Investigation of Indoor Air Quality in Residential Buildings by Measuring CO₂ Concentration and a Questionnaire Survey

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Abstract: Indoor air quality (IAQ) in houses is often deteriorated by chemical substances emitted from heating, building materials, or other household goods. Since it is difficult for occupants to recognize air pollution, they rarely understand the actual conditions of the IAQ. An investigation into the actual condition of IAQ in houses was therefore conducted in this study. Carbon dioxide (CO₂) concentrations in 24 occupied houses were measured, and the results from our analysis showed that the use of combustion heaters increased the concentration of CO₂ and led to indoor air pollution. Results indicate that as outdoor temperature decreased, the frequency of ventilation decreased simultaneously, and CO₂ concentration increased. Results of the questionnaire survey revealed that the actual IAQ in each house did not match the level of awareness its occupants had regarding ventilation. Along with this difficulty in perceiving air pollution, the lack of knowledge about ventilation systems and the effects of combustion heating may be additional barriers to IAQ awareness.

Keywords: indoor air quality; ventilation; CO₂ concentration; in-home sensing

1. Introduction

This study investigates the actual indoor air quality (IAQ) in Japanese houses by measuring carbon dioxide (CO₂) concentrations and using questionnaire surveys.

Modern people spend most of their day indoors [1,2]. The IAQ in residential buildings is often poor, polluted by chemical substances emitted from heating appliances, building materials, or other household goods. Bolstered by the increase in highly airtight houses, there have been rising concerns about the increased health risks to occupants due to exposure to indoor pollutants such as CO₂, carbon monoxide (CO), nitrogen oxides (NOₓ), and volatile organic compounds (VOCs). Despite this concern, it has proven difficult for occupants to recognize air pollution, thus preventing them from understanding the actual IAQ conditions in their homes.

Ventilation is generally recommended to prevent IAQ deterioration. In Japan, the Building Standard Law was amended to require the installation of mechanical ventilation systems in all houses built after July 2003; however, this law only mandated the installation of ventilation equipment, and it is left to occupants to ensure that they are properly ventilating their homes. In addition, houses built before July 2003 were not considered for this mandatory ventilation installation. In Japan, roughly 26% of houses were estimated to have been built since 2003 relative to the total number of houses as of 2018 [3,4]. Multiple studies have reported that the amount of ventilation obtained by activities like opening windows decreases in the winter season [5,6], and there are concerns about the deterioration of air quality in highly airtight houses in recent years.

Another factor that causes air indoor pollution is the use of combustion heaters [7–11]. Combustion heating is recognized as a major source of CO₂, sulfur dioxide (SO₂), and NOₓ emissions [8,10,12], and exposure to these substances can cause sick building syndrome [13,14]. Gas and kerosene heaters still account for a large percentage of heating devices used in Japan [15–17], and the use of combustion heating has been reported to cause CO₂ concentrations to reach 4000–5000 ppm [9–11].
The CO₂ concentration is an indicator of the retention of harmful substances, as its concentration increases with inadequate ventilation in buildings [18–22]. Many countries have regulatory standards and guidelines to maintain CO₂ concentrations below a fixed level (around 1000 to 1500 ppm) within buildings such as offices, schools, and houses [18,22,23]. The CO₂ concentration also increases with human breathing; in addition to being an indicator of the retention of harmful substances, high concentrations are also known to increase the risk of respiratory diseases, impair thinking, and lower concentration [24–27]. It has also been reported that high concentrations of CO₂ can affect the quality of sleep as well as overall performance the next day [28].

From the studies mentioned above, it can be gathered that there are two major factors that lead to air pollution in houses: inadequate ventilation and the use of combustion heaters. It is also worth considering the influence of outdoor temperature, because several studies suggest that seasonal changes affect ventilation rates [5,6,29,30]. Another important aspect is the difficulty for occupants to recognize the deterioration of IAQ. If occupants are not aware of the conditions in their immediate environment, it will be difficult for them to take appropriate actions to maintain a healthy IAQ.

Existing studies on the direct measurement of ventilation rate involve fan pressurization [5,31–33] and tracer gas [6,13,29,30], which are extremely intrusive and require expensive instruments and experts. Non-intrusive approaches that can be measured easily and at a low cost are required for widely adopted residential IAQ monitoring. CO₂ concentration is therefore focused on because it is utilized as an indicator of IAQ and can be measured easily and at low cost.

In this study, a CO₂-based investigation was conducted on the actual conditions of IAQ in Japanese houses, focusing on the following three aspects:
(i) The relationship between combustion heating and indoor CO₂ concentration.
(ii) The influence of outdoor temperature on indoor CO₂ concentration.
(iii) The gap between occupants’ awareness of ventilation and the actual IAQ in their homes.

A CO₂ sensor kit, which is inexpensive and easy to handle, was developed in this study. The CO₂ concentration in houses was measured from autumn to winter, targeting houses with different housing attributes and heating methods. A questionnaire on occupants’ knowledge and awareness of indoor ventilation was also administered. Based on the results of these investigations, the influence of combustion heating, outdoor temperature, and occupants’ attitudes on the residential IAQ are discussed hereafter.

2. Background
2.1. CO₂ Concentration as an Indicator of IAQ

CO₂ concentration is widely utilized as a comprehensive indicator of air pollution in IAQ [18–22]. Table 1 summarizes the CO₂ concentration standards and guidelines for various countries [18,22,23]. In many countries, standards and guidelines are set at 1000–1500 ppm. In Canada, a 24 h average value is defined as the exposure time. Health Canada set its acceptable long-term exposure range to 3500 ppm in its 1987 report [34]; however, this standard was changed to 1000 ppm (24-h average) in 2021 [18]. In the United States, the standard is set at 700 ppm above the outdoor level [23]. Atmospheric CO₂ concentrations have continued to rise year after year, with a global average of 414.72 ppm as of 2021 [35]. In Japan, the Building Standard Law sets the CO₂ concentration standard at 1000 ppm for buildings within a certain area, while there are no standards or guidelines for residential buildings. In addition, no specific exposure times are determined in this law.
Table 1. CO\textsubscript{2} concentration standards and guidelines in each country [18,22,23].

| Country    | Value      | Target                                      |
|------------|------------|---------------------------------------------|
| Canada     | 1000 ppm   | Residence                                   |
| Finland    | 1200 ppm   | Residence, office, school                   |
| France     | 1000 ppm   | School and office                           |
| Germany    | 1500 ppm   | School                                      |
| Holland    | 1000–1500 ppm | Residence                                |
| Japan      | 1000 ppm   | Buildings over a certain size               |
| Korea      | 1000 ppm   | Residence, office, school                   |
| New Zealand| 1000 ppm   | School                                      |
| Norway     | 1000 ppm   | School                                      |
| United States | <700 ppm  | above outdoor level Indoor                  |

Indoors with high CO\textsubscript{2} concentrations tend to retain harmful substances such as VOCs and PM\textsubscript{2.5}, because of inadequate ventilation. The second major source of pollutants in residential buildings is the use of combustion heating appliances (typically in winters). There is a close relationship between the use of combustion heating and air quality, especially the CO\textsubscript{2}, CO, NO\textsubscript{x}, SO\textsubscript{2}, and VOCs concentration, as reported in several pre-existing studies [8–11]. Combustion heating with gas or kerosene is still the main heating method in Japan [15–17], and the WHO reports that these remain in use in some parts of the world [7].

Exposure to these harmful substances, due to a lack of ventilation, has been reported to increase the risk of various respiratory diseases [36–39]. For example, Sun et al. investigated the relationship between the amount of ventilation and sick building syndrome in Chinese homes [13].

Simultaneously, high CO\textsubscript{2} concentrations may have adverse effects of their own. As mentioned in Section 1, CO\textsubscript{2} concentration increases with human breathing as well as the use of combustion appliances, and high CO\textsubscript{2} concentrations are also known to increase the risk of respiratory diseases, impair thinking, and lower concentration, quality of sleep and overall performance the next day [24–28].

2.2. In-Home Sensing with IoT Sensors

Studies on residential monitoring have been increasing owing to the highly economical Internet of Things (IoT) sensors [40–42]. In-home sensing is mainly utilized for healthcare monitoring systems, which are collectively called ambient assisted living [43–46].

On-site real-time measurement of the ventilation rate can be replaced by the collection of CO\textsubscript{2} sensor data. As mentioned in Section 1, direct ventilation measurement is both intrusive and expensive, and is also difficult to measure for a long period of time in a large number of houses. Sensor-based approaches are therefore expected to alleviate the impact on research participants, while achieving cost-effective measurements. These advantages allow ventilation monitoring for larger numbers of houses over a longer period of time.

Existing studies on IAQ in houses, described in Section 2.1, focus on the CO\textsubscript{2} concentration as an air quality indicator and investigate its relationship with ventilation and combustion heating. However, comparisons among different heating appliances and the effects of seasonal variations are limited, and there are still unknowns in these areas. Existing studies [8–11] on combustion heating only investigated the impact of combustion, and did not compare it to homes without combustion heating (i.e., they had no controls in their study for comparison). Shinohara et al. observed the influence of the amount of ventilation in the house and seasonal variation, but argued that individual differences were much higher in Japan [6]. The following aspects are therefore necessary for an accurate investigation of the IAQ:

First, a survey must be conducted on the various patterns of indoor heating, in addition to houses using combustion heating. It is necessary to investigate air quality in a wide range of homes, including those that use only combustion heating, those that do not use...
combustion heating, and those that use multiple heating systems; this will clarify the relationship with the heating appliances used.

Second, the aforementioned investigation should not be limited to a short period of time, but should be conducted to consider seasonal changes such as in autumn and winter. There is a close relationship between awareness of ventilation and IAQ, which is greatly affected by outdoor temperature. For example, measuring the transition from autumn to winter would enable an investigation that is closer to the actual situation.

3. Experimental Design

3.1. Scope of the Investigation

The CO$_2$ concentration is investigated as an indicator closely related to IAQ, and actual measurement of the CO$_2$ concentration in houses was conducted for six months, i.e., from 1 October 2020, to 31 March 2021. Results of the questionnaire survey on the awareness of ventilation and the implementation of ventilation in each season are also considered, and their relationship with the measured IAQ is discussed.

As mentioned in Section 1, in order to clarify the actual state of the IAQ in houses, it is necessary to conduct an investigation focusing on three points: (1) the influence of heating appliances on IAQ; (2) the influence of outdoor temperature; and (3) the gap between occupants’ awareness of ventilation and actual IAQ. In section 4, experimental results of the measurement of the CO$_2$ concentration are analyzed from these points of view. The results for (1) and (2) are described in Section 4.1, focusing on the measurement results, and results for (3) are mentioned in Section 4.2, focusing on results of the questionnaire.

3.2. Research Participants

In order to measure the CO$_2$ concentrations in occupied homes, 24 research participants living in urban areas were selected; Table 2 lists the participants’ houses and housing attributes. As shown in Figure 1, to exclude extremely warm or cold regions, participants’ houses were selected from the same climatic zone as Tokyo, according to definitions by Japan’s Ministry of Land, Infrastructure, Transport and Tourism [47]; Table 3 lists the climate data for Tokyo.

Figure 1. Target area of the experiments (in red). Extremely warm or cold regions were excluded.
Table 2. Characteristics of research participants for the experiments.

| ID | House   | Structure     | Year Built | # of Occupants | Heating Appliances in the Living Room |
|----|---------|---------------|------------|----------------|----------------------------------------|
| 1  | Apartment| RC            | 1999       | 3              | Elec. heater                           |
| 2  | Apartment| RC            | 2003       | 5              | AC (Air Conditioner), floor heating    |
| 3  | Apartment| RC            | 2002       | 1              | AC                                     |
| 4  | Apartment| RC            | 2002       | 1              | AC                                     |
| 5  | Apartment| Steel-framed  | 1981       | 3              | AC, elec. heating carpet               |
| 6  | Apartment| RC            | 2000       | 2              | AC, elec. heater                       |
| 7  | Apartment| RC            | 1986       | 1              | AC, elec. heater                       |
| 8  | Apartment| Wooden        | 1966       | 1              | AC                                     |
| 9  | Detached | Wooden        | 2011       | 5              | Floor heating                          |
| 10 | Detached | Wooden        | 2012       | 3              | AC, floor heating                      |
| 11 | Detached | Wooden        | 2013       | 4              | AC, kotatsu (table over an electric heater) |
| 12 | Detached | Wooden        | 1975       | 5              | AC, Central AC                         |
| 13 | Detached | Wooden        | 2021       | 2              | AC                                     |
| 14 | Detached | Wooden        | 1989       | 4              | AC, floor heating, elec. heater        |
| 15 | Detached | Wooden        | 1987       | 2              | Gas heater                             |
| 16 | Detached | Steel-framed  | 2014       | 2              | Gas heater, kotatsu                    |
| 17 | Detached | Wooden        | 1990       | 4              | Gas heater, AC                         |
| 18 | Detached | Wooden        | 2010       | 4              | Kerosene heater, AC, heating carpet    |
| 19 | Detached | Wooden        | 1964       | 2              | Kerosene heater, AC, elec. heater, kotatsu |
| 20 | Detached | Wooden        | 1988       | 2              | Gas heater                             |
| 21 | Detached | Wooden        | 1979       | 3              | Gas heater, floor heating              |
| 22 | Detached | Wooden        | 1975       | 3              | Kerosene heater, AC, kotatsu           |
| 23 | Detached | RC            | 2000       | 4              | Gas heater, AC                         |
| 24 | Detached | Wooden        | 1997       | 3              | Kerosene heater, AC, elec. heater      |

Table 3. Daily mean of outdoor temperature for Tokyo, Japan.

| Day | 2020  | 2021  |
|-----|-------|-------|
|     | Oct.  | Nov.  | Dec.  | Jan.  | Feb.  | Mar.  |
| 1   | 19.5  | 14.3  | 10.2  | 4.4   | 7.2   | 11.8  |
| 2   | 21.0  | 15.6  | 8.2   | 4.8   | 8.8   | 13.5  |
| 3   | 21.7  | 14.8  | 8.1   | 3.7   | 6.2   | 7.4   |
| 4   | 22.0  | 13.7  | 9.2   | 5.8   | 7.0   | 9.0   |
| 5   | 21.7  | 13.4  | 6.6   | 6.0   | 7.1   | 11.8  |
| 6   | 21.0  | 12.8  | 8.2   | 5.3   | 8.9   | 13.8  |
| 7   | 18.3  | 15.5  | 9.7   | 6.3   | 9.9   | 7.8   |
| 8   | 14.7  | 17.3  | 11.4  | 2.4   | 6.1   | 6.6   |
| 9   | 14.5  | 13.5  | 9.8   | 2.9   | 4.7   | 9.6   |
| 10  | 16.0  | 11.9  | 9.3   | 2.6   | 6.7   | 12.0  |
| 11  | 19.8  | 11.9  | 10.2  | 2.3   | 8.7   | 9.9   |
| 12  | 21.5  | 10.2  | 11.4  | 3.4   | 7.8   | 12.7  |
| 13  | 22.1  | 13.7  | 9.9   | 5.8   | 10.4  | 11.1  |
| 14  | 20.3  | 14.7  | 8.5   | 7.9   | 12.3  | 12.5  |
| 15  | 16.8  | 13.4  | 6.1   | 6.6   | 11.4  | 12.9  |
| 16  | 16.1  | 14.7  | 4.6   | 10.0  | 10.6  | 14.5  |
| 17  | 12.7  | 15.2  | 4.3   | 6.1   | 7.6   | 13.7  |
| 18  | 14.3  | 15.8  | 6.1   | 4.3   | 4.3   | 12.3  |
| 19  | 13.1  | 19.1  | 5.6   | 4.4   | 6.9   | 12.9  |
| 20  | 15.6  | 21.9  | 4.4   | 3.9   | 10.2  | 14.1  |
| 21  | 16.0  | 16.6  | 5.3   | 4.8   | 13.9  | 16.7  |
| 22  | 17.4  | 15.0  | 5.6   | 8.7   | 14.9  | 12.1  |
| 23  | 16.8  | 15.5  | 7.7   | 6.4   | 11.0  | 10.8  |
| 24  | 17.3  | 11.8  | 8.0   | 4.3   | 6.4   | 13.8  |
| 25  | 15.5  | 10.5  | 8.7   | 7.6   | 6.6   | 14.5  |
| 26  | 16.2  | 12.8  | 6.4   | 7.5   | 8.7   | 14.5  |
| 27  | 16.7  | 11.6  | 7.8   | 10.3  | 5.7   | 13.7  |
| 28  | 16.6  | 11.8  | 8.5   | 4.4   | 6.6   | 16.5  |
| 29  | 17.3  | 10.1  | 8.7   | 5.3   | -     | 17.5  |
| 30  | 14.9  | 9.9   | 6.9   | 4.1   | -     | 17.8  |
| 31  | 13.8  | -     | 3.4   | 5.4   | -     | 17.9  |

Participants’ houses were selected to have a diverse, holistic representation of types of dwelling, their structure, and the age of the building. Since the purpose of this experiment was to investigate the relationship between the heating equipment used and air pollution,
we selected 14 houses that do not use combustion heating equipment and 10 houses that do. As shown in Table 2, most houses that use combustion heating also use multiple heating appliances such as air conditioners (ACs).

3.3. Measurements And Questionnaires

Experiments consisted of measurements in the participants’ houses and a questionnaire survey completed by the participants.

A sensor kit (see Figure 2) was installed in the living room of each house to measure the indoor CO$_2$ concentration and temperature. This kit was developed based on the Raspberry Pi 3 B+, and measurement data were automatically uploaded to a cloud server through an LTE modem. CO$_2$ concentration was measured using a Figaro CDM7160-C00 gas sensor, which can measure in the range of 360–5000 ppm in 1 ppm increments, with an accuracy of ±(50 ppm + 3%), and is pre-calibrated. An OMRON 2JCIE-BU01 environmental sensor was used to measure indoor temperature. Software programs to collect sensor data were also developed by the authors for the experiments, with each data being collected in real time at 10 s intervals. The installation of this sensor kit required a space that was approximately 20 cm in width and depth, and 15 cm in height. Each sensor costs approximately USD $350, which can be reduced to approximately $150 by minimizing the components to only measure the CO$_2$ concentration. The sensor kits were all shipped to the research participants, who assembled and installed them independently following the instructions shown in Figure 3. Sensor kits were requested not to be installed on the floor or near heating and ventilation equipment.

Figure 2. Sensor kit for measuring CO$_2$ concentration.

**Instructions for assembling the sensor kit**

Please connect the USB devices and the power outlet as shown in the figure below.

Figure 3. Instructions for assembling the sensor kit (distributed to research participants).
The questionnaire was conducted once online in mid- to late-December 2020, asking participants to provide detailed answers about their housing attributes, building age, the number of occupants, household composition and heating methods, as well as questions about their awareness of ventilation and how often they ventilate their homes each season. Figure A1 in Appendix A shows the list of all questions of the questionnaire survey. In addition to these measurements and questionnaires, participants were approached separately if any additional details needed to be understood from their measurement data or questionnaire responses.

4. Results of Field Investigation

4.1. Measurement Results

4.1.1. Effect of Combustion Heating Use

Figure 4 shows the monthly distribution of CO$_2$ concentrations from October 2020 to March 2021 as a box plot. This box plot shows the maximum value excluding outliers, upper quartile, median, lower quartile, and minimum value excluding outliers, respectively, from top to bottom. In Figure 4, the vertical axis represents the CO$_2$ concentration, while the horizontal axis represents the identification number, i.e., ID of each participant’s house. As shown in Table 2, houses from ID 15 onwards use combustion heating.

The results shown in Figure 4 indicate that the CO$_2$ concentration in many houses with combustion heating equipment (i.e., ID 15–24) had risen significantly since December 2020, reaching between 3500 ppm and 5000 ppm (in rare cases), as compared to houses without combustion heating. This result shows a similar trend to that of the existing surveys [9–11]. However, it cannot be concluded from this that the air is clean just because combustion heating is not used, as the concentration reaches around 3000 ppm in some houses (i.e., ID 1–14) that do not use combustion heating at all. This peculiarity is discussed in Section 5.

The aforementioned results also show that there are some houses with low CO$_2$ concentrations, despite their use of combustion heating. This may be due to the use of other heating appliances such as air conditioners, although this balance varies from house to house. Figure 5 shows the CO$_2$ concentration and indoor temperature on any given day for a house using both combustion heaters and air conditioners.

In both types of houses, a sharp increase in the CO$_2$ concentration was observed at around 7:00 a.m., and the indoor temperature increased at the same time, which can be attributed to the use of combustion heating. At ID 17, as shown in Figure 5a, the CO$_2$ concentration exceeded 3500 ppm in the morning and often reached 2000–3000 ppm during the day thereafter. In contrast, ID 24, as shown in Figure 5b, showed that the CO$_2$ concentration reached 2500 ppm for a short period in the morning, but then remained in the range of 1000–2000 ppm. Based on indoor temperature trends, it can be estimated that the occupants of both houses are in the living room from morning to nighttime, or at least continue to use some kind of heating system in these rooms. Therefore, these results suggest that while IDs 17 and 24 use both combustion heating and air conditioning, the former uses combustion heating for a relatively long period of time, while the latter uses it for a short period of time. When participants were interviewed about their heating habits, it was found that occupants of ID 24 used combustion heating only for rapid heating when the indoor temperature was low, and air conditioning was the main heating source for the rest of the day. This difference in behavioral habits can be seen in the difference in concentration distribution after December, as shown in Figure 4.
| Month          | Identification number | CO₂ [ppm] | Houses NOT using combustion heating | Houses using combustion heating |
|---------------|-----------------------|-----------|-------------------------------------|---------------------------------|
| October, 2020 | 1-14                  | 1-14      | 1-14                                | 1-14                            |
| November, 2020| 1-14                  | 1-14      | 1-14                                | 1-14                            |
| December, 2020| 1-14                  | 1-14      | 1-14                                | 1-14                            |
| January, 2021 | 1-14                  | 1-14      | 1-14                                | 1-14                            |
| February, 2021| 1-14                  | 1-14      | 1-14                                | 1-14                            |
| March, 2021   | 1-14                  | 1-14      | 1-14                                | 1-14                            |

Figure 4. Monthly distribution of CO₂ concentration in participants’ houses.
4.1.2. Relationship between CO₂ Concentration and Outdoor Temperature

Figure 6 shows the daily averages of outdoor temperature and indoor CO₂ concentration inside houses, values for which are plotted on a scatter plot. Each plot shows the fitting line, its equation, and the coefficient of determination $R^2$. Note that the range taken by the vertical axis depends on the concentration distribution of each house, in order to show the relative trend.

Results indicate that the outdoor temperature and CO₂ concentration have negatively correlation in all houses except for ID 13, regardless of the heating appliance(s) used, although the strength of the correlation varies from house to house. As shown in Figure 4, the increase in CO₂ concentration is more obvious in the winter season, when the outdoor temperature drops in houses using combustion heating; the same trend of increasing concentration can also be observed in houses that are not using combustion heating. This is especially noticeable in apartment houses ID 1–8, where the number of houses with concentrations reaching 2000 ppm increases as the outdoor temperature decreases.

The CO₂ concentration trend for ID 14 is shown in Figures 7 and 8 as examples of a house that can be assumed to have decreased ventilation under the influence of a decrease in outdoor temperature; gray periods in Figure 7 represent the missing measurements due to sensor failure. In this experiment, the missing rate of measurement was 1.38%. Since ID 14 does not use combustion heating, the CO₂ concentration does not increase because of the use of a heating appliance. However, Figures 7 and 8 show that the concentration increases from November to January. From this observation, it can be assumed that the ventilation frequency and volume gradually decreased as the outdoor temperature became colder.
Figure 6. Relationship between daily averages of indoor CO₂ concentration and outdoor temperature.
Figures 9 and 10 show the trend of CO$_2$ concentration for ID 18, which uses combustion heating; the results shown in Figure 9 indicate that the indoor CO$_2$ concentration in this residence increased rapidly after mid-December. ID 18 shows a similar gradual upward trend as ID 14 from October to November 2020, but the CO$_2$ concentration begins to reach 3000 ppm at certain times of the day from mid-December onward, becoming higher still in January. The relationship between the outdoor temperature and indoor concentration shown in Figure 6, the difference is clear: ID 14 shows a linear relationship between outdoor temperature and concentration, although the $R^2$ value for ID 18 (0.633) is higher than the value for ID 14 (0.489), while ID 18 shows a non-linear change after an outdoor temperature of approximately 10 °C. The same trend is observed in IDs 16, 20, 22, etc., where combustion heating is used. The sudden increase in the concentration indicates that combustion heating begun to be used. From Figures 6 and 10, it can be inferred that the timing of use in ID 18 is when the outdoor temperature drops to approximately 10 °C. On the other hand, ID 5, 10, and 21 apparently deviated from the negative correlation when the outside temperature was below 10 °C. In these houses, ventilation behavior, such as not opening windows to ventilate when it is cold outside, may have had an impact.
Thus, regardless of the type of heating equipment used, CO$_2$ concentration tends to increase as the outdoor temperature decreases. The causes for this trend include combustion heating and a lack of ventilation.

For ID 13, the concentration distribution in January 2021 was lower than that in December 2020, as shown in Figure 4; the relationship between CO$_2$ concentration and outdoor temperature for ID13 differed from that for the other houses, with a weak positive correlation, as shown in Figure 6. As for the former, it can be gathered from the results of the interviews that the door to the adjacent room was opened because the air conditioner broke down, and that the ventilation fan was cleaned in early January 2021, both of which may have affected the results. For the latter, the interviews revealed that pets were often in the living room and the air conditioner was always in use, except on days when the outdoor temperature was high. Owing to these circumstances, ID 13 showed a different trend from the other houses.

4.2. Questionnaire Results

This section describes the results of the questionnaire survey of participants regarding their awareness of ventilation and people’s behavior regarding ventilation.

Q7 and Q8 in Table 4 show the results of questions about interest in ventilation and whether the home is ventilated. In Q7, 20 out of the 24 participants answered that they were interested in ventilation. The majority of the respondents in Q8 answered that their self-evaluation of ventilation was “well enough done” or “more or less done,” reflecting the high level of interest in ventilation indicated in Q7.

Results of the questionnaire also supported the notion that the ventilation frequency was influenced by seasonal variations. In Q9-10 of Table 1, the number of participants who answered “always” decreased from 7 in spring and autumn to 2 in summer and winter. Conversely, the number of respondents who answered “almost never” increased from two to eight. Even among the participants who responded that the frequency of ventilation had not decreased, most of them showed an increase in the CO$_2$ concentration with a decrease in temperature, as shown in Figure 6, which suggests that the frequency of ventilation decreased.

Q11 in Table 4 are the results of a question regarding the frequency of cleaning 24-h ventilation and ventilation openings in bathrooms and toilets. More than half of the participants answered “not at all” or “not sure.” High interest in ventilation does not necessarily lead to proper management of ventilation equipment.

Table 5 shows the results of the question about reasons for wanting to ventilate, and Table 6 shows the results of the question about reasons for not needing to ventilate. “Want to bring in fresh air” was indicated as the most common reason given for wanting ventilation; on the other hand, the most common reason for not ventilating was “because it’s cold (or hot),” which is consistent with the trend shown in Figure 6.
Table 4. Responses to questions about ventilation concerns and behaviors. The darker the color of the answer, the worse it is for indoor air quality.

| ID | Q7: Concern about Ventilation | Q8: How Well Is Your House Ventilated? | Q9-10: Frequency of Ventilation | Q11: Frequency of Cleaning the Ventilation Filter |
|----|------------------------------|---------------------------------------|-------------------------------|---------------------------------|
| 1  | Strongly interested          | More or less done                     | Always                        | Almost once a day               | About once every few months    |
| 2  | Strongly interested          | More or less done                     | Always                        | Almost never                    | Not at all                     |
| 3  | Not interested at all        | Not done at all                       | Almost never                  | Not done                        | Not sure                      |
| 4  | Strongly interested          | Not done at all                       | Almost never                  | Almost never                    | Not sure                      |
| 5  | Slightly interested         | More or less done                     | About once every few hours    | About once every few hours      | Not sure                      |
| 6  | Slightly interested         | Well done enough                      | About once every few hours    | About once every few hours      | Not sure                      |
| 7  | Slightly interested         | More or less done                     | About once every few hours    | About once every few hours      | Not sure                      |
| 8  | Strongly interested          | More or less done                     | At least once an hour         | At least once an hour           | About once every few months   |
| 9  | Strongly interested          | More or less done                     | Always                        | Almost never                    | About once every few months   |
| 10 | Not very interested         | More or less done                     | About once a day              | About once a day                | About once a year              |
| 11 | Not very interested         | Not much done                         | About once a day              | Almost never                    | Not sure                      |
| 12 | Not very interested         | More or less done                     | About once a day              | Almost never                    | Not sure                      |
| 13 | Slightly interested         | More or less done                     | About once every few hours    | About once every few hours      | About once a year              |
| 14 | Strongly interested          | Well done enough                      | Always                        | Always                          | Not at all                     |
| 15 | Strongly interested          | Not much done                         | About once every few hours    | About once a day                | About once a year              |
| 16 | Slightly interested         | Well done enough                      | About once every few hours    | About once every few hours      | About once a year              |
| 17 | Slightly interested         | Well done enough                      | Always                        | Almost never                    | Not at all                     |
| 18 | Slightly interested         | Well done enough                      | Always                        | About once every few hours      | Not at all                     |
| 19 | Slightly interested         | More or less done                     | Always                        | About once every few hours      | Not at all                     |
| 20 | Slightly interested         | More or less done                     | About once a day              | About once a day                | About once a year              |
| 21 | Slightly interested         | Not much done                         | About once every few hours    | About once every few hours      | About once a year              |
| 22 | Slightly interested         | Not much done                         | About once a day              | About once every few hours      | About once a year              |
| 23 | Slightly interested         | Not much done                         | About once a day              | About once every few hours      | About once a year              |
| 24 | Strongly interested          | Not much done                         | About once a day              | Almost never                    | Not at all                     |

Table 5. Answers to a question about the need for ventilation (multiple answers possible).

**Q12: Why do you want to ventilate the room?**

| Answer                                                                 | # of Responses |
|------------------------------------------------------------------------|----------------|
| To bring fresh air.                                                    | 22             |
| To adjust the indoor temperature                                       | 5              |
| It’s good for health.                                                  | 3              |
| To prevent colds and other infectious diseases.                        | 7              |
| To prevent condensation and mildew on windows.                         | 8              |
| The room smells bad.                                                   | 11             |

Table 6. Answers to a question about when ventilation is not needed (multiple answers possible).

**Q13: Why do you think it is not necessary to ventilate the room?**

| Answer                                                                 | # of Responses |
|------------------------------------------------------------------------|----------------|
| Because the air outside is so polluted.                                | 0              |
| Because it’s cold (or hot) when ventilated.                           | 19             |
| Because it’s already ventilated.                                       | 2              |
| Because I’m using an air purifier.                                     | 1              |
| Because some of us have hay fever.                                    | 4              |
| Because some of us have respiratory problems.                         | 0              |
| I’ve never considered that I don’t need to ventilate.                  | 4              |

5. Discussion

The state of IAQ was investigated through the measurement of CO₂ concentrations in houses and questionnaire surveys, and these findings are discussed in this section.

5.1. IAQ Pollution from Combustion Heating

The use of oil- and gas-fired heating appliances was found to cause significant increases in CO₂ concentrations, leading to indoor air pollution with concentrations ranging from 3000-5000 ppm. This is similar to the results of the existing studies described in Section 2; such an environment is both uncomfortable and raises concerns about health effects due to long-term exposure.

In contrast, the CO₂ concentration was relatively lower in houses with multiple heating appliances, such as air conditioners, than in houses with only combustion heating, suggesting the possibility of reducing air pollution by using multiple heating methods.
Although it is necessary to consider other factors, such as the airtightness of the house and the amount of ventilation, this result implies that the combined use of air conditioners and other devices might lead to IAQ improvement.

All of the existing measurement case studies were conducted only for the use of combustion heating, and the results described in this paper are findings obtained by targeting houses with various heating methods.

5.2. Influence of Outdoor Temperature on Ventilation

As shown in Figures 4 and 6, the CO$_2$ concentration tends to increase with decreasing outdoor temperature in many houses. This result can be attributed to a decrease in the frequency of ventilation, including window opening, in order to avoid a drop in room temperature due to air exchange. This is supported by the results of the questionnaire responses described in Section 4.2 and by the existing study [48].

Various pollutants such as CO, NO$_x$, SO$_2$, and VOCs are likely to be retained in houses with high CO$_2$ concentrations and insufficient ventilation, which may cause Sick Building Syndrome and respiratory diseases caused by long-term exposure [13,14,36–39]. In addition, even when considering the effects of CO$_2$ alone, high concentrations have negative effects, such as reducing the ability to think, concentrate, and sleep [26–28].

Changes in the CO$_2$ concentration are difficult for occupants to perceive. It is necessary to implement methods to maintain a clean IAQ without relying on human senses, such as constantly measuring the concentration and encouraging ventilation at appropriate times.

5.3. Gap between Occupants’ Awareness of Ventilation and the Actual IAQ

The results of the measurements in houses and the questionnaire survey conducted in this study showed that the actual IAQ does not match occupants’ awareness of ventilation. This could be attributed to the inability of occupants to perceive air pollution, as well as a lack of knowledge about the ventilation system of the house and the effects of combustion heating as barriers.

On the other hand, occupants are highly interested in ventilation in their homes, and there is considerable room for improvement in residential IAQ. If appropriate solutions for improvement can be presented to occupants based on the findings of this study, they will be able to understand the actual conditions in their homes, and can be expected to change their behavior to achieve a healthy and comfortable air environment.

6. Conclusions

In this study, the true condition of residential IAQ was investigated by measuring the CO$_2$ concentration and a questionnaire survey. From the results obtained, the relationship between factors such as the heating method, outdoor temperature, and air pollution was clarified. The main findings and suggestions obtained in this study are as follows:

- The CO$_2$ concentration increased significantly with the use of combustion heating equipment, resulting in air pollution in the house. This air pollution could be reduced by using non-combustion heating methods such as air conditioners.
- In many houses, mainly apartment complexes, it was found that the CO$_2$ concentration tends to increase as the outdoor temperature decreases. This result is presumably due to the fact that the frequency of ventilation, such as window opening, decreases in order to avoid a decrease in indoor temperature in the winter season, when the outdoor temperature decreases.
- The actual IAQ in each house does not match occupants’ awareness of ventilation. In addition to the occupants’ difficulty in perceiving air pollution, the lack of knowledge about the ventilation system and the effects of combustion heating might be additional barrier.

Based on these results, methods to improve residential IAQ should be studied in future work. Specifically in addition to the CO$_2$ concentration, substances such as CO, NO$_x$, and VOCs should be measured to clarify the relationship between each substance, and to
investigate which behaviors lead to deterioration of the IAQ. Methods to improve the IAQ can subsequently be developed through technologies such as information provision and automation systems. It is important to utilize these methods to raise awareness of IAQ and to inform occupants about the harmful effects of pollutants. Since ventilation causes a decrease in heating efficiency, energy conservation in heating use is also an important issue. Future studies should also include methods to achieve both healthy IAQ and high energy efficiency.

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Appendix A

Figure A1 shows a list of the questions from the questionnaire conducted for the subjects.
| Question                                                                 | Answer                                                                 |
|--------------------------------------------------------------------------|------------------------------------------------------------------------|
| Q1. Choose your type of residence.                                       | ☐ Rented house (detached)                                               |
| Q2. Choose the housing structure of your house.                          | ☐ Wooden                                                               |
| Q3. Fill in the age of your house.                                       | (Fill in the number)                                                   |
| Q4. Fill in the number of occupants in your house.                       | (Fill in the number)                                                   |
| Q5. Fill in the household composition of your residence.                 | (Fill in letters)                                                      |
| Q6. Choose the heating appliances used in the living rooms of your residence. | ☐ Air Conditioner                                                     |
| Q7. Are you concerned about ventilation in your house?                   | ☐ Strongly interested                                                   |
| Q8. How well is your house ventilated?                                   | ☐ Well enough done                                                     |
| Q9. When you are at home in the spring or autumn, how often do you open the windows to ventilate your home? | ☐ Always                                                               |
| Q10. When you are at home in the summer or winter, how often do you open the windows to ventilate your home? | ☐ Always                                                               |
| Q11. How often do you clean your ventilation filters?                    | ☐ More than once a month                                               |
| Q12. Why do you want to ventilate the room?                              | ☐ To bring fresh air                                                   |
| Q13. Why do you think it is not necessary to ventilate the room?         | ☐ Because the air outside is so polluted.                              |

Figure A1. Questionnaire survey regarding housing attribute, their awareness and behavior of ventilation.
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