Research Article
Towards Healthy Levels of Carbon Dioxide in Schools of the National Oil Company of Abu Dhabi

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In their annual indoor air quality assessment for ADNOC Schools, the Abu Dhabi Education Council has reported hazardous levels (~3000 ppm) of carbon dioxide in fifteen classrooms. Exposure of 5,090 students attending the school for ~eight hours (typical school day) to such high levels of carbon dioxide would induce adverse health conditions like headaches, drowsiness, and lack of concentration on the short term and serious diseases like asthma and sick building syndrome on the long term. The Health, Safety, and Environment committee of the school has identified clogged air intake vents and dirty AC filters as the main cause of the high carbon dioxide concentrations reported. The outdoor (ambient) carbon dioxide level is measured and has an eight-hour average value of 419 ppm. After cleaning thoroughly, the indoor levels of carbon dioxide, temperature, and relative humidity were monitored simultaneously in each classroom and have average values of ~1117 ppm, ~24°C, and ~37%, respectively. In addition, the average indoor-to-outdoor ratio of carbon dioxide has been improved from 3000/419 ≈ 7.2 before cleaning the AC filters to an average ratio of (1,117/419 ≈ 2.7) after cleaning. Thus, ventilation rates in the classrooms monitored in this project are adequate and the corrective actions taken were effective.

1. Introduction

Data of the US Environmental Protection Agency (EPA) indicate that indoor pollution levels may be 2–5 times higher than those of outdoor levels [1]. High levels of indoor air pollution are of particular interest because it is estimated that people spend most (~90%) of their times indoors [2]. The exposure to high levels of indoor air pollutants has increased over the past several decades. This increase may be attributed to reduction of ventilation rates to save energy; use of synthetic building materials and furnishings; and use of chemically formulated personal products, pesticides, and cleaning supplies.

In schools, good indoor air quality (IAQ) contributes to a favourable learning environment for students, protects health, and assists with the core mission—education. The presence of a wide variety of emission sources like art and science supplies makes sustaining good IAQ a challenge [3]. In particular, children are more sensitive to pollutants than adults because they have high inhalation rates per body mass and their respiratory and immune systems are still developing [4]. Failure to respond promptly to IAQ problems in schools may lead to short- and long-term respiratory health issues [5] as dry cough, rhinitis, and nasal patency in children [6]; occurrence of sick building syndrome among students [7, 8]; asthma [9]; and poor academic achievement [10].

The adequacy of the supply of fresh air in buildings including schools is commonly evaluated by investigating the level of carbon dioxide (CO₂) concentration in a room [11, 12]. This gas is a natural constituent of the atmosphere and is emitted from humans during exhalation. High concentration levels of CO₂ indicate poor air quality due to inadequate ventilation. This may cause students to loss conscious (fainting), to get headaches, or to function with lower activity levels. The relation between CO₂
concentration and student absences was investigated [8, 13]. The relation between certain CO₂ concentration levels and the corresponding IAQ effects is summarized by Pietrucha [14] in Table 1.

The concentration of CO₂ gas in a given sample of air is relatively easy to measure [15]. Its concentration is expressed in units of parts per million (ppm); a ratio that indicates the number of CO₂ molecules per million molecules of air. Outdoor CO₂ levels must be measured when assessing indoor concentrations because the outdoor CO₂ directly impacts the indoor concentration. In outdoor air, CO₂ concentration normally varies from 350 to 450 ppm [16]. The adequacy of ventilation may be measured by the number of cubic feet of air per minute (cfm) provided per person. Alternatively, adequacy of ventilation can be evaluated by indoor CO₂ concentrations. For instance, a CO₂ level of 1000 ppm is equivalent to 15 cubic feet of fresh air per minute per person [17]. The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) has recommended indoor CO₂ levels that do not exceed the local outdoor concentration by more than about 700 ppm [18]. The ASHRAE standard 62.1–2013 recommends indoor CO₂ levels at less than 1000 ppm in schools and 800 ppm in offices [19]. The National Institute for Occupational Safety and Health (NIOSH) considers that indoor air concentrations of CO₂ that exceed 1000 ppm are a marker of inadequate ventilation [20]. Indoor air temperature (T) and relative humidity (RH) are key indicators of occupants’ thermal comfort [21]. High RH may cause condensation and mould formation, which is unhealthy for occupants and children [22].

In their annual IAQ walk-through assessment of ADNOC Schools, the Abu Dhabi Education Council (ADEC) has reported hazardous levels (~3000 ppm) of CO₂. Such high levels of CO₂ would induce adverse health conditions like asthma, headaches, drowsiness, and lack of concentration to a large number of personnel (~6304) distributed among 6 campuses of ADNOC Schools. In particular, 5090 students spending ~8 hours of their time indoors would be affected mostly as their respiratory system is still developing. Therefore, the Health, Safety, and Environment (HSE) committee of the school has decided to reduce the reported high CO₂ concentration levels. The aim of this study is to evaluate the indoor air quality before and after a set of corrective actions were taken.

2. Methodology

The environment inside a building can be controlled by a system of heating, ventilation, and air-conditioning (HVAC). This system maintains a comfortable humidity level and uses a thermostat to control the air temperature inside a room by heating or cooling. The HVAC system dilutes indoor pollutants with outdoor air. Fans circulate air through filters to extract dust. To supply clean air, an inlet is placed (on roof) as far as possible from the ground. However, leaky windows allow dust to clog filters, which slows air circulation and causes buildup of high CO₂ levels. In ADNOC Schools, a mechanical (SKM, model APCN-5240Y) HVAC system has been placed on the rooftop. This system incorporates bag and metal filters to extract dust from air flowing to the buildings. The manufacturer recommends a quarterly cleaning for most air filters. However, the UAE has a dusty environment, which demands a more frequent cleaning of AC filters.

In resolving the high CO₂ levels reported by the ADEC, clogged filters have been cleaned thoroughly and defective bag filters are replaced. Windows’ rubber frames have been maintained. Figure 1 shows a random AC filter before and after cleaning.

Effectiveness of the corrective actions taken in this project has been evaluated by monitoring the CO₂ concentration levels before and after cleaning the clogged AC filters. Ten-minute walk-through measurements were taken before and after cleaning the filters. Measurements were made using the portable Fluke model 975 air meter, which monitors CO₂ concentration levels, temperature, and relative humidity simultaneously. The range, resolution, and accuracy of this instrument are summarized in Table 2 below.

Since the indoor CO₂ concentrations are directly impacted by the outdoor CO₂ levels, the ASHRAE recommends an indoor CO₂ standard maximum level that does not exceed the outdoor concentration by more than about 700 ppm [23]. Thus, another identical air meter was placed on the rooftop near the inlet of the AC ventilation to quantify the background CO₂ levels. Care was taken to place air meters in locations that would not be directly impacted by the breath of individual children. In each location, the meter was placed one meter above the floor at the level of student desk and about one meter from the walls, away from doors and windows, thus avoiding possible air disturbances as can be noticed in Figure 2.

To reach a steady state of occupancy and ventilation, doors and windows of each classroom are kept locked and a reasonable time (~5 minutes) was allowed before each measurement could be made. Ten-minute measurements could be made during lessons (occupied periods). The code number of each classroom is stored in the memory of the air meter ahead of measurements. Following this methodology, a real-time monitoring of CO₂ levels, temperature, and RH is made in fifteen locations indoors of the male campus building of ADNOC Schools before and after cleaning of the AC filters.

3. Results and Discussion

Air quality was evaluated during the typical school day of January 8th 2015. Indoor CO₂ concentrations are directly impacted by the outdoor (background) CO₂ levels. Thus, the indoor and outdoor CO₂ levels, air temperature (T), and RH were measured simultaneously.

3.1. Outdoor Air Quality. The outside air concentration of CO₂ is measured close to the region where the fresh air is drawn into the building. An air meter was placed on the
central area of the rooftop near the inlet of the AC units. The outdoor air quality has been measured continuously as a function of Abu Dhabi local time from 7:00 am to 3:00 pm with two-minute intervals. This measurement monitored the background CO$_2$ levels as referenced to the primary axis of Figure 3, while the ambient temperature in degree Celsius and RH are both measured and referenced to the secondary axis.

Outdoor CO$_2$ concentrations varied from 404 ppm at 9:45 am to 435 ppm at 7:31 pm with an eight-hour average value of 419 ppm. This background CO$_2$ is normal and primarily due to vehicle emissions. Outdoor air temperature has varied from 21°C at 7:11 am to 28°C at 2:19 pm with an average of $\sim$26°C, while the RH has varied from 40% at 2:21 pm to 77% at 7:11 am with an average of $\sim$57%.

Bus loading/unloading areas, staff parking lot, swimming pools, and shaded playground shown in Figure 4 are identified as hazardous zones (for students/staff who are in these areas) during the time intervals 7:10–8:00 am and 2:30–3:00 pm. These zones are all outdoor locations. During bus loading and unloading times, students and staff who are close to buses are advised to wear a face mask as they are exposed directly to CO$_2$ levels that are much higher than those detected on the rooftop.

Table 1: Description of indoor air quality on the basis of CO$_2$ concentrations.

| Indoor CO$_2$ | Description of indoor air quality |
|---------------|-----------------------------------|
| 350–400 ppm   | Normal background concentration in outdoor ambient air |
| 400–1,000 ppm | Concentrations typical of occupied indoor spaces with good air exchange |
| 1,000–2,000 ppm | Complaints of drowsiness and poor air |
| 2,000–5,000 ppm | Headaches, sleepiness, and stagnant, stale, stuffy air. Poor concentration, loss of attention, increased heart rate, and slight nausea may also be present |
| 5,000 ppm     | Workplace exposure limit (as 8-hour TWA) in most jurisdictions |
| >40,000       | Exposure may lead to serious oxygen deprivation, resulting in permanent brain damage, coma, even death |

Figure 1: Typical HVAC filter precleaning and postcleaning in ADNOC Schools.

Table 2: Accuracy, resolution, and range of Fluke 975 air meter.

| Measured parameter | Range         | Display resolution | Accuracy % of reading |
|--------------------|---------------|--------------------|-----------------------|
| CO$_2$             | 0 to 5000 ppm | 1 ppm              | 2.75% + 75 ppm        |
| Temperature        | $-20^\circ$ to $50^\circ$ C | 0.1°C | $\pm$0.5°C from 5°C to 40°C |
| Relative humidity  | 10 to 90% RH  | 0.1%               | $\pm$3% RH from 10 to 90% RH |

Figure 2: Air-quality monitors used in this study.
3.2. Indoor Air Quality. To assess the impact of cleaning AC filters on indoor air quality, the indoor CO₂ levels were measured before and after cleaning the clogged AC filters in fifteen locations within the main campus of ADNOC Schools. The locations selected include ten classrooms, four labs, and one cafeteria. Cafeteria and labs are included as they represent spaces with different occupancy, area, and activity levels. Ten-minute walk-through CO₂, temperature, and RH measurements with one-minute increment have been made; their averages are summarized in Table 3. The results are represented by time-series graphs in Figure 5, and their average values are represented in the bar graphs of Figures 6–8.

Figure 5 shows data sets of CO₂ levels, air temperature, and RH simultaneous measurements in fifteen indoor locations (Classrooms, Labs) after the cleaning of the AC filters. Each graph can be identified with the name and code of the class/lab. The indoor CO₂ curves are referenced to the primary axis, while the indoor air temperature and RH curves are referenced to the secondary axis (to the left of each graph). The graphs are arranged in the same sequence during the time that data have been collected.
Table 3: Indoor air-quality parameters precleaning and postcleaning the AC filters.

| Location          | Code  | Vol. (m³) | No. of occupants | Grade level | CO₂ levels (ppm) | T (°C) | RH (%) | CO₂ indoor/outdoor | CO₂ levels (ppm) | T (°C) | RH (%) | CO₂ indoor/outdoor |
|-------------------|-------|-----------|------------------|-------------|------------------|--------|--------|---------------------|------------------|--------|--------|---------------------|
| Arabic classroom  | G138  | 238       | 12               | 9           | 2,893            | 27     | 63     | 6.90                | 1,048            | 25     | 38     | 2.50                |
| Math classroom    | G009  | 253       | 7                | 12          | 2,897            | 25     | 63     | 6.91                | 1,189            | 24     | 37     | 2.84                |
| English classroom | G008  | 156       | 8                | 12          | 3,311            | 25     | 64     | 7.90                | 1,308            | 24     | 38     | 3.12                |
| Chemistry lab     | G123  | 140       | 10               | 10          | 2,792            | 24     | 69     | 6.66                | 1,033            | 23     | 43     | 2.47                |
| Cafeteria         | G106  | 756       | 44               | 6–12        | 3,381            | 25     | 66     | 8.00                | 1,087            | 24     | 41     | 2.60                |
| Physics lab       | G003  | 349       | 13               | 12          | 2,778            | 25     | 65     | 6.63                | 971              | 24     | 39     | 2.32                |
| Hum. classroom    | G074  | 196       | 10               | 8           | 3,009            | 24     | 65     | 7.18                | 1,272            | 23     | 41     | 3.00                |
| Hum. classroom    | G075  | 196       | 13               | 8           | 2,625            | 25     | 62     | 6.26                | 1,330            | 24     | 34     | 3.17                |
| Arabic classroom  | G134  | 238       | 17               | 7           | 3,117            | 25     | 61     | 7.44                | 1,286            | 24     | 32     | 3.07                |
| Art lab           | G087  | 349       | 21               | 10          | 3,107            | 25     | 65     | 7.42                | 1,046            | 24     | 39     | 2.50                |
| Math classroom    | G014  | 253       | 9                | 11          | 2,822            | 25     | 60     | 6.74                | 920              | 24     | 32     | 2.20                |
| Physics lab       | G080  | 349       | 19               | 11          | 2,897            | 25     | 61     | 6.91                | 1,167            | 24     | 32     | 2.80                |
| Hum. classroom    | G072  | 196       | 19               | 6           | 3,275            | 24     | 60     | 7.82                | 1,014            | 23     | 31     | 2.42                |
| English classroom | G020  | 156       | 20               | 10          | 2,993            | 25     | 61     | 7.14                | 763              | 24     | 34     | 1.82                |
| Time-based averages|       |           |                  |             | ~3000            | ~25    | ~63    | ~7.2                | ~1,117           | ~24    | ~37    | ~2.7                |

The indoor CO₂ averages are summarized in Table 3. Though the number of students in the English (G020) classroom is higher than that in the Humanities (G075) classroom, and the volume of G020 is less than that of the G075 classroom, the highest CO₂ average (1,330 ppm) belongs to G075, while the lowest CO₂ average (763 ppm) belongs to G020. This effect is mainly due to the discrepancy of the sampling time during each lesson and during the day. Indoor CO₂ levels at the end of the lesson could be significantly greater than that at the beginning due to concentration buildup. In G020, the sampling was performed during the first lesson 8:10 to 8:19 am as can be seen from Figure 5, while in G075, it was performed in the last lesson during 1:50–2:00 pm. The same reasoning could be extended to temperature and relative humidity.

In most of the remaining locations, the CO₂ values oscillate in the ASHRAE standard (1119 ppm). However, the average value for all measurements is 1117 ppm, which is below the ASHRAE standard.

The highest temperature average (25°C) belongs to the Arabic classroom (G138), while the lowest (23°C) is attained by various classes (G123, G074, and G72). Since the temperature varies within a range of 2°C only, nothing can be concluded as this discrepancy is close to that of the precision of the temperature sensor. In all locations, the temperature curves oscillate between 23°C and 25°C with an average of ~24°C. The temperature curve is stable, and all measurements are between the 20°C ASHRAE standard minimum and the 27°C ASHRAE standard maximum.

The RH curve is relatively variable with the highest average (43%) belonging to Chemistry Lab (G123) and the lowest (31%) belonging to the Humanities classroom (G72). The average RH is ~37%. All indoor RH oscillates between the 30% ASHRAE standard minimum and the 60% ASHRAE standard maximum.

These indoor air-quality parameters will be compared with those measured before cleaning the AC filters in the following sections.

3.2.1. Indoor CO₂ Levels. The indoor concentration of CO₂ gas is a key indicator of the adequacy of the supply of fresh air in buildings including schools. The ASHRAE recommends an indoor CO₂ standard maximum level that does not exceed the outdoor concentration by more than about 700 ppm [23]. Keeping in mind that the CO₂ outdoor background (Figure 3) has varied from 404 to 435 ppm (with an 8-hour average value of ~419 ppm), the ASHRAE standard maximum would be 1119 ppm (419 + 700 ppm). This standard is shown in Figure 6 as a dashed red line.

The CO₂ levels before and after cleaning the clogged AC filters are shown in Figure 6. Before cleaning the AC filters, the CO₂ levels in all fifteen locations were above the 1119 ppm AHRAE standard maximum. As can be noticed from Table 3, the CO₂ levels have varied from 2625 ppm in classroom G075 to 3381 ppm in the cafeteria (G106) with an average value of ~3000 ppm. This CO₂ concentration corresponds to the 4th danger level listed in Table 1. It would induce headaches, sleepiness, poor concentration, and loss of attention.

After cleaning the AC filters, the CO₂ levels have varied from 763 ppm in classroom G020 to 1330 ppm in classroom G075. The indoor CO₂ concentrations have exceeded the 1119 ppm ASHRAE standard maximum slightly in few classrooms. However, the average indoor CO₂ concentration (1117 ppm) is within the recommended 1119 ppm ASHRAE standard maximum.

The adequacy of ventilation may be measured by the number of cubic feet of air per minute (cfm) provided per person. Alternatively, adequacy of ventilation can be
Figure 5: Continued.
Figure 5: Continued.
Figure 5: Indoor CO$_2$ levels in ADNOC Schools postcleaning AC filters. (a) Classroom G020, (b) classroom G014, (c) classroom G083, (d) classroom G072, (e) classroom G123, (f) classroom G087, (g) classroom G138, (h) classroom G106, (i) classroom G080, (j) classroom G009, (k) classroom G074, (l) classroom G134, (m) classroom G008, (n) classroom G132, and (o) classroom G075.
evaluated by indoor CO$_2$ concentrations. For instance, a CO$_2$ level of 1000 ppm is equivalent to 15 cubic feet of fresh air per minute per person [17]. Thus, the indoor CO$_2$ average of 1117 ppm (after cleaning the AC filters) indicates that the indoor ventilation rates are adequate and healthy for a learning environment.

An extensive IAQ study by Sviták et al. [24] demonstrates that in controlled ventilation, CO$_2$ levels are significantly higher than those with switched-off ventilation. CO$_2$ peaks of ~3000 ppm in naturally ventilated classrooms have been reported by Corsi et al. [23]. In ADNOC Schools, though the ventilation is always switched on, with clogged air filters the situation was equivalent to switched-off ventilation as the dirt on filters limits or even blocks air circulation in the classrooms and consequently allows CO$_2$ to build up significantly.
To better quantify the impact of cleaning the AC filters on indoor air quality, indoor-to-outdoor CO₂ ratios have been calculated for all fifteen locations before and after cleaning the AC filters. As can be deduced from Table 3, the average indoor-to-outdoor CO₂ ratio has been improved from $3000/419 \approx 7.2$ before cleaning the AC filters to an average ratio of $(1,117/419 \approx 2.7)$ after cleaning, which evidences effectiveness of the corrective actions taken.

3.2.2. Indoor Air Temperature. Indoor air temperature is a key indicator of occupants’ thermal comfort. The room temperature has a preset value of 23°C in each location (Classroom/Lab). To make sure that the HVAC built-in thermostat maintains the selected temperature, the indoor air temperature in each location is monitored by the air meter before and after cleaning the AC filters. It is evident from the bar graph of Figure 7 that indoor air temperatures after cleaning the filters are slightly lower than those measured before cleaning the filters. However, the measured temperatures (precleaning and postcleaning the AC filters) are all between the recommended 20°C ASHRAE standard minimum and the 27°C ASHRAE standard maximum, indicating thermally comfortable learning environments.

Though the indoor environment is thermostat controlled, the indoor temperature is significantly impacted by the outdoor ambient temperature. Thus, the selection of 23°C as a preset temperature would allow a logical investigation of the functionalities of both the heating coils and the cooling chillers of the HVAC units. Figure 3 shows that the outdoor air temperature has varied from 21°C at 7:11 am to 28°C at 2:19 pm with an average of $\sim 26°C$.

Table 3 indicates that before cleaning the AC filters, the indoor air temperature has varied from 24°C to 27°C with an average value of $\sim 25°C$. After cleaning the AC filters, indoor air temperature has varied from 23°C to 25°C with an average value of $\sim 24°C$. Both averages of air temperature are slightly higher than the preset value of 23°C. This slight difference could be attributed to the locations of the air meter (on the student’s desk) and that of the AC monitor.

3.2.3. Indoor Relative Humidity. Relative humidity is a key indicator of occupants’ thermal comfort. Occupants’ contribution to RH occurs as a consequence of exhalation. High RH may cause condensation and mould formation, which is unhealthy for occupants and children [22].

The indoor RH in each location is monitored before and after cleaning the AC filters. As can be noticed from the bar graph of Figure 8, before cleaning the AC filters, the RH in all locations (classrooms/labs) oscillates around the 60% ASHRAE standard maximum. After cleaning the AC filters, all measurements are between the recommended 30% ASHRAE standard minimum and the 60% ASHRAE standard maximum.

As can be seen from Table 3, before cleaning the AC filters, RH has varied from 60% to 69% with an average value of $\sim 63%$, which is above the ASHRAE standard maximum. After cleaning the AC filters, RH has varied from 31% to 43% with an average value of $\sim 37%$, which is well below the 30% ASHRAE standard minimum and the 60% ASHRAE standard maximum. As can be noticed from Figure 3, the ambient (outdoor) RH measured during the same day has varied from 40% at 2:21 pm to 77% at 7:11 am with an average of $\sim 57%$.

The impact of cleaning the AC filters is evident in Figure 8; it has decreased the indoor RH from above the ASHRAE standard maximum to the vicinity of the ASHRAE standard minimum. This is due to the fact that a well-cleaned AC system directly lowers the level of RH in classrooms as it circulates the indoor air and removes the excess moisture at the exhaust of the AC units. The significant increase in RH levels measured before cleaning the AC filters is correlated with the high CO₂ levels measured simultaneously. The correlation between RH and CO₂ concentrations was reported by similar studies, for example, Lazovic et al. [25].

4. Conclusions

This project has identified dirty filters of air-conditioning units and clogged air intake vents as the main cause of high concentration levels ($\sim 3000$ ppm) of carbon dioxide in several classrooms. After thorough cleaning, an extensive indoor air quality assessment has been conducted in fifteen classrooms. The indoor and outdoor air-quality parameters of carbon dioxide levels, temperature, and relative humidity have been monitored simultaneously. During an 8-hour ambient air quality measurement, it has been observed that bus exhaust emissions are the main source of background carbon dioxide. Thus, few places like bus loading/unloading zones, staff parking lots, and playgrounds were identified as hazardous during certain times. Students are advised to wear face masks during these times.

The indoor carbon dioxide levels have varied from 763 ppm to 1330 ppm. The average indoor carbon dioxide level for all locations has been estimated to be $\sim 1117$ ppm; below the widely used 1,119 ppm American Society of Heating Refrigerating and Air-Conditioning Engineers standard maximum. On average, this measurement indicates that the indoor ventilation rates are adequate and healthy for a learning environment. Moreover, the average indoor-to-outdoor carbon dioxide ratio has been improved from $(3000/419 \approx 7.2)$ before cleaning the filters of air-conditioning units to an average ratio of $(1,117/419 \approx 2.7)$ after cleaning, indicating the effectiveness of the corrective actions taken.

Abbreviations

ADNOC: Abu Dhabi National Oil Company
ADEC: Abu Dhabi Education Council
HSE: Health, Safety, and Environment
IAQ: Indoor air quality
WHO: World Health Organization
EPA: Environmental Protection Agency
ASHRAE: American Society of Heating Refrigerating and Air-Conditioning Engineers
NIOSH: National Institute of Occupational Safety and Health
HVAC: Heating, ventilation, and air-conditioning units.
Data Availability

Our data (experimental results that we have obtained) are shown in the figures listed within the manuscript. Data like standards are referenced wherever used in the body of the manuscript.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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