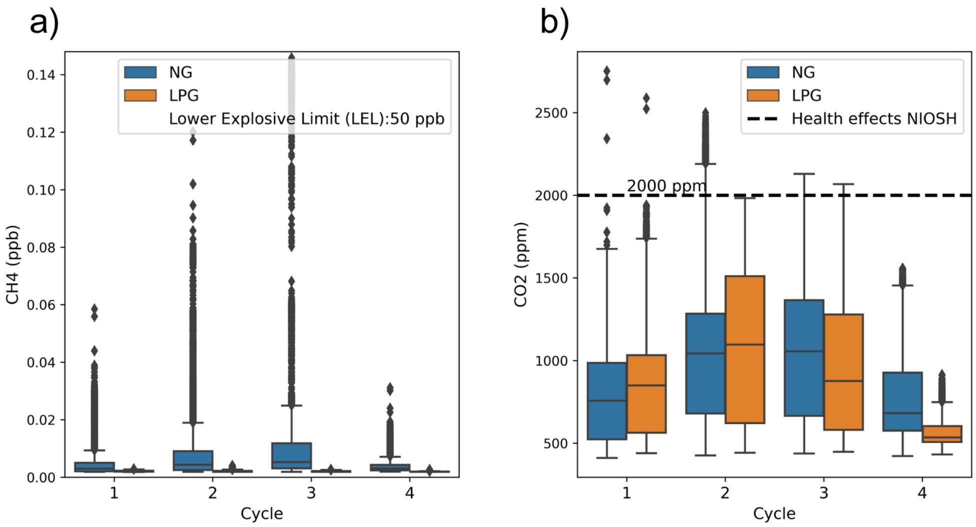

Figure 6. Variability in gas concentrations across the different monitored ~~homes.~~ households using Natural Gas (NG) and Liquefied Petroleum Gas (LPG): **(a)** For methane ~~.~~ (CH$_4$), with the lower explosive limit indicated at 50 ppm; and **(b)** For carbon dioxide (CO$_2$), with the health effect threshold set by NIOSH at 2000 ppm.

to precisely quantify the difference between the two fuels due to the wide data distribution. For NO$_2$, the concentrations for both LPG and NG during the cycles exceeded the WHO recommendation of 106 ppb for 1-hour exposure. Additionally, a significant increase in concentrations from Cycle 1 to Cycle 2 was observed for both NO and NO$_2$.

3.3 Emission rate

The emission rate refers to the amount of pollutant released per unit of time and is commonly used to assess emissions in specific operations or direct measurements at sources. The emission factor, on the other hand, relates the quantity of pollutant emitted to the activity that generated it, such as fuel combustion.

Table 2 ~~contains the average emission rates~~shows the Median, First and Third quartiles, allowing a more complete analysis of the data distribution, highlighting central tendency and variability. These values were calculated during the combustion process (~~steady state~~ St_ON) for ~~each gas, natural gas~~ natural and liquefied petroleum gas. ~~The table shows the averages without the extreme points (outliers) and in parentheses with the outliers.~~

~~Although the average emission rates for~~ Median CO$_2$ ~~are similar for NG and LPG,~~ emission rates are lower for NG than for LPG, and the distribution of ~~the~~ rates shows notable differences. For NG, Figure 8a illustrates a range of values from 0 to 600 g/h, while for LPG, the values are consistently higher, ranging from 180 to 700 g/h.

The methane emission rates clearly highlight the difference between NG and LPG (Fig. 8b). For LPG, emissions are almost non-existent, resulting in no distribution. In contrast, NG shows a wide data distribution, with extreme values, including nega-

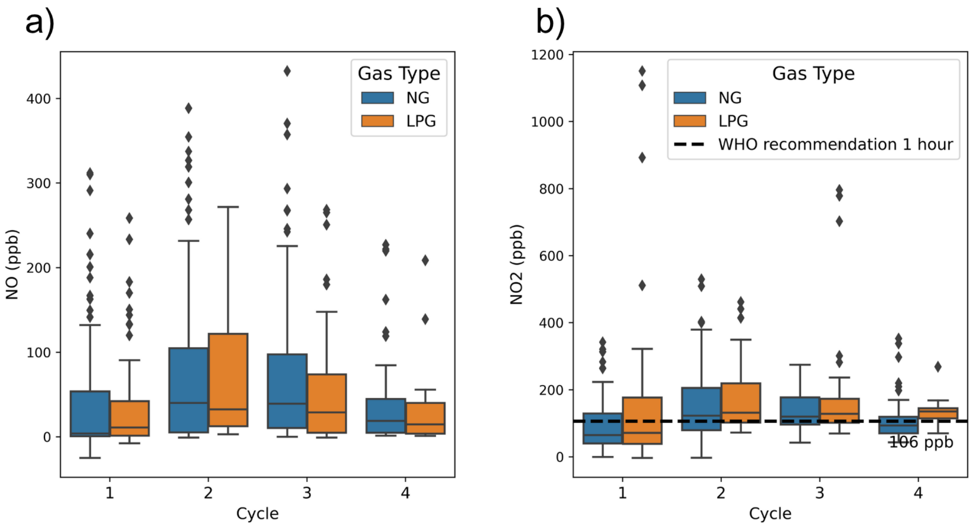

Figure 7. Variability in gas concentrations across the different monitored ~~homes.~~ households using Natural Gas (NG) and Liquefied Petroleum Gas (LPG): **(a)** For ~~nitric~~ nitrogen oxide ~~.~~ (NO); and **(b)** For nitrogen dioxide (NO_2), with the health WHO recommendation for 1 hour at 106 ppb.

Table 2. Emission rate for CO_2, CH_4, and NO_2 for NG and LPG with Median, First and Third quartile (Q1 and Q3).

~~Compound~~	~~Natural Gas (NG)~~	**Natural Gas (NG)**	~~Liquefied Petroleum Gas (LPG)~~	**Liquefied Petroleum Gas (L**
~~CO_2~~ **Compound**	~~207.02 (212.08) g/h~~ **Median**	~~256.33 (270.66) g/h~~ **Q1**	**Q3**	**Median**
~~CH_4~~ height**CO_2 (g/h)**	~~147.68 (495.34) mg/h~~ 238	~~16.57 (16.57) mg/h~~ 124	322	282
~~NO_2~~ **CH_4 (mg/h**	~~2.99 (7.75) mg/h~~ 121	~~4.86 (13.65) mg/h~~ 0	504	0
NO_2 (mg/h)	1	0	9	1

tive emissions and rates exceeding 2000 mg/h, and an even more extreme outlier above 8000 mg/h. It is worth noting that the ~~average emission rate, including outliers, was 406~~ Third quartile, was 504 mg/h. Negative emissions values indicate that, even with the kitchen closed, there was a gas leak, highlighting the difficulty of achieving proper sealing in some homes with high ventilation, which is a common characteristic in Brazilian residences.

Figure 8c shows that NO_2 emission rates are similar for NG and LPG. There are no significant differences between these gases in this dataset. However, for LPG, a greater range of values and outliers is observed, reaching levels above 150 mg/h. One hypothesis raised is that LPG is more commonly used in houses rather than apartments. In the sampled houses, close proximity to the street was noted, which may contribute to increased NO_2 levels indoors. External interference may also occur for the same reason, due to inadequate sealing and high air exchange in some homes.

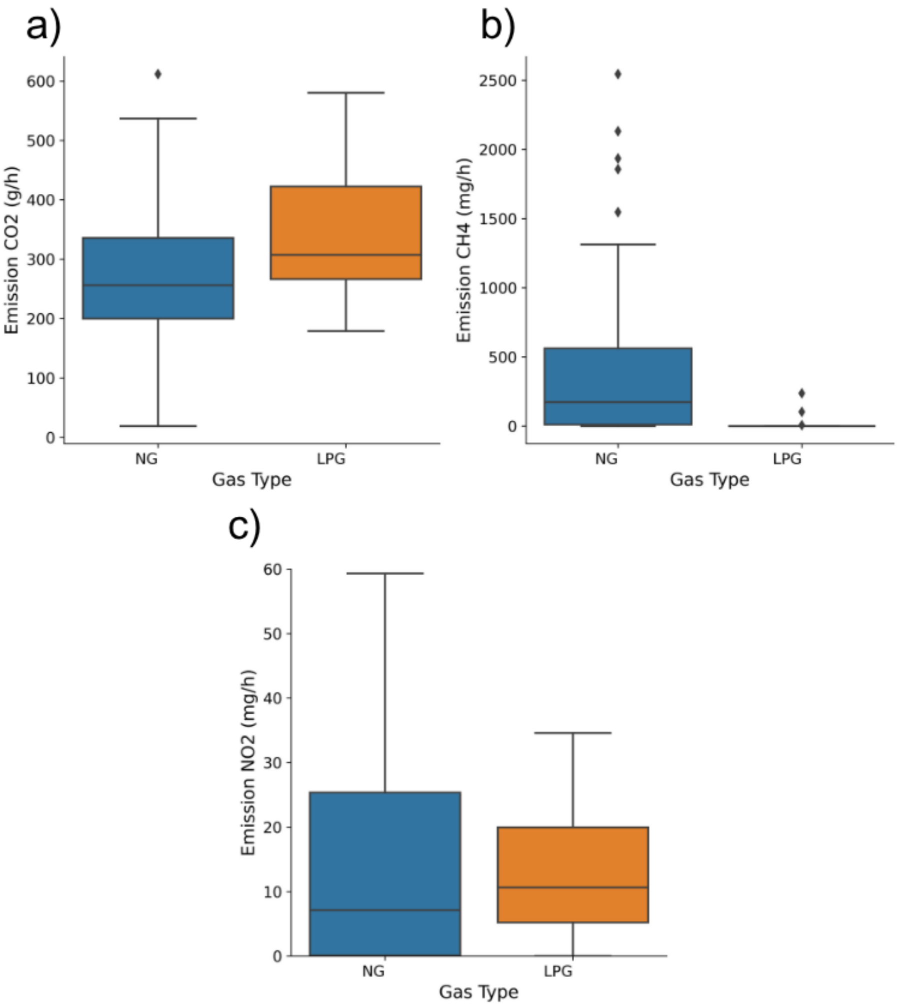

Figure 8. Emission rate. **(a)** For carbon dioxide in grams per hour (g/h). **(b)** For methane in miligrams per hour (mg/h). **(c)** For nitrogen dioxide in miligrams per hour (mg/h).

3.4 Emission factor

According to the national greenhouse emission inventory, Brazil could ~~useuses~~ use IPCC emission factors to estimate household CO_2 and methane emission values. The factor emission for CO_2 is the same as the IPCC, ~~for GN~~ 56100 kg/TJ for NG and 63100 kg/TJ for ~~GLP~~LPG. However, the factor adopted in Brazil for CH_4 (LPG = 1.1 kgCH_4/TJ and NG = 1 kgCH_4/TJ), diverges from the IPCC (NG = LPG = 5 kgCH_4/TJ), because of the adaptations of brazilian gas specification and composition (MCTI, 2020; IPCC, 2019).

Considering the values used in the Brazilian inventory and an average gas consumption of 0.25 m^3/h (Petrobras, 2022). The ~~average~~ methane emission factor obtained from the measurements median by NG taken was ~~14.58~~ 11 kg/TJ~~without the~~

Table 3. Emission factor for CO_2, CH_4, and NO_2.

~~Compound~~

	~~Natural Gas (NG)~~	**Natural Gas (NG)**			
Compound	~~Liquefied Petroleum Gas (LPG)~~ **Median**	**Q1**	**Q3**	**Brazil Factor**	**IPCC**
~~CO_2~~ height**CO_2 (kg/TJ)**	~~20,440 (20,940) g/MJ~~ 23543	~~14,580 (20,940) g/MJ~~ 12315	31834	56100	56100
~~CH_4~~ **CH_4 (kg/TJ)**	~~14.58 (48.92) mg/MJ~~ 12	~~1.60 (1.60) mg/MJ~~ 0	50	1.1	5
~~NO_2~~ **NO_2 (kg/TJ)**	~~0.29 (0.76) mg/MJ~~ 0	~~0.46 (1.31) mg/MJ~~ 0	1	-	-
		Liquefied Petroleum Gas (LPG)			
Compound	**Median**	**Q1**	**Q3**	**Brazil Factor**	**IPCC**
CO_2 (kg/TJ)	27337	18403	39078	63100	63100
CH_4 (kg/TJ)	0	0	0	1	5
NO_2 (kg/TJ)	0	0	1	-	-

~~outliers and with one hundred percent of the data was 48.92 g/TJ, 49~~ , 11 times higher than the national factor and ~~9.8~~ 2 times higher than the ~~IPCC (2019)~~ IPCC (2019) value in kg/TJ. And by LPG the ~~average was 1.60 kg/TJ, 1.454 times higher than the Brazilian inventory value and 0.32 times lower than~~ values were zero, indicating no emission, that is lower than Brazilian inventory and the IPCC value for methane (MCTI, 2020; IPCC, 2019).

The emission factor for CO_2 obtained was around 20,~~000~~ 981 kg/TJ for NG and ~~14,000~~ 24,363 kg/TJ for LPG, both lower than the values used in the national inventory, similar to that of the IPCC (MCTI, 2020; IPCC, 2019). For NO_2 the emission was ~~0.29 g~~0 kg/TJ for NG ~~, and 0.46 kg/TJ without outliers and 1.3 kg/TJ with all data for LPG~~and for LPG, indicating no emission. Table 3 summarized the emission factor values obtained.

4 Discussion and Conclusion

Liquefied petroleum gas (LPG) and natural gas (NG) are the primary fuels used in residential settings in Brazil, playing a critical role in meeting household energy needs.The residential sector accounts for 78% of the final consumption of LPG in the country (EPE, 2023). Its importance in this sector is highlighted by the fact that, in 2020, LPG was the primary cooking fuel used in 94% of households across Brazil (EPE, 2022). These further underscores the widespread reliance on LPG for cooking in Brazilian homes. In São Paulo, LPG remains the dominant fuel for residential kitchens, particularly in areas lacking the infrastructure for NG distribution. It is widely utilized in both urban and rural regions. However, the use of NG is gradually expanding, especially in urban centers and metropolitan areas where pipeline networks enable its direct delivery to homes (*Associação Brasileira das Empresas Distribuidoras de Gás Canalizado - Abegás*) ~~.~~ (ABEGÁS, 2020). This study aimed to investigate GHG emissions under conditions related to domestic cooking practices in São Paulo, Brazil, focusing on natural gas (NG) and liquefied petroleum gas (LPG) stoves.

The time series analysis highlights distinct response behaviors of gases NO_2, NO_x, CH_4 and CO_2 under closed ambient conditions. For both natural gas (NG) and liquefied petroleum gas (LPG), concentrations of gases such as CH_4 and CO_2 show significant responses under closed environments, whereas their presence under ambient conditions is very low. When comparing NG and LPG, CH_4 concentrations exhibit significant differences. NG homes consistently show higher CH_4 levels, but the concentrations remain far below the lower explosive limit of 50,000 ppm established by the National Fire Protection Association (NFPA). On the other hand, CO_2 concentrations vary among homes but display similar trends between NG and LPG, likely influenced by uncontrolled factors such as device types and operational conditions. Meanwhile, NO_2 values sometimes exceed WHO's recommended 1-hour limit of 106 ppb even before the stoves are turned on (St_OFF), which may be associated with the main pollution issue in São Paulo: vehicular emissions.

This difference between LPG and NG gases primarily lies in the composition specifications related to CH_4. LPG, regulated by the National Agency of Petroleum, Natural Gas, and Biofuels (ANP), is predominantly composed of propane (C_3 H_8) and butane (C_4 H_10), with minor amounts of other hydrocarbons such as ethane (C_2 H_6). To enhance safety, a sulfur-based odorant, typically ethyl mercaptan (C_2 H_6S), is added to make leaks easily detectable by smell. LPG is widely distributed in 13 kg (P13) cylinders, which are commonly used for home cooking (EPE, 2023). Natural gas (NG) is primarily composed of methane CH_4, making up over 70% of its composition, followed by smaller proportions of ethane (C_2 H_6) and propane (C_3 H_8). Its gaseous state under normal atmospheric conditions makes it suitable for direct distribution via pipelines.

The study further dissects gas concentration behavior across different operational cycles. For CH_4, homes using NG display a clear increase in CH_4 levels during operation cycles, whereas LPG homes maintain concentrations close to ambient levels, reflecting a minimal response. CO_2 present variability in both across cycles and within each cycle, primarily linked to stove burner activity. Elevated CO_2 levels in certain cases during Cycle 2 highlight the influence of cooking on air quality. NG homes exhibit higher NO concentrations compared to LPG, but the difference is not mirrored for NO_2 , which remains consistently elevated for both fuels. And, across all cycles, NO_2 concentrations exceed WHO recommendations, underscoring the potential risk associated with residential fuel combustion. In general, Cycle 4 (ambient conditions) recorded the lowest gas concentrations for all compounds and fuels, reaffirming the importance of adequate ventilation in reducing pollutant exposure indoors.

From a health perspective, the findings indicate that pollutant concentrations generally remain within safety thresholds under standard operational conditions. For CO_2 typically below the National Institute for Occupational Safety and Health limit of 2,000 ppm, with some exceptions during Cycle 2 (NIOSH, 2022, 2025). NO concentrations stay within the NIOSH recommended exposure limits (RELs), as time-weighted average (TWA) of 25 ppm during normal operations. NO_2: Despite exceeding WHO's recommended values, NO_2 concentrations remain under the NIOSH REL, as a short-term (ST) limit of 1 ppm for occupational exposure.

However, the absence of established air pollutant standards for residential environments, to define the direct assessment of health impacts is complicated by this factor. In additional São Paulo's urban air quality is heavily influenced by traffic-related NO_x emissions, exacerbates the baseline exposure to these pollutants.

The study provides important insights into (CO_2, CH_4, and NO_2 emissions associated with residential cooking practices, particularly the differences between ~~homes~~ houses using Natural Gas (NG) and Liquefied Petroleum Gas (LPG) as a fuel source. Residences relying on NG demonstrated higher mainly methane emissions compared to those using LPG. This finding underscores the importance of considering fuel type when evaluating greenhouse gas (GHG) emissions from residential sectors. The variability of concentrations can have various influences such as leaks, age and model of the stove, in addition to external sources such as automotive pollution, which is highly applicable in the case of São Paulo.

Although NG usage for cooking remains limited in São Paulo, its adoption is steadily increasing, driven by the expansion of pipeline infrastructure in urban areas. This trend positions NG as an emerging component of Brazil's energy matrix, though the country still lags behind other Latin American nations in NG penetration. LPG, however, continues to dominate as the primary cooking fuel, reflecting its widespread availability and affordability across urban and rural regions.

Transitioning to cleaner cooking technologies, like electric stoves, offers opportunities and challenges. The IPCC highlights that these transitions could significantly reduce methane emissions, which is a major component of natural gas (NG) and a potent greenhouse gas (GHG). However, in Brazil, adopting electric stoves may unintentionally lead to higher residential emissions because of the country's electricity generation mix. Additionally, for low-income households, the financial feasibility of making this transition is uncertain due to the high upfront costs and ongoing expenses associated with electric stoves.

The findings also highlight the scarcity of robust statistical data on residential emissions in Brazil, as noted by SEEG (Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa) (SEEG, 2021). Emissions are currently estimated using IPCC emission factors. The estimated methane (CH_4) emission factors of natural gas were significantly higher than the values of the national inventories and the IPCC. This would mean that the previous estimates were lower than the actual emission rates for domestic use of natural gas. Emissions of carbon dioxide CO_2, however, were consistently lower than the IPCC estimates for natural gas and liquefied petroleum gas. These estimates, although widely used, are sources of data uncertainty due to differences in gas, stove and household characteristics. These differences occur not only from one country to another, but also between smaller regions.

These results show the need to study domestic emissions in greater detail to elucidate their effects on indoor air quality and climate change. In the construction of emission inventories this lack of data presents a significant barrier to fully understanding and addressing the impact of residential energy use on GHG and indoor pollutant emissions. Addressing this gap through targeted research and data collection is essential for developing effective policies and strategies to mitigate residential emissions, particularly as the use of NG continues to expand.

~~This study aimed to investigate GHG emissions under conditions related to domestic cooking practices in São Paulo, Brazil, focusing on natural gas (NG) and liquefied petroleum gas (LPG) stoves. The study revealed significant differences in emissions of methane (CH_4), carbon dioxide (CO_2), and nitrogen oxides (NO_2). Stoves using natural gas emitted higher levels of CH_4 compared to those using liquefied petroleum gas (LPG). In addition, NO_2 levels exceeded the standards set by the World Health Organization (WHO) of 106 ppb per hour, indicating probable risks to health, especially indoors.~~

~~The estimated methane (CH_4) emission factors of natural gas were significantly higher than the values of the national inventories and the IPCC. This would mean that the previous estimates were lower than the actual emission rates for domestic~~

~~use of natural gas. Emissions of carbon dioxide CO_2, however, were consistently lower than the IPCC estimates for natural gas and liquefied petroleum gas.~~

~~The study also shows the variability of concentrations of these gases (CH_4, CO_2, and NO_2) by house, this variability can have various influences such as leaks, age and model of the stove, in addition to external sources such as automotive pollution, which is highly applicable in the case of São Paulo.~~

~~These results show the need to study domestic emissions in greater detail to elucidate their effects on indoor air quality and climate change.~~ It is worth noting that this work offers a partial view of a broader and more complex issue, indicating the need for new research at state and national levels, as such studies can help in the development of inventories of the residential sector, which would help to obtain strategies for both public health and sustainability for this sector.

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