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Research Article

The Association between Indoor Carbon Dioxide Reduction by Plants and Health Effects

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Residents and workers exposure to high carbon dioxide (CO_2) levels in buildings may cause headache, dyspnea, fatigue, or drowsiness. However, the effect of plants on in-building CO_2 reduction and adverse effect relief is largely unknown. We recruited 36 healthy participants from an office room with plants and 32 healthy participants from another office room without plant in the same office building in Taipei. The participants in the office room with plants during 2020 would move to the office room without plant in 2021. The twelve repeated measurements per year of CO_2, fine particles ($PM_{2.5}$), total volatile organic compounds (TVOCs), blood pressure (BP), serum CO_2 (TCO_2), and four rating questions of headache, dyspnea, fatigue, and drowsiness were obtained for each participant. The statistical results showed that levels of drowsiness and systolic BP were significantly lower among participants in the office room with plants compared to those in the office room without plants by t-test and paired t-test. The associations between increased indoor CO_2 and increased serum CO_2 were observed in the office room with plants (1.32%) and without plant (4.52%) by mixed-effects models. Also, the associations between indoor CO_2 and drowsiness were observed in office rooms (with plants: 14.57%; without plant: 3.82%). The conclusion of the present study is that plants in office environment can reduce CO_2 levels and may lower CO_2-related health effects.

1. Introduction

Carbon dioxide (CO_2) level can be used as an indicator of indoor air quality in buildings. The concentrations of CO_2 are significantly correlated with factors that affect indoor air quality, such as ventilation rate, temperature, and humidity. Moreover, the results of locations where CO_2 is monitored reflect the actual conditions residents and workers are exposed to [1]. High CO_2 levels in buildings are often the result of poor ventilation. Most buildings, especially office buildings, are enclosed indoor spaces. Besides, high-rise office buildings often rely on central air conditioning systems for ventilation. However, office buildings using glass facades can easily develop poor ventilation over time, allowing CO_2 to build up and exposing residents and workers to adverse health effects, such as headache, dyspnea, fatigue, and drowsiness [1, 2].

Previous studies have demonstrated high relative risks of sick building syndrome symptoms and respiratory illnesses for a low ventilation rate compared to a high ventilation rate. Increases in ventilation rate could significantly reduce adverse health effects and improve indoor air quality [3]. Therefore, effective ventilation in buildings is one component of a comprehensive method to create and maintain a comfortable and healthy indoor air environment. However, increases in ventilation may increase building energy consumption [4, 5]. High energy consumptions would result in high greenhouse gas emissions and then make the world less sustainable [6].

Plant needs CO_2 to grow and propagate in the world [7]. Previous studies have reported the abilities of an indoor plant on CO_2 reduction [8–10]. Also, plant is one of the effective methods to sustain indoor air quality using nonmechanical and at the same time reduce energy consumption. However, the biological mechanism linking indoor CO_2 levels to perceived health effects and adverse health effects is still unclear.

Therefore, the present study was designed to investigate the association between indoor CO_2, serum CO_2, blood pressure (BP), and perceived health effects among healthy participants in an office room with indoor plants and an office room without plants. The study results might reveal whether indoor CO_2, serum CO_2, blood pressure (BP), and perceived health effects would respond to indoor CO_2 variation by plants.

2. Methods

2.1. Study Subjects and Study Design. The present study recruited 68 healthy subjects aged 32 to 43 years living in the Taipei metropolitan area, which includes Taipei, New Taipei City, and Keelung. These participants work in a document and legal word processing company in an office building in Taipei. Thirty-six of these participants work in an office room with plants while the others work in an office without plants. This company was one of the 41 companies in Taipei metropolitan area invited by the principal investigator and agreed to join our study after the present study design had been explained. These participants were healthy nonsmokers without cardiopulmonary diseases according to the company's health examination records.

The study is a cross-over study design (Figure 1) that included 24 measurements of 8-hour averaged CO_2, fine particles ($PM_{2.5}$), total volatile organic compounds (TVOCs), temperature and humidity, and 24 measurements of BP, serum CO_2, and four rating questions about headache, dyspnea, fatigue, and drowsiness (from 0 (never) to 10 (extremely)) at the end of the work (approximately 5 : 00 p.m.) for each participant. The 24 measurements (twelve measurements per year for each participant) were occurred at one-month intervals from January 2020 to December 2021. Each participant's characteristics, such as gender, body mass index (BMI), and age, were recorded using a questionnaire at first measurement (January 2020). The 36 participants who worked in an office room with plants in 2020 were moved to an office room without a plant in 2021. On the other hand, the 32 participants who worked in an office room without a plant in 2020 were moved to an office room with plants in 2021. The office movement was routinely arranged by the company's human resource department according to the company's annual schedule. The principal investigator discussed with the manager of the human resource department and then recruited participants from these two offices. The size of the office room was approximately 1765 square feet, and the height was about 12 feet for the office room. The plants in the office room with plants were 30 *Epipremnum aureum*. The rate at which outdoor air was supplied to the office room was set to 15 cubic feet per minute per person. The ventilation rate was measured once a month on a working day by the occupational health and safety department according to the company's annual schedule using AccuBalance® Air Capture Hood 8380 (TSI Inc., Shoreview, MN, USA). The average ventilation rates of the two offices were 14.5 and 14.6 cubic meter per hour, respectively, during the study period.

Our study design was reviewed and approved by a local ethics committee in Taipei, Taiwan. Written informed consent was obtained from each subject before the study.

2.2. Indoor Air Pollution and Weather Monitoring. We used Q-TRAK IAQ (model 8551; TSI, Shoreview, MN, USA) for indoor CO_2 monitoring. A dust monitor (DUST-check portable dust monitor, model 11A; temperature and humidity sensor, model 1.153FH; Grimm Labortechnik Ltd., Ainring, Germany) was used for indoor $PM_{2.5}$, temperature, and relative humidity monitoring. A MiniRAE 3000 (model PGM-7320; RAE Systems, Inc., San Jose, CA, USA) was used for TVOC monitoring. All air pollutants, temperature, and humidity were monitored every minute. These monitors were calibrated by manufacturers before sampling. All data were matched with the sampling time of BP monitoring and then computed to 8-hour means if 75% of the data were present.

2.3. Serum CO_2. The serum CO_2 was measured by total concentration carbon dioxide (TCO_2 mmol/L). The trained nurses collected blood (0.5 mL) that was collected from the brachial vein into a disposable 1.5 mL tube with anticoagulant heparin lithium. Blood samples were stored on ice in coolers before use, and TCO_2 were measured immediately after blood sample collection. TCO_2 of blood samples were evaluated using the Abbott i-STAT portable clinical analyzer and CG8+ cartridges (Abbott Laboratories, Nepean, Canada).

2.4. BP Monitoring. A portable cardiac monitor (DynaPulse, model 5000A; Pulse Metric, San Diego, CA) was used to measure systolic BP (SBP) and diastolic BP (DBP) at the end of the work. We used a mercury blood pressure monitor and stethoscope to calibrate our portable cardiac monitor before all measurements (24 measurements for each participant).

2.5. Statistical Analysis. *t*-tests were used for the between-group comparisons between the participants in office room

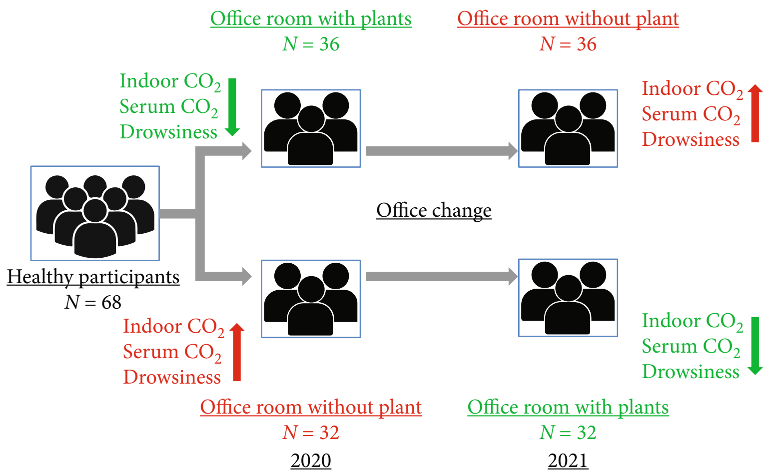

FIGURE 1: Cross-over study design.

with plants and participants in office room without a plant. Paired t-tests were used for within-group comparisons within the participants in office room with plants and the same participants in office room without a plant. The association of indoor CO_2 with serum CO_2, BP, or drowsiness was examined by mixed-effects model. The exposure variables were 8-hour means of CO_2, $PM_{2.5}$, and total VOCs, and the outcome variables were SBP, DBP, serum CO_2, and drowsiness. The participant's sex, age, BMI, temperature, humidity, and air pollution were treated as fixed effects, and the participant was fitted as a random intercept term in our mixed-effects model. The plant (with plants versus without a plant) was only adjusted in all data (all study participants) mixed-effects models. The effects of pollution on health variables were expressed as percent changes multiplied by the interquartile range (IQR) changes, i.e., $[\beta \times \text{IQR} \div M] \times 100\%$, where β and M are the estimated regression coefficient and the mean of BP and serum CO_2, respectively. All statistical analyses were performed with the R Statistical Software, V.4.2.1 [11].

3. Results

The mean age of 68 nonsmoking participants was 33.2 years ((standard deviation, SD) = 2.5), the mean BMI was 23.6 kg/m^2 (SD = 1.9), and the male/female ratio was 1 : 1.42 (28 versus 40). The mean serum CO_2, SBP, and DBP were 22.9 mmol/L (SD = 1.5), 117.3 mmHg (SD = 13.2), and 75.6 mmHg (SD = 11.2), respectively. There were no significant differences in age, BMI, and between the two groups (36 participants work in an office room with plants versus 32 participants work in an office room without a plant in 2020). None of them had cardiopulmonary diseases or took related medicine.

Table 1 summarizes the blood pressure, serum CO_2, 8-hour mean indoor CO_2, air pollution and weather, and the between-group comparisons between the office room with plants and office room without a plant. The participants in the office room without a plant were exposed to relatively higher CO_2, and $PM_{2.5}$ levels had higher serum CO_2, SBP, and drowsiness scores compared with those in the office

TABLE 1: Summary statistics for the blood pressure, serum CO_2, 8-hour mean indoor CO_2, air pollution and weather, and the between-group comparisons between the office room with plants and office room without a plant.

	With plants $N = 1632$	Without plant $N = 1632$	t-test p value
CO_2, ppm			
Mean ± SD	912 ± 321	1343 ± 745	<0.01
IQR	342	823	
$PM_{2.5}$, $\mu g/m^3$			
Mean ± SD	6.8 ± 3.1	9.5 ± 4.2	0.03
IQR	4.7	5.6	
TVOCs, ppb			
Mean ± SD	48.1 ± 16.7	47.9 ± 15.6	0.67
IQR	28.4	26.2	
Temperature, °C			
Mean ± SD	25.5 ± 1.1	23.4 ± 1.0	0.87
Humidity, %			
Mean ± SD	65.7 ± 2.1	65.3 ± 2.4	0.79
Serum CO_2, mmol/L			
Mean ± SD	20.1 ± 0.9	25.5 ± 2.4	0.04
SBP, mmHg			
Mean ± SD	112.3 ± 13.4	124.5 ± 14.0	0.04
DBP, mmHg			
Mean ± SD	72.4 ± 10.6	78.4 ± 11.8	0.08
Headache			
Mean ± SD	3.4 ± 0.3	2.6 ± 0.6	0.54
Dyspnea			
Mean ± SD	2.1 ± 0.2	2.9 ± 0.5	0.76
Fatigue			
Mean ± SD	5.1 ± 1.2	6.3 ± 1.9	0.61
Drowsiness			
Mean ± SD	2.1 ± 0.6	4.5 ± 1.0	0.04

Table 2: Summary statistics for the blood pressure, serum CO_2, 8-hour mean indoor CO_2, air pollution and weather, and the within-group comparisons between the office room with plants and office room without a plant.

	With plants $N = 1632$	Without plant $N = 1632$	t-test p value
CO_2, ppm			
Mean ± SD	899 ± 307	1498 ± 692	<0.01
IQR	365	973	
$PM_{2.5}$, $\mu g/m^3$			
Mean ± SD	5.6 ± 2.9	10.7 ± 6.3	<0.01
IQR	2.2	6.9	
TVOCs, ppb			
Mean ± SD	50.8 ± 22.4	46.2 ± 19.3	0.52
IQR	31.5	27.4	
Temperature, °C			
Mean ± SD	24.3 ± 1.0	24.2 ± 1.1	0.83
Humidity, %			
Mean ± SD	64.2 ± 2.3	64.9 ± 2.2	0.81
Serum CO_2, mmol/L			
Mean ± SD	21.9 ± 1.1	27.3 ± 2.7	0.04
SBP, mmHg			
Mean ± SD	115.1 ± 12.5	123.5 ± 13.0	0.05
DBP, mmHg			
Mean ± SD	75.7 ± 11.2	77.8 ± 12.0	0.13
Headache			
Mean ± SD	2.8 ± 0.4	2.3 ± 0.9	0.68
Dyspnea			
Mean ± SD	2.3 ± 0.3	2.8 ± 0.4	0.81
Fatigue			
Mean ± SD	5.8 ± 1.1	6.2 ± 1.5	0.68
Drowsiness			
Mean ± SD	2.6 ± 0.5	5.3 ± 1.4	0.03

room with plants (t-test, p value <0.05). There were no significant differences in gender, age, BMI, temperature, and relative humidity between participants in the office room without and with plants. For the within-group comparisons between the office room with plants and office room without a plant (Table 2), the participants in the office room without plants had relatively higher levels of CO_2 and $PM_{2.5}$ exposure as well as higher serum CO_2, SBP, and drowsiness scores compared to their values when they were in the office room with plants (paired t-test, p value <0.05).

In order to investigate the impact of plants on CO_2 concentrations in office rooms, we summarized the 8-hour mean level of CO_2 in the two office rooms on Sundays (no participant in the two office rooms) during the study period. The result of between-group comparison showed that the office room with plants had significantly lower CO_2 concentration ($\text{mean} \pm \text{SD} = 310 \pm 93$) than the office room without plants ($\text{mean} \pm \text{SD} = 433 \pm 112$) ($p$ value <0.01). Also, the result of within-group comparison showed that the office room with plants had significantly lower CO_2 concentration ($\text{mean} \pm \text{SD} = 354 \pm 101$) than the office room without plants ($\text{mean} \pm \text{SD} = 448 \pm 127$) ($p$ value <0.01).

Table 3: Percentage changes of health variables for an interquartile range change of air pollution levels[a] in mixed-effects models.

	All data[b] $N = 1632$	Without plant $N = 816$	With plants $N = 816$
CO_2			
Serum CO_2	1.61*	4.52*	1.32*
SBP	1.33*	2.41*	0.38
DBP	-1.4	1.5	-2.3
Drowsiness	7.62*	14.57*	3.82*
$PM_{2.5}$			
Serum CO_2	-0.04	1.34	-0.97
SBP	2.56*	3.66*	1.12
DBP	0.98	-1.45	0.78
Drowsiness	1.98	-0.34	2.99
TVOCs			
Serum CO_2	0.61	-0.78	1.01
SBP	1.28	2.41*	0.99
DBP	0.35	1.04	1.39
Drowsiness	-1.93	2.11	0.91

[a]The values are presented as percentage changes and 95% confidence intervals for interquartile range changes after adjusting for sex, age, body mass index, temperature, and humidity in 27 mixed-effects models. [b]The plant (with plants versus without plant) was only adjusted in 9 all data mixed-effects models. *p value <0.05.

Table 3 reports percentage changes in serum CO_2 and BP and drowsiness for an IQR change of air pollution levels among 68 participants in different modes. We found that indoor CO_2 was significantly associated with increased serum CO_2 in all data, with plants and without plant modes (1.61%; 4.52%; 1.32%). Also, the significant association between indoor CO_2 and drowsiness was observed in all data, with plants and without plant modes (7.62%; 14.57%; 3.82%). However, $PM_{2.5}$ and TVOCs were not associated with increased serum CO_2. For BP, the association of increased SBP with CO_2, $PM_{2.5}$, and TVOCs was observed in without plant modes. Moreover, the relationship between increased SBP and $PM_{2.5}$ exposure was found in all data modes.

We further explored the association between serum CO_2 and drowsiness. The results showed that elevated serum CO_2 was significantly associated with an increased drowsiness score among participants in the room with plants (6.78%) and all data (2.52%). There was no significant association between serum CO_2 level and drowsiness score among participants in the room without a plant.

4. Discussion

The present study observed the association between 8-hour mean CO_2 exposure and increased level of BP and serum CO_2 among a panel of healthy participants in an office building. The participants in the office room with plants had lower CO_2 and $PM_{2.5}$ exposures compare to those in the office room without a plant. Also, levels of SBP and serum CO_2 were relatively low among the participants in the office room with plants. These findings suggest that indoor plants might play an important role in indoor CO_2 reduction and health improvement for workers in an office building. Theoretically, in-building CO_2 is mainly from human breathing during normal respiration process. CO_2 would become an indoor air quality issue when the indoor level is increased above threshold limit [12], which have been set in the building that is below 1000 ppm [13]. Once CO_2 concentration is over 1000 ppm, adverse effects of CO_2 on cardiopulmonary system including drowsiness, increased heart rate, and elevated BP may occur among residents and/or workers in that indoor environment. Indoor plant is a possible solution to modify the association between high-level CO_2 exposure and adverse health effects. Previous studies have demonstrated the abilities of an indoor plant on indoor air quality enhancement for health benefits by air pollution reduction including $PM_{2.5}$, TVOCs, and CO_2 [8–10, 14]. The present study findings on indoor air quality improvement are consistent with previous findings and provide further support to our previous study's conclusions [15].

The present study observed the association of elevated SBP with increased $PM_{2.5}$ and TVOCs among participants during 8-hour working in the office room without a plant. Such findings not only support the statement of the American Heart Association expert panel on biological mechanisms of air pollution effects on the cardiovascular system involving autonomic dysfunction [16] but also confirm previous findings on the association between SBP, $PM_{2.5}$, and TVOCs in an epidemiological study [17] and a randomized, double-blind cross-over trial [18]. Furthermore, the present study did not observe the relationship between air pollution and BP among participants in the office room with plants. Such finding is consistent with our previous observations demonstrating effects of houseplant on $PM_{2.5}$ reduction and decreased SBP among elderly participants [15]. According to previous studies, Pegas et al. [19] explored the effect of plants on indoor air quality in a primary school by a 9-week intensive monitoring campaign of air pollution in a classroom without and with plants. They found a decrease of approximately 30% in PM_{10} concentrations during periods of occupancy with the presence of 6 potted plants. El-Tanbouly et al. [20] studied the role of indoor plants in air purification and human health by reviewing related publications. They concluded that the use of indoor plants is a new possible ecofriendly tool for indoor air purification and for reducing the spread of bioaerosol in confined places. Hence, the present findings provided evidence to support previous findings and suggested that indoor plant can be a part of a comprehensive strategy to improve indoor air quality and its health effects.

Although the actual biological mechanism linking indoor CO_2 to fatigue, drowsiness, or tiredness is not fully understood, the observed association of drowsiness with indoor CO_2 or serum CO_2 in the present study was in accordance with previous findings. Vehviläinen et al. [21] found that blood CO_2 level was significantly higher after the 4-hour meeting in the nonventilated office room (CO_2 max 4917 ppm) than after the 4-hour meeting in the ventilated office room (CO_2 max 1452 ppm). The subjective sleepiness assessed by the KSS questionnaire increased in the nonventilated room. No significant change in the KSS Scale was observed in the ventilated room. Satish et al. [22] conducted a controlled exposure study using a chamber outfitted like an office with CO_2 concentrations of 600, 1,000, and 2,500 ppm. The result showed that CO_2 level at 1000 ppm was associated with a reduction in the decision-making performance. The reduction of decision-making performance was reported to be influenced by fatigue [23] and drowsiness [24]. These findings may suggest that the relationship between CO_2 exposure and drowsiness is biologically plausible.

There were limitations in our study that should be noted. First, the present study design could not entirely exclude contributions of unmeasured indoor air pollution, such as bioaerosols from indoor sources. Therefore, exposure misclassification and/or measurement error could be possible and bias the observed relationships in the present study [25]. Second, the subjective bias of headache, dyspnea, fatigue, or drowsiness measurement could not be completely excluded. The study subjects were not blinded to the office room with or without a plant. However, the consistency of between-group, within-group, and mixed-effects model results regarding indoor CO_2 exposure and drowsiness makes it impossible that the present findings arose entirely from subjective bias. Finally, the present findings could not be extrapolated to various building patterns with longer working hours or different ventilation conditions.

Although these study limitations should be considered carefully when we interpret our study results, the present findings generally suggest that indoor CO_2 is associated with increased serum CO_2, SBP, and drowsiness. The reduction of indoor CO_2 by plants is a sustainable strategy to improve indoor air quality and lower SBP and drowsiness levels among a panel of healthy participants in an office environment.

Data Availability

The indoor monitoring data and questionnaire data used to support the findings of this study have not been made available due to the nondisclosure agreement signed with the company.

Additional Points

Practical Implications. Plants in the office environment can reduce CO_2 and particle levels and may lower CO_2-related health effects including less drowsiness and decreased systolic blood pressure.

Disclosure

The funder had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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