Atmospheric Environment 382 (2026) 122199

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Determination of NO_2 emission rates from residential gas stoves with continuous indoor monitoring

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HIGHLIGHTS

- NO_2 emission rates from gas stoves measured in 22 households in Guangzhou, China.
- Steady-state indoor NO_2 reach 1107 and 796 μg/m^3 during use of NG and LPG stoves.
- Mean NO_2 emission rates were 54.3 mg/h (NG stoves) and 40.0 mg/h (LPG stoves).
- Indoor NO_2 shows rapid total decay (mean of 6.5 h^{-1}) due to air exchange and net loss rate.
- Neglecting net decay rate in mass-balance model underestimates emission rate by 16-87%.

ARTICLE INFO

Keywords:
Indoor air pollution
NO_2
Gas stove
Emission rate
Air exchange rate
NO_2 decay

ABSTRACT

Natural gas (NG) and liquefied petroleum gas (LPG) are often promoted as "clean" residential fuels, yet their combustion emits nitrogen dioxide (NO_2), a pollutant with well-documented health risks. Household gas stoves are a predominant source of indoor NO_2. We conducted a campaign with on-site monitoring of NO_2 emissions in 22 residential homes in Guangzhou, China. The air exchange rates (*AER*) and NO_2 decay rates were measured in each of the households. NO_2 concentrations surged rapidly after ignition, reaching steady-state concentrations of 1107.1 μg/m^3 (NG) and 796.0 μg/m^3 (LPG) within 15~20 min—far exceeding the World Health Organization's 1-h NO_2 guideline (200 μg/m^3). Higher gas flow rates or thermal loads are correlated with increased NO_2 emission rates. Specifically, for NG with flow rates varying from 0.17 to 0.54 m^3/h, the NO_2 emission factors increased from 1.36 to 8.32 ng NO_2/J. For LPG combustion with flow rates ranging from 12.11 to 69.99 g/h, the NO_2 emission factors spanned from 0.30 to 2.28 mg NO_2/g LPG. Overall, NG stoves have a higher mean NO_2 emission rate (54.3 mg/h) than LPG stoves (40.0 mg/h). Critically, emission rates with models using measured NO_2 decay rates were 116-187% that of those using *AER* alone. It demonstrates the necessity of measuring the NO_2 decay rates for accurate NO_2 emission quantification for gas stoves. We recommend that future research integrates NO_2 decay rate measurements to enhance indoor air quality evaluation and better characterize indoor NO_x chemical processes.

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https://doi.org/10.1016/j.atmosenv.2026.122199
Received 3 June 2025; Received in revised form 21 June 2026; Accepted 22 June 2026
Available online 23 June 2026

1. Introduction

Rapid urbanization and rising concerns about ambient air pollution have prompted millions of households worldwide to replace inexpensive solid fuels (coal, wood, crop residues) with ostensibly "clean" energy sources such as natural gas (NG), liquefied petroleum gas (LPG) and electricity. Between 2005 and 2015, the proportion of homes relying on clean fuels rose from 24% to 61% across nine middle-income countries in Asia, Africa and Latin America, reflecting a global policy push toward cleaner combustion and lower outdoor emissions (Shupler et al., 2019). From 2010 to 2020, NG and LPG usage rate among Chinese residents has shown a consistent upward trend, increased from 22.7 billion cubic meters (NG) and 15.4 million tons (LPG) in 2010, to 56 billion cubic meters (NG) and 28.6 million tons (LPG) (Statistics, 2022). By 2021, the number of people in China using NG and LPG reached 442 million and 102 million, respectively, with total supply reaching 172.11 billion cubic meters (NG) and 8.6 million tons (LPG) (National Bureau of Statistics, 2021). NG and LPG significantly contribute to alleviating atmospheric and indoor air pollution by reducing the emission of particulate matter, carbon monoxide (CO), and sulfur dioxide (SO_2) (Bilsback et al., 2019; Shen, 2016; Zhang and Smith, 2007).

Although NG and LPG are considered clean residential energy sources, they are not entirely clean during use. NG and LPG combustion are known to emit nitrogen oxides (NO_x), carbon monoxide (CO), and recently aromatic compounds (e.g., benzene) were also identified (Dėdelė and Miškinytė, 2016; Kashtan et al., 2023; Smith, 1999; Ye et al., 2023; Zheng et al., 2022). In indoor environments, combustion of NG and LPG by gas stoves occurs in open spaces. The pollutants are released directly into the kitchen air, and could be readily transported to other rooms, which may lead to an increase in indoor NO_2 concentration that exceeding the 1-h limit value of Indoor Air Quality Standards of China and the WHO's 1-h guideline value of 200 $\mu g/m^3$, causing short-term high NO_2 exposure levels. Agbo et al. (2021) found that when cooking with LPG, indoor NO_2 concentrations increased to 174 $\mu g/m^3$. Daouda et al. (2024) observed that when cooking with gas stoves, NO_2 concentrations in the kitchen increased from 34 to 377 $\mu g/m^3$ (median value), whereas negligible increment in NO_2 concentration was observed when using induction cookers. Human health risks increase with higher average indoor NO_2 concentrations. Indoor NO_2 may cause oxidative damage to the respiratory tract, leading to inflammation and an increased risk of sensitization (Guarnieri and Balmes, 2014). Daily average NO_2 concentrations showed a consistent correlation with the incidence of heart disease: for every 18.4 ppb increase in NO_2 concentration, the number of visits for myocardial infarction and angina pectoris increased by 2.1 percent and 2.6 percent, respectively (Stieb et al., 2009). Moreover, short-term exposure to high NO_2 deserves attention as it has adverse health effects including asthma in children, pneumonia, respiratory and cardiovascular diseases (Bevelander et al., 2007; Hussain et al., 2004; Marika Berglund, 1993; Poynter et al., 2006; Rumchev, 2004).

However, previous studies have predominantly utilized offline methods, such as passive sampler, and obtained the average indoor NO_2 concentrations (Agbo et al., 2021; Hu et al., 2022; Tan et al., 2012; Yang et al., 2004; Yin et al., 2019), which have a low temporal resolution and cannot reflect the short-term variations in NO_2 exposure. Continuous monitoring of indoor NO_2 is possible using sensor technology, which overcomes the weakness of low time resolution by offline sampling and is able to respond to the fast variation of indoor NO_2. Sensors with low cost and low power consumption, high temporal resolution can effectively generate information on pollutant changes over time, improving the understanding of indoor pollutant dynamics (Afroz et al., 2023; Baldelli, 2021; Chatzidiakou et al., 2019; Singh et al., 2024; Tryner et al., 2021; Wei et al., 2018).

Being a vital appliance in residential environment, the gas cook stove is an important indoor NO_2 source, however, data on NO_2 emission rate remain scarce, and the online sensor technology has been rarely applied to determine the NO_2 emission. A common method for measuring emission rates is the indoor mass balance model. Some simplifications have been made in many of the previous studies, such as overlooking the air exchange rate. Zheng and Ye et al. approximated the air exchange rate to be zero by closing the kitchen doors and windows during measurement, which may lead to an underestimation of emission rates (Ye et al., 2023; Zheng et al., 2022). NO_2 is also a reactive gas and can be adsorbed onto indoor materials or undergo chemical reactions on indoor surfaces (Spicer, 1989; Spicer et al., 1993), especially on various impermeable surfaces (Deng et al., 2021). NO_2 decay influences the indoor steady state concentration, and if not accounted, will lead to an underestimation of the emission rates. However, existing studies commonly used empirical NO_2 decay rates but did not measure the actual NO_2 decay rates during fuel combustion (Dimitroulopoulou et al., 2006; Singer et al., 2017). Furthermore, the NO_2 emission rate from gas stoves is influenced by factors such as fuel type and combustion efficiency, which have not been systematically studied.

Despite the well-documented health risks associated with indoor NO_2 exposure, accurately measuring emission rates from gas stoves remains a challenge, largely due to the reliance on oversimplified models that overlook actual air exchange rates and NO_2 decay rates. To address this critical gap, this work employs continuous monitoring to quantify NO_2 emission rates from both NG and LPG stoves in 22 residential settings. Additionally, we determine the actual NO_2 decay rates within kitchen environments and evaluate the discrepancies arising from calculations that rely solely on *AER* compared to those incorporating total decay rates. Through these efforts, this study provides a more precise estimation of NO_2 emissions, thereby contributing to improved IAQ modeling and the development of effective mitigation strategies.

2. Methods

2.1. Measurement household

In this study, we conducted measurements of NO_2 emissions from residential gas stoves in 22 households from the Panyu, Haizhu, Huangpu, Tianhe, and Yuexiu districts of Guangzhou in April and November 2023, through online recruitment. The households were distributed across major urban and suburban areas of Guangzhou, encompassing buildings with different characteristics and varying traffic environments. Table S1 (in Supporting Information, SI) provides the information and photo of the kitchens. The kitchen volumes ranged from 4.7 to 24.3 m^3, with a median of 8.71 m^3. Of the 22 kitchens, 13 were equipped with NG stoves and 9 have LPG stoves, from a total of 18 brands. All the stoves functioned normally for cooking.

2.2. Instruments and measurement procedure

In the study, the IAQ-PRO series indoor air quality monitor (Sapiens Environmental Technology Co Ltd, Shenzhen, China), equipped with a NO_2 sensor, was employed to measure NO_2 concentrations. This instrument features a time resolution of 1 min, a detection range of 0–5 ppm, a detection limit of 0.01 ppm, and a resolution of 0.001 ppm. The NO_2 sensor has been factory calibrated before delivery, and good agreement was observed with reference analyzer up to concentrations over 250 ppb. However, the concentration of the NO_2 calibration gas used did not cover the full range encountered in the actual kitchen environment, which is a limitation of the study. Its capacity to transmit data via 4G networks enabled real-time monitoring through a cloud platform, ensuring continuous access to NO_2 concentration data. Additionally, the IAQ-PRO incorporates dynamic baseline tracking technology, which minimizes the effects of temperature and humidity fluctuations on sensor signals (Sun et al., 2017; Wei et al., 2018). To measure indoor CO_2 concentrations, a CO_2 monitor (model S21A2, Fala Electronic Technology Co., Xuzhou, China) was used to measure indoor CO_2 concentrations. This device employs an infrared sensor and

dual-beam non-dispersive infrared technology to enhance measurement accuracy. It offers 1 min time resolution, a measurement range of 0–10000 ppm with ±3% of accuracy, and operates effectively between −20 and 60 °C. It also supports real-time data monitoring via a cloud platform. Both instruments have been factory-calibrated before use.

To further validate the IAQ-PRO's performance, it was compared against a standard chemiluminescence NO_X monitor (model 42i, Thermo Fisher Inc., USA) at an atmospheric monitoring station. The comparison yielded strong correlation with an R^2 of 0.979, and with a slope of 0.663 (see SI Figure S1). Based on this calibration, IAQ-Pro NO_2 data were calibrated before data processing to account for any systematic bias. However, no intercomparison has been conducted before the second measurement in November, which cannot catch potential sensor drift (if there is any) between April and November, and it is a limitation of present study.

The measurement procedure was designed to separate NO_2 emissions from gas stoves while minimizing interference from other pollutant sources. Instruments were positioned in the kitchen at a height of about 1.5 m above the floor and at least 1 m from walls to ensure representative sampling of the indoor air. To avoid confounding emissions from cooking activities, the gas stoves were used solely to heat 10 L of tap water, rather than for food preparation. Each measurement cycle consisted of three phases: a pre-ignition period to establish background NO_2 and CO_2 concentrations, a 30 – 40 min combustion period during which the stove was operated, and a post-combustion period following stove shutdown to monitor concentration decay (see Fig. 1). The background concentrations of NO_2 and CO_2 were determined during the preignition phase of each measurement cycle. Specifically, the preignition background monitoring duration was set to 20 min, which is sufficient to obtain a stable baseline concentration without interference from stove combustion. Throughout these phases, NO_2 and CO_2 concentrations were real-time monitored with the IAQ-PRO and CO_2 monitor, respectively. Additional measurements were conducted at varying burner strengths to assess the impact of combustion intensity on NO_2 emissions. It should be emphasized that all measurements, including the CO_2 decay tests, were conducted in unoccupied residences except two researchers. During the entire measurement process, the researchers stayed in the bedroom or rooms which are not adjacent to the kitchen and only entered or exited the kitchen quickly to turn the cooking appliance on or off. To minimize interzonal air exchange and external CO_2 input, the tested kitchen could be separated from adjacent rooms by closing the door.

2.3. Measurement of air exchange rate and NO_2 decay rates

To quantify the factors influencing indoor NO_2 concentrations, the indoor-outdoor air exchange rate (*AER*) and NO_2 decay rate were determined using the inert tracer gas techniques. The *AER* was measured via the inert tracer gas decay method, employing CO_2 as the tracer. Throughout the observation period, the kitchen windows and doors were kept in a consistent state (either open or closed) to maintain a stable air exchange between the indoor and outdoor environments. First, a controlled amount of CO_2 was released from a pressurized cylinder into the kitchen and its natural decay was monitored using the CO_2 monitor described in Section 2.2 and CO_2 decay was fitted to an exponential model in Equation (1). The decay curve of indoor CO_2 concentration after the gas stove was turned off was also fitted to the exponential model, and reported as the final *AER* values:

$$(c - c_b) = (c_0 - c_b)^* e^{-\alpha t} \quad (1)$$

where c is the real-time CO_2 concentration (ppm), c_0 is the initial CO_2 concentration immediately following release, c_b is the indoor background CO_2 concentration prior to the experiment. t is the time (h), and α represents the *AER* (h^{-1}). By fitting the measured CO_2 decay data to this equation, the *AER* was calculated.

Unlike CO_2, NO_2 is a reactive pollutant that can undergo deposition or chemical reactions with organic matter on kitchen surfaces, contributing to its decay beyond simple air exchange. To capture this total decay, the decline in NO_2 concentration was measured after stove shutdown and fitted to the same exponential form as Equation (1), yielding the total NO_2 decay rate (m, h^{-1}). The net NO_2 decay rate (k, h^{-1}), attributable to surface interactions and reactions, was then derived by subtracting the *AER* from the total decay rate, as shown in Equation (2):

$$k = m - AER \quad (2)$$

This approach isolates the reactive component of NO_2 loss, providing a comprehensive assessment of its behavior in the indoor environment. It is important to note that the calculation of the k value (net NO_2 loss rate) is highly dependent on the accuracy of the air exchange rate (*AER*), and errors in *AER* will directly propagate to the k value. If *AER* is underestimated (e.g., due to imperfect mixing of the tracer gas or unaccounted external CO_2 input), the k value will be overestimated.

To account for the uncertainty of *AER* and NO_2 decay rates obtained from regression fit, a recursive regression approach was implemented across the CO_2 and NO_2 decay phases. For each sub-segment, the regression time window was expanded minute-by-minute from a minimum of 10 min to the full segment duration, generating a comprehensive distribution of possible decay rates. The final time window was determined using NO_2 regression fit with the highest R^2 value. The exact time windows identified above were strictly mapped to the contemporaneous CO_2 concentration profiles for calculating the *AER*. Detailed description is provided in the SI.

2.4. Calculation of NO_2 emission rate and emission factor

The NO_2 emission rate and emission factor were calculated using an indoor air quality mass balance model, integrating the concentration data with *AER* and decay rate measurements. The model relates the NO_2 emission rate (E, mg/h) to the indoor NO_2 concentration (c, mg/m^3), kitchen volume (V, m^3), *AER* (h^{-1}), and net NO_2 decay rate (k, h^{-1}), as described by the differential equation:

$$\frac{dc}{dt}V = E - cV(AER + k) \quad (3)$$

During stove operation, NO_2 concentrations reached a quasi-steady state. At this equilibrium, where $\frac{dc}{dt} = 0$, the emission rate was derived from Equation (4) as:

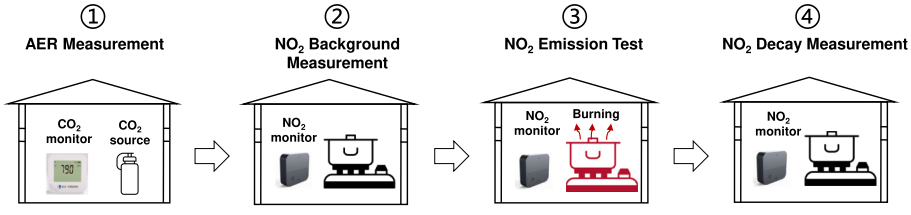

Fig. 1. Schematic of the NO_2 emission measurement procedure (Note that during NO_2 decay phase, CO_2 decay was also fitted, and the obtained AER was used to calculate the net NO_2 loss rate).

$$E = \bar{c}V(AER + k) \quad (4)$$

Here, $\bar{c}$ is the steady-state NO_2 concentration measured with the IAQ-PRO monitor at 1-min intervals, providing high temporal resolution for accurate equilibrium assessment.

For natural gas (NG) stoves, the emission factor (EF_{NG}, ng·NO_2/J) was calculated by normalizing the emission rate to the energy consumption rate, using Equation (5):

$$EF_{NG} = \frac{N_a}{N_b} QM\beta\gamma \quad (5)$$

where, N_a/N_b represents the ratio of background-corrected NO_2 concentration (ppm) to CO_2 concentration (ppm), and Q represents the fuel energy content. We used a value of 1.02 mol CO_2/MJ of fuel based on Guangzhou Gas Group. M is the molar mass of NO_2 (46 g/mol), and β and γ are unit conversion factors, which are MJ/10^3 kJ and 10^6 μg/g, respectively.

Based on the LPG consumption and flow rate (Q) during the combustion phase, the emission rate (E, mg/h) was converted to the emission factor (EF, mg·NO_2/g·LPG) using Equation (6):

$$EF_{LPG} = \frac{E}{Q} \quad (6)$$

2.5. Estimation of LPG consumption

Since the amount of LPG used during monitoring was relatively small and there is no flow meter installed on the LPG cookstove, the LPG consumption (M, mg) was estimated indirectly based on the increased CO_2 concentration and carbon emission factor in the carbon balance model, using Equation (7):

$$M = \frac{(C_{CO2,t} - C_{CO2,0})44V}{22.4 \times 3.10} \quad (7)$$

Here, $C_{CO2,t}$ and $C_{CO2,0}$ are the CO_2 concentrations (ppm) at time t and at background, respectively, V is the kitchen volume (m^3), 44 is the molecular weight of CO_2 (g/mol), 22.4 is the molar volume of gas (L/mol) at standard conditions, and 3.10 is the carbon emission coefficient (kg CO_2/kg LPG) (GB/T 2589, 2020). This approach assumes complete combustion and a consistent fuel composition, providing an approximate mass of LPG consumed, which was then converted to a flow rate (Q, g/h) by dividing by the combustion duration. It is necessary to point out that the estimation method on LPG consumption is prone to relatively large uncertainty and may affect the accuracy of estimated NO_2 emission factors from LPG stoves.

2.6. Experimental condition controls

During the entire CO_2 decay test (30–45 min), researchers entered the kitchen quickly only to open and close the gas cylinder, and then exited the kitchen immediately. To minimize the impact of ambient air infiltration on the kitchen conditions, all tested kitchens were independent spaces that could be physically separated from adjacent rooms by closing doors. There are no other active combustions running in the tested houses such as water heaters throughout the time of measurement, and the gas stoves were equipped with electrical lighter. The Ventilation configuration including using of range hoods, the opening position of windows and doors were set to the exact same configuration before, during, and after each gas stove measurement experiment.

3. Results and discussion

3.1. Variation of NO_2 concentrations in kitchens after gas stove use

Fig. 2 shows the changes of NO_2 concentrations in kitchen over time before, during and after the use of gas stoves at medium burning rate. The results at high burning rate were shown in SI Figure S2. When the gas stoves were in use, a similar pattern of indoor NO_2 concentration was observed. After the gas stoves were ignited, NO_2 concentrations in the kitchen increased rapidly within a short period, stabilizing after 10–15 min at a relatively constant level. The rapid NO_2 increase within 10–15 min suggested efficient mixing in kitchens, likely due to stove proximity and airflow. However, the steady state NO_2 concentrations from different households varied widely, ranging from 71.2 to 2330.0 μg/m^3, with most cases exceeding 500 μg/m^3, indicates variability in stove emission rates, kitchen volume, and ventilation. The average cooking time of the gas stoves was 0.74 h (0.50–1.28 h, sd = 0.17), which is similar to the duration of daily cooking activities. The average cooking time of 0.74 h (44.4 min) in the study is the single continuous combustion time of the gas stove (heating 10 L of water from room temperature to boiling and maintaining boiling), which is designed to simulate the actual continuous cooking time of a single meal (e.g., stir-frying, boiling soup) in Chinese households—this is a typical cooking duration for southern Chinese families (Guangzhou), which is longer than the short cooking time in Western households (10–15 min). When the combustion stopped, NO_2 concentration decreased rapidly, with a 70.0% reduction within approximately 0.2 h.

Due to the poor sealing of the kitchen in one household (Household H-18), which was a self-built temporary structure, and the strong outdoor wind on the measurement day, the air exchange rate in the kitchen was high and unstable, significantly lowering the indoor NO_2 concentrations. Therefore, the data from this household were excluded from the following analysis. After statistical analysis, the average NO_2 concentration in the steady-state from the 21 households was 1048.9 μg/m^3 (124.0–3326.9 μg/m^3, sd = 706.7), far exceeding China's indoor air quality standard and the WHO's 1-h NO_2 concentration guideline (200 μg/m^3).

Fig. 3 shows the increment of NO_2 during the use of gas stoves. In the 13 households with natural gas stoves, the kitchen background NO_2 concentrations ranged from 11.4 to 54.2 μg/m^3. The NO_2 concentration

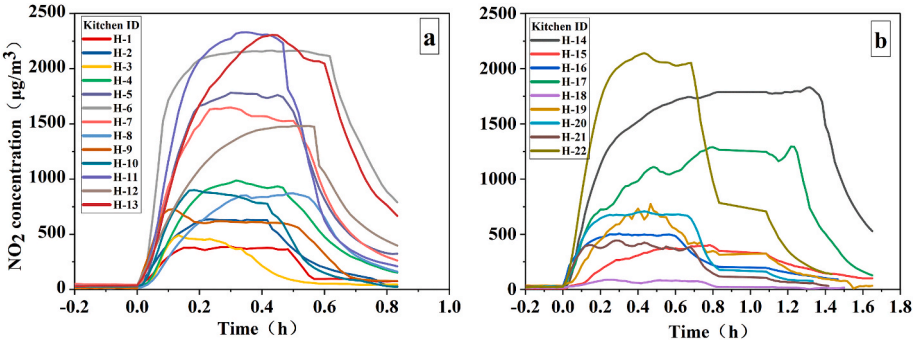

Fig. 2. Temporal changes in NO_2 concentration in the kitchen at medium burning rate of (a) NG cook stoves, (b) LPG cook stoves. Time 0 represents the moment the gas stove was ignited.

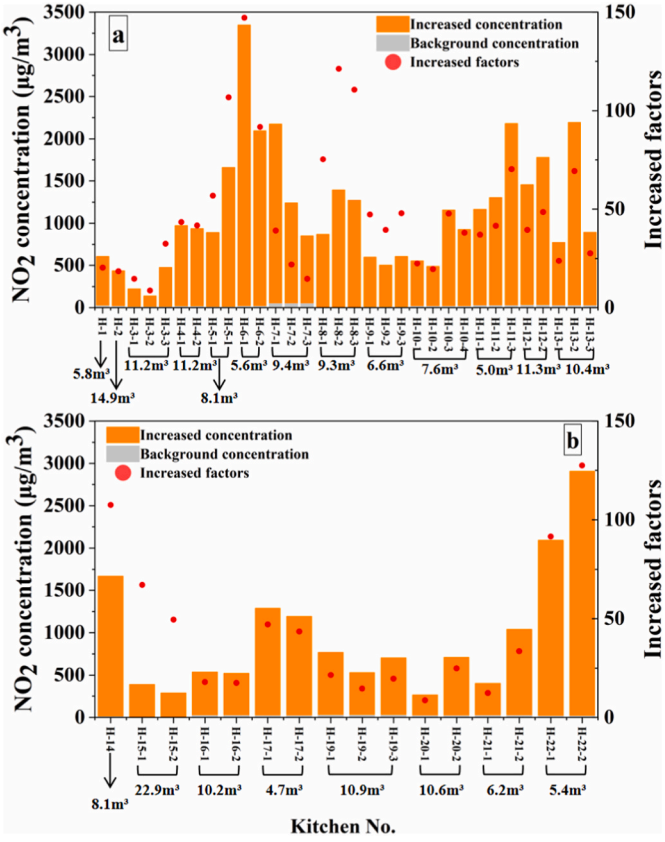

Fig. 3. The increment of NO_2 concentrations in the kitchen and increased factors compared with background concentrations after the use of NG and LPG stoves: (a) NG cook stoves, (b) LPG cook stoves. The numbers 1, 2 and 3 in the identification code correspond to the different combustion conditions at the designated household.

increased by 8.7–147.2 times (median: 41.7 times) after 10–15 min of combustion, reaching an average steady state concentration of 1107.1 μg/m^3 (124.0–3326.9 μg/m^3, sd = 697.5). The average steady state NO_2 concentration in 8 kitchens with LPG stoves was 796.0 μg/m^3 (237.9–2884.0 μg/m^3, sd = 743.8), increased by 3.6–127.6 times (median: 20.5 times), compared with the background concentrations. In 98% of the cases, steady state NO_2 concentrations from both NG and LPG kitchens exceeded the WHO's 1-h NO_2 concentration guideline (200 μg/m^3). The NO_2 concentration in kitchens with natural gas stove was generally higher than that with LPG stove, which may be related to the combustion temperature during gas use. We noticed that the flames of LPG combustion had a yellowish tint, indicating incomplete combustion condition and lower flame temperatures (see SI Figure S3).

Spearman correlation analysis between LPG kitchen volume and steady state NO_2 concentration showed a significant negative correlation, with a correlation coefficient of −0.79 ($p < 0.05$) (See SI Figure S4). It agrees with the fact that as the kitchen volume increased, the steady state NO_2 concentration decreased due to the larger space facilitating gas diffusion and dilution.

3.2. Air exchange rates and NO_2 decay rates

Throughout the measurement period, the state of the kitchen doors and windows remained unchanged, and the actual air exchange rate in each household's kitchen was measured using the CO_2 decay method during the decay phase after the gas stove was turned off (see Section 2.3). The obtained *AER*s are shown in Table 1.

The average *AER* for the 21 households was 4.97 h^{-1} (range: 1.65–9.59 h^{-1}), with the average *AER* for natural gas kitchens and LPG kitchens being 5.43 h^{-1} (range: 2.76–9.59 h^{-1}) and 4.21 h^{-1} (range: 1.65–8.02 h^{-1}), respectively. The average *AER* for both natural gas and LPG kitchens exceeded the kitchen ventilation rate of 3 h^{-1} specified in GB 50736 (2012). After the gas stoves were turned off, the decline in indoor NO_2 concentration was primarily attributed to air exchange and the NO_2 decay. By fitting the data exponentially, The total NO_2 decay rate (m) was calculated; based on Equation (3), the net NO_2 loss rate (k) was obtained (see Table 1).

Table 1
Air exchange rates and NO_2 decay rates in the kitchens of the studied households.

Household Nr.	Kitchen Volume (m^3)	*AER* (h^{-1})	Total NO_2 decay rate m (h^{-1})	Net NO_2 loss rate k (h^{-1})	range of k (h^{-1})	SD of k
H-1	5.76	8.58	13.15	4.57	[3.13, 5.55]	±0.83
H-2	14.95	9.59	12.56	2.98	[1.49, 3.95]	±0.83
H-3	11.22	4.96	8.24	3.28	[2.79, 3.57]	±0.19
H-4	24.3	4.33	4.45	0.12	[0.02, 0.24]	±0.08
H-5	8.09	3.76	5.53	1.77	[1.77, 1.77]	±0.00
H-6	5.6	3.23	5.02	1.79	[0.07, 2.47]	±0.60
H-7	9.38	5.06	5.87	0.81	[0.68, 0.95]	±0.10
H-8	9.33	5.85	7.16	1.31	[1.28, 1.35]	±0.02
H-9	6.59	7.48	8.93	1.46	[0.34, 2.09]	±0.61
H-10	7.62	2.76	4.82	2.06	[1.13, 2.68]	±0.39
H-11	4.97	5.38	7.48	2.10	[1.59, 2.57]	±0.31
H-12	11.26	5.44	6.19	0.75	[0.69, 0.82]	±0.04
H-13	10.38	4.18	4.64	0.46	[0.27, 0.66]	±0.16
H-14	8.02	3.28	4.32	1.04	[0.93, 1.17]	±0.05
H-15	22.9	1.93	2.42	0.49	[0.02, 0.68]	±0.13
H-16	10.2	3.18	3.42	0.24	[0.10, 0.37]	±0.11
H-17	4.66	4.45	5.07	0.62	[0.29, 0.89]	±0.16
H-19	10.93	5.51	6.54	1.03	[0.11, 1.81]	±0.60
H-20	10.55	1.65	5.40	3.75	[3.01, 4.55]	±0.73
H-21	6.5	8.02	8.63	0.61	[0.61, 0.61]	±0.00
H-22	5.35	5.68	7.38	1.70	[1.23, 2.10]	±0.23

Note: Households H-1 to H-13 used natural gas as fuel while households H-14 to H- 22 used LPG as fuel. Different combustion experiments correspond to respective AER and total NO_2 removal rate.

As shown in Table 1, the k values exhibited considerable variation across the 21 households. Eight households had k values below 1.0 h^{-1}, seven fell within the range of 1–2 h^{-1}, and the remaining seven showed values exceeding 2 h^{-1}. The use of different time windows in the regression fits yielded varying decay rates for NO_2 and CO_2, resulting in a notably wide range of k values, particularly among households with high k values (e.g., H-1, H-10, H-11, H-19, H-20, H-22). This observation highlights the necessity of designing a systematic regression fitting strategy to obtain optimized and reliable results.

Active combustion during stove operation generates significant turbulence and buoyancy, altering interzonal airflows and effective mixing/ventilation relative to the stove-off period, thereby invalidating the

direct application of CO_2-based *AER* estimates to the NO_2 decay period. The present results agree with previous studies (Spicer, 1989; Ozkaynak, 1982; Yamanaka, 1984), which demonstrated the impact of different indoor building materials on NO_2 concentration decay, suggesting that indoor building materials act as sinks for NO_2, adsorbing or reacting with NO_2 at a relatively fast rate. However, they reported an average net NO_2 decay rate of 2.0 h^{-1} (Dobbin et al., 2018), which is higher than this study through actual observations (1.57 h^{-1}). Other studies used empirical values of 0.7 and 0.99 h^{-1} (Dimitroulopoulou et al., 2006; Singer et al., 2017), which are at the lower end of the values in this study. However, available data on NO_2 decay rates are very limited, and further study is needed to better understand the net NO_2 decay rates in different indoor environments, which is crucial for obtaining more accurate NO_2 emissions.

3.3. NO_2 emission rates and emission factors

3.3.1. NO_2 emission rates

As presented in Tables S2 and S3, the NO_2 emission rates span from 3.84 mg/h to 121.5 mg/h, with a median value of 41.66 mg/h. Specifically, for natural gas stoves, the NO_2 emission rates range between 3.84 mg/h and 121.5 mg/h, with a median of 44.33 mg/h. In contrast, LPG stoves exhibit NO_2 emission rates ranging from 7.61 mg/h to 103.2 mg/h, with a median of 39.48 mg/h. A comparative analysis stoves indicates that the median NO_2 emission rate of natural gas stoves (44.33 mg/h) is substantially higher than that of LPG stoves (39.48 mg/h). The average NO_2 emission rate of most natural gas stoves (mean: 54.29 mg/h) is higher than that of LPG stoves (mean: 40.02 mg/h). Furthermore, the majority of natural gas stoves demonstrated higher NO_2 emission rates compared to their LPG counterparts.

Table 2 summarizes the NO_2 emission rates and emission factors in the literature for natural gas and LPG stoves. Ye et al. found that when the LPG flow rate was in the range of 1000–2000 mg/min, the median NO_2 emission rate was 0.134 mg/min (Ye et al., 2023), which is significantly lower than present study. The NO_2 emission rates obtained in this study for NG stoves fall within the range reported in the literature but are higher than most previous results. This discrepancy may be related to factors such as the combustion rate of the gas and underestimation or overlook of NO_2 decay rate in the literature.

3.3.2. NO_2 emission factors

As shown in Table S2, the NO_2 emission factors for NG stoves range from 1.36 ng NO_2/J to 8.32 ng NO_2/J, with a median value of 6.15 ng NO_2/J. For LPG stoves, the NO_2 emission factors range from 0.30 mg NO_2/g LPG to 2.28 mg NO_2/g LPG. Current studies indicate that the NO_2 emission factors for NG stoves during operation typically fall within the range of 5–15 ng/J (Jaffe and Creekmore, 2024; Lebel et al., 2022; Singer et al., 2017; Tan et al., 2012). In this study, the NO_2 emission factor for natural gas stoves (median: 6.15 ng NO_2/J) aligns well with the range reported in the literature. However, the NO_2 emission factor for LPG (median: 0.88 mg NO_2/g LPG) is significantly lower than Ye et al. (2023) (median: 111 mg NO_2/g LPG). This discrepancy may be attributed to differences in combustion conditions during gas use and variations in the brands of gas stoves employed, and whether LPG burns completely.

3.4. Factors influencing NO_2 emission rates from gas stoves

3.4.1. Fuel combustion rates

Fig. 4 illustrates the relationship between NO_2 emission rates and gas flow rates. Spearman correlation analysis reveals a significant positive correlation between NO_2 emission rates and NG flow rates (in the range of 0.174 to 0.543 m^3/h) during combustion ($R = 0.40$, $P < 0.05$). In contrast, as depicted in Fig. 4(b), no significant correlation is observed between NO_2 emission rates and LPG flow rates. Due to the relatively low consumption of liquefied petroleum gas during combustion, it was difficult to obtain the LPG consumption for each individual measurement using gravimetric methods. Instead, LPG consumption was approximately estimated by conversion based on steady-state CO_2 concentrations. This estimation approach may introduce considerable errors, which may explain why LPG did not exhibit a similar trend to natural gas.

3.4.2. Influence of using AER or total NO_2 decay rates

We compared the NO_2 emission rates using both the *AER* and the total NO_2 decay rate (m) in the mass balance model (Fig. 5). Specifically, in the natural gas combustion scenario, the emission rate at low thermal load (27.97 ± 14.56 mg/h) was 11.5% higher than the *AER* model (25.08 ± 13.74 mg/h). At high thermal load, the difference was 15.9 mg/h ($p < 0.001$). The LPG combustion experiments revealed a similar pattern (Fig. 5(b)): the emission rates calculated based on total NO_2 decay rate (m) were on average 10.7%–86.8% higher than those from the *AER* model.

This discrepancy primarily stems from secondary decay processes such as microenvironment surface adsorption and chemical reactions, which contributed 13.2%–89.3% to the total decay rate. The results demonstrated that the model using *AER* systematically underestimated the NO_2 emission rates, and this underestimation showed a nonlinear increasement as the thermal load increases. Therefore, when assessing NO_2 emission rates from gas stove, and also other indoor NO_2 sources, it is essential to consider both *AER* and microenvironment-specific decay rates to reduce systematic underestimation.

Table 2
NO_2 emission rates and emission factors from gas stoves in current study and in literature.

Fuel type	AER	Net NO_2 loss rate	Emission rate (mg/h)	Emission factor	Reference
NG	range: 1.05~9.59 h^{-1} average: 4.8 h^{-1}	range: 0.12~4.57 h^{-1} average: 1.29 h^{-1}	range: 3.84~121.5 median: 44.33	range: 1.36~8.32 ng·NO_2/J median: 6.15 ng·NO_2/J	This study
NG	-	-	26.0	5.8 ng/J	Jaffe and Creekmore (2024)
NG	average: 3.3 h^{-1}	-	65.5	5.4 ng/J	Tan et al. (2012)
NG	range: 0.7~2.3 h^{-1}	average: 2.0 h^{-1}	36	-	Dobbin et al. (2018)
NG	average: 1.0 h^{-1}	empirical value: 0.99 h^{-1}	range: 15.6~21.9	-	Dimitroulopoulou et al. (2006)
NG	-	-	-	range: 13.9~28.3 ng NOx/J average: 21.7 ng NOx/J 7.8 ng NO_2/J and14.0 ng NO/J)	Lebel et al. (2022)
NG	-	empirical value: 0.7 h^{-1}	-	range: 30~45 ng(NO + NO_2)/J NO_2 < 25 ng/J	Singer et al. (2017)
LPG	range: 0.57~8.02 h^{-1} average: 4.48 h^{-1}	range: 0.06~3.75 h^{-1} average: 1.05 h^{-1}	range: 7.61~103.2 Median: 39.48	range: 0.3~2.28 mg NO_2/g LPG median: 0.88 mg NO_2/g LPG	This study
LPG	-	-	range: 0.24~44.76 median: 8.34	range: 1.84 ~ 611 mg NO_2/kg LPG median: 111 mg NO_2/kg LPG	Ye et al. (2023)

Note: In the table, "-" indicates that the data were not mentioned or were unavailable.

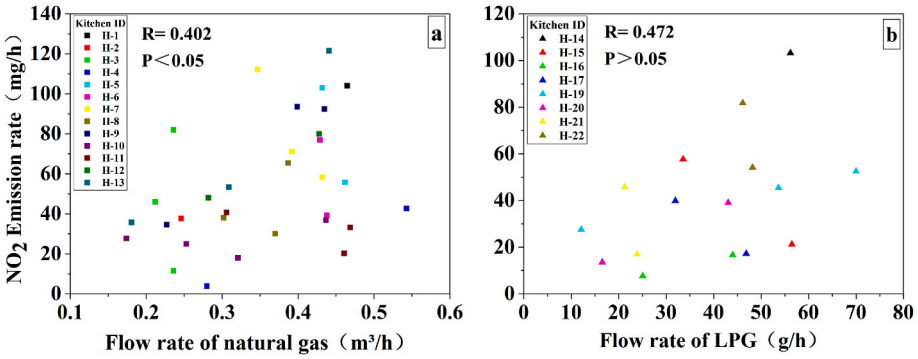

Fig. 4. NO_2 emission rates and gas flow rates during gas stove use in (a) NG kitchens, (b) LPG kitchens.

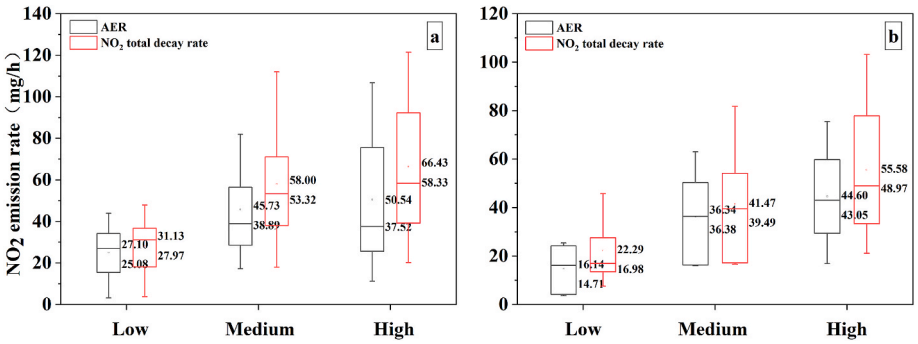

Fig. 5. Emission rates of NO_2 from gas stoves (a) NG (b) LPG with *AER* and total NO_2 decay rate, respectively in the mass balance model at different thermal loads.

Table 2 summarizes the related studies on NO_2 emission from gas stoves. While the indoor mass balance model was the primary method for estimating NO_2 emission rates, most previous studies did not account for NO_2 decay rates, and some even simplified the *AER* to be zero. A few studies considered NO_2 decay rates but used empirical values (0.7–1.0 h^{-1}). Compared to previous studies, this study is the first to systematically measure the microenvironment-specific NO_2 decay coefficients ($k = 1.56 \pm 1.21$ h^{-1}) in kitchens.

3.5. Implication on indoor chemistry

Research findings indicate that following combustion activities, the decay rate of NO_2 significantly surpasses the indoor air exchange rate. This phenomenon is likely attributable to the adsorption of NO_2 onto surfaces or its removal via reactive processes, both of which expedite the decay of NO_2. Heterogeneous reactions are recognized as the principal chemical mechanism involving NO_2 in indoor settings. These reactions result in the formation of nitrous acid (HONO), a precursor for atmospheric OH radical. HONO could also induce asthma and cause negative effects to the respiratory system (Ohyama et al., 2018a, 2018b, 2022). Meanwhile, relevant studies have demonstrated that elevated humidity thickens the water film on kitchen surfaces, substantially facilitating the interfacial hydrolysis reaction of NO_2 and accelerating its decay rate (Pandit and Grassian, 2022). In the present study, the relative humidity of the tested kitchen ranged from 40.9% to 80.3%, with approximately 67% of the measured data collected under environmental conditions where the relative humidity exceeded 60%. Spearman correlation analysis demonstrated that the k (h^{-1}) had a statistically significant positive correlation with the average indoor relative humidity (%) of kitchens at the 5% significance level ($R = 0.345$, $p = 0.016$). This indicates that environments with higher relative humidity are likely associated with a greater net loss rate of NO_2.

The primary indoor sources of HONO are direct emissions from fuel combustion and secondary reactions involving NOx. Among these, NO_2 is the main precursor of HONO through heterogeneous reactions on indoor surfaces (Chen et al., 2020). Studies have demonstrated that in indoor environments, NO_2 produced during combustion can be more efficiently converted into HONO. Moreover, the frequent use of gas stoves has been shown to significantly increase the concentration of indoor HONO (Li et al., 2025). In experiments where the combustion rate was controlled, Park et al. (2008) observed that the peak concentration of HONO is closely associated with the combustion rate: the higher the combustion rate, the greater the peak concentration of HONO. In addition, the peak concentration of HONO typically occurs 10 to 15 min after combustion ceases. This suggests that heterogeneous reactions of NO_2 following combustion may represent the dominant pathway for HONO formation.

Therefore, accurately measuring the concentration of NO_2 and its emission rates during fuel use is essential for evaluating the generation of HONO, which will be vital in further optimizing indoor air quality management and indoor chemistry research.

4. Conclusions

Residential gas stove is a major indoor source of NO_2, yet their emission rates remain poorly quantified. We continuously monitored NO_2 in 22 Guangzhou households and found that concentrations rose to steady-state levels within 15–20 min of ignition, averaging 1107 $\mu g/m^3$ for natural-gas (NG) stoves and 796 $\mu g/m^3$ for LPG stoves—5.5 and 4.0 times the WHO 1-h guideline (200 $\mu g/m^3$), respectively. Measured total NO_2 decay (mean 6.53 h^{-1}) exceeded the air-exchange rate (*AER*: 4.96 h^{-1}). The net decay attributable to surface uptake and chemistry ($k = 1.56 \pm 1.21$ h^{-1}) was comparable in magnitude to *AER*, showing that neglecting this term in a mass-balance model underestimates stove emissions by 16–87%. Incorporating NO_2 total decay yielded mean emission rates of 54.3 mg/h for NG and 40.0 mg/h for LPG. NO_2 emission rate was positively correlated with the natural gas flow rate. For LPG combustion, the flow rate ranged from 12.11 to 69.99 g/h, and the

NO_2 emission factor ranged from 0.30 to 2.28 mg NO_2/g LPG. Overall, actual indoor NO_2 emissions from gas stoves are significantly higher than prior estimates that ignore net NO_2 loss rate. Future work should examine NO_2 surface interactions and heterogeneous chemistry to improve exposure assessments and mitigation strategies.

CRediT authorship contribution statement

Xinchen Le: Investigation, Writing – original draft. **Jianwei Gu:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Xu Du:** Investigation. **Qiaoqiao Wang:** Resources, Writing – review & editing. **Xiaoliang Qin:** Methodology, Validation. **Zhi Ning:** Resources, Writing – review & editing. **Ming Zhou:** Methodology, Writing – review & editing. **Guiying Li:** Writing – review & editing. **Taicheng An:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The study was supported by the National Natural Science Foundation of China (grant number: 42477430), the Introduction Innovative and Research Teams Project of Guangdong Pearl River Talents Program (2023ZT10L102), and special fund of Key Laboratory of Formation and Prevention of Urban Air Pollution Complex, Ministry of Ecology and Environment (grant number: SEPAir-2024080218).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2026.122199.

Data availability

Data will be made available on request.

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