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Indoor Environmental Quality Evaluation of Lecture Classrooms in an Institutional Building in a Cold Climate

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Abstract: In this paper, ventilation, indoor air quality (IAQ), thermal and acoustic conditions, and lighting were studied to evaluate the indoor environmental quality (IEQ) in an institutional building at the University of Alberta in Edmonton, Canada. This study examined IEQ parameters, including pressure, illuminance, acoustics, carbon dioxide (CO_2) concentration, temperature, and humidity, with appropriate monitors allocated during a lecture (duration 50 min or 80 min) in four lecture classrooms repeatedly ($N = 99$) from October 2018 to March 2019 with the objectives of providing a comprehensive analysis of interactions between IEQ parameters. The classroom environments were maintained at 23 ± 1 °C and 33% ± 3% RH during two-season measurements. Indoor mean CO_2 concentrations were 550–1055 ppm, and a mean sound level of 58 ± 3 dBA was observed. The air change rates were configured at 1.3–6.5 per hour based on continuous CO_2 measurements and occupant loads in the lectures. A variance analysis indicated that the within-lecture classroom variations in most IEQ parameters exceeded between-lecture classrooms. A multilayer artificial neural network (ANN) model was developed on the basis of feedforward networks with a backpropagation algorithm. ANN results demonstrated the importance of the sequence of covariates on indoor conditions (temperature, RH, and CO_2 level): Air change rate (ACR) > room operations (occupant number and light system) > outdoor conditions.

Keywords: indoor environmental quality (IEQ); lecture classrooms; HVAC systems; ventilation; correlation; artificial neural network

1. Introduction

During the past three decades, indoor air quality (IAQ) has received increased research attention, and a wide range of indoor air pollutants, such as volatile organic compounds (VOCs), particulate matter, inorganic compounds, and radon, have been assessed and characterized in various indoor environments: Offices, schools, supermarkets, houses, and so on [1–10]. Over the years, comprehensive knowledge on the mechanisms of, and health effects from, exposure to indoor pollutants has been reviewed and asthma, allergies, and heart attack are highly correlated with indoor air pollution [1,11–16]. Recently, indoor environmental quality (IEQ) has received increasing attention from the public under the context of global climate change and the green building initiative. Aspects of IEQ that directly influence the comfort, health, productivity, and satisfaction of occupants of a building include ventilation, IAQ, acoustic and thermal conditions, and illumination.

Several studies have examined IEQ in homes and K-12 schools with young kids as research objects [17–25]. While children and youth represent a potentially vulnerable population, adult students in universities are a large prospective cohort whose institutional environment should be explored.

In 2017, there were 1.7 million students in Canadian universities and around 20 million students at universities in the United States [26,27]. Unfortunately, in these institutions, classroom IEQ, especially in large lecture classrooms, are scarcely explored. Despite this lack of attention, the effects of deficient IEQ, such as low ventilation, hot or cool conditions, dry or humid conditions, too noisy or too quiet background, as well as too bright or too dark lighting, may adversely affect student and academic staff performance and attendance [28].

Excluding comprehensive walkthrough investigations and measurements of physical and/or chemical indoor elements, some IEQ-related research collected occupants' responses to questions such as health issues, exposure data, and sensations, to a built environment through a questionnaire survey and provided acceptance or satisfaction criteria and health implications of a building's IEQ [28–33]. Several attempts have been made to conduct on-site standardized academic or physical tests, such as cognitive tests, spirometry tests, memory tests, and mathematics and reading tests, to evaluate how IEQ elements affect learning performance in elementary and middle school classrooms or productivity in offices [33–41]. Since ventilation is a critical parameter for indoor environmental performance, most research used experimental, modeling or field-testing methods to examine natural ventilation or natural ventilation combined with a simple fan system to observe the impacts of outdoor environmental parameters on IEQ [25,31,42–46]. Mechanical systems are another prevailing ventilation method, especially in non-mild climate zones or noisy or polluted regions. However, limited research has explored the interactions between IEQ parameters and how mechanical systems and occupant behavior affect IEQ. Although inadequate mechanical ventilation leading to poor indoor air quality was reported in some papers [2,22,23,47], there were no detailed characteristics of the employed mechanical ventilation systems used in their studies. ASHRAE Guideline 10-2016 is the most up-to-date document to describe the IEQ interactions for achieving acceptable indoor environments [48]. The current study will provide new scientific evidence to promote the new version of the guideline in the near future.

In order to update professional knowledge on the design and construction of healthy, sustainable, and energy-efficient IEQ for institutional buildings, this study was conducted with three objectives: (1) Providing evidence to define IEQ performance metrics for lecture classrooms in a very cold region, (2) further exploring interactions of IEQ parameters in order to update currently available knowledge of interactions from ASHRAE Guideline 10-2011, and (3) quantifying the impacts of mechanical systems on IEQ for the development of advanced IEQ design guides for institutional buildings. This paper reports on IEQ elements repeatedly measured in four large lecture classrooms over two seasons in a conventional institutional building in a cold climate and provides statistical analysis results to reveal the science associated with the interactions of IEQ parameters and factors impacting on IEQ.

2. Materials and Methods

2.1. Selection and Characteristics of the Building

Edmonton is a Canadian city with a population of over 1 million and cold continental winters. An institutional building, the engineering teaching and learning complex (ETLC) (53.527° N, 113.529° W in Figure 1), a typical teaching building, at the University of Alberta (UAlberta), Edmonton, Alberta, Canada, was selected for sampling from October 2018 through March 2019. The winter of 2019 in February was an unusually cold with a daily average of −19 °C, which is 11 °C lower than the normal historical mean of −8 °C in February. The sampling campaign was conducted in the fall and winter semesters since lecture classrooms had regular classes. The sampling campaign took place during the coldest days to highlight the IEQ control capability of the subject building during the heating season. Samples were balanced by classroom and season.

The ETLC building is located on the western edge of the UAlberta North Campus, on the southern bank of the North Saskatchewan River, surrounded on three sides by other engineering buildings to the north, south, and west, and faces a large lawn to the east. The building is not adjacent to main roads or factories. The 6-story building was constructed in 2001 and is a state-of-the-art teaching and learning facility, which is home to several thousand engineering students. Walls are made of concrete with a minimum sound transmission class (STC) rating of 52 to reduce room to room noise transmission. The central mechanical ventilation system is installed in the neighboring building's west side, connected and composed of a large central air handling unit (AHU), a steam-water/glycol heating system for air preheating to 13 °C, and split-chilled water-cooling system, shown in Figure 2. In 2017, two 200 kW fans in the central AHU were replaced by sixty 7.5 kW fans, known as a fan wall, which is one of the largest in North America in 2018. The fan wall system gives more capacity and reliability; previously, losing one large fan would cause major building interruptions. The mechanical system is set to standby status from 11 pm to 6 am weekdays and more on weekends and holidays (average around 10 hours per day). The building is humidified to 25% relative humidity (RH) indoors when the outdoor air temperature is above 0 °C and 17% below 0 °C. The AHU supplies a minimum of 80% outdoor air. It is noted that the tested building is a conventional institutional building rather than a green-certified one.

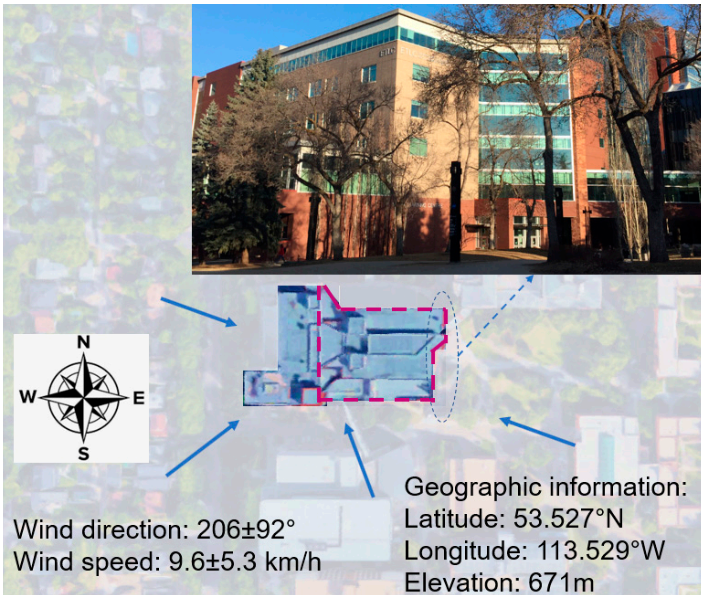

Figure 1. Site analysis.

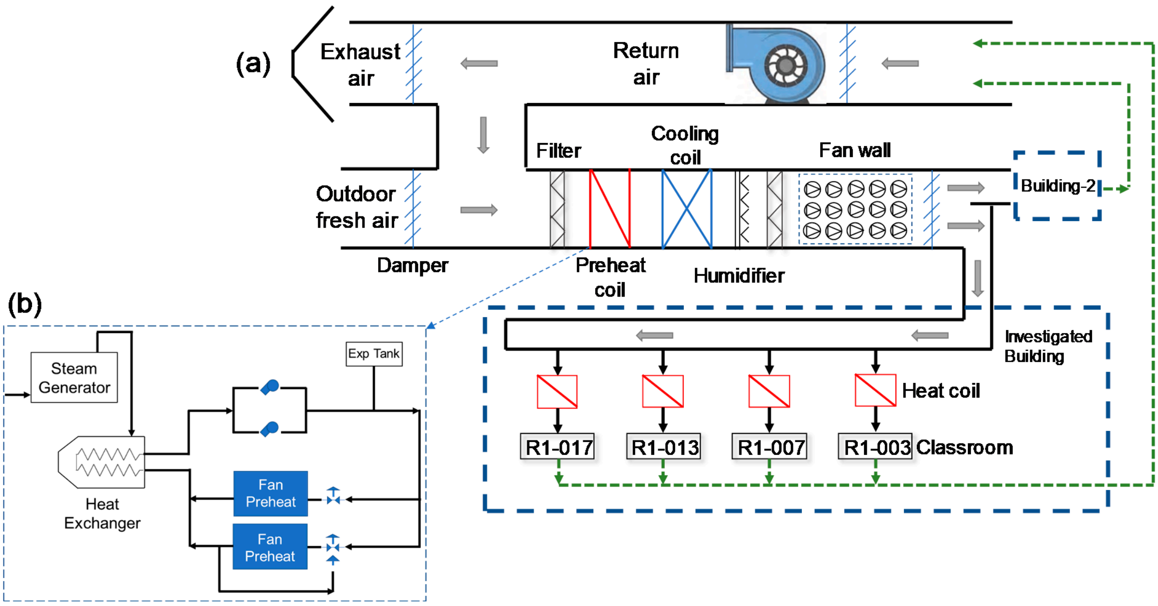

Figure 2. (**a**) Central mechanical heating, ventilation, and air conditioning (HVAC) system combined with unit heating system for investigated lecture classrooms and (**b**) steam–water/glycol preheating system.

2.2. Selection and Characteristics of the Lecture Classrooms

Lecture classrooms were designed to be located on the ground floor and north and south sides of ETLC building near entrances to facilitate access. Four large lecture classrooms (R1-003, R1-007, R1-013, and R1-017), with areas of 362 m^2, 368 m^2, 384 m^2, and 386 m^2 (average 4.5 m height) and a maximum occupancy of 220 were selected for repeated IEQ sampling and investigations. All lecture classrooms have three entrances to the room. Variable air volume (VAV) terminal reheat boxes were mounted in the ceiling to provide a targeted room temperature of 22 °C with an acceptable range of 20–23.5 °C in occupied winter seasons. Occupied and unoccupied temperature setpoints were 19 °C and 18 °C, respectively. Automatic-on occupancy sensors installed in each room were expected to adjust room supply airflow dependent on occupied (400–600 L/s) or unoccupied scenarios (minimum 40 L/s). Tested lecture classrooms were windowless, and 6-row artificial lights on the ceiling provide the appropriate illumination levels. Light-emitting diode (LED) lighting systems accommodated a dimmer function, controlled from within the room. Figure 3a shows the typical internal view in the lecture hall under test, where three fans controlled by a thermostat were responsible for providing the conditioned air to a classroom.

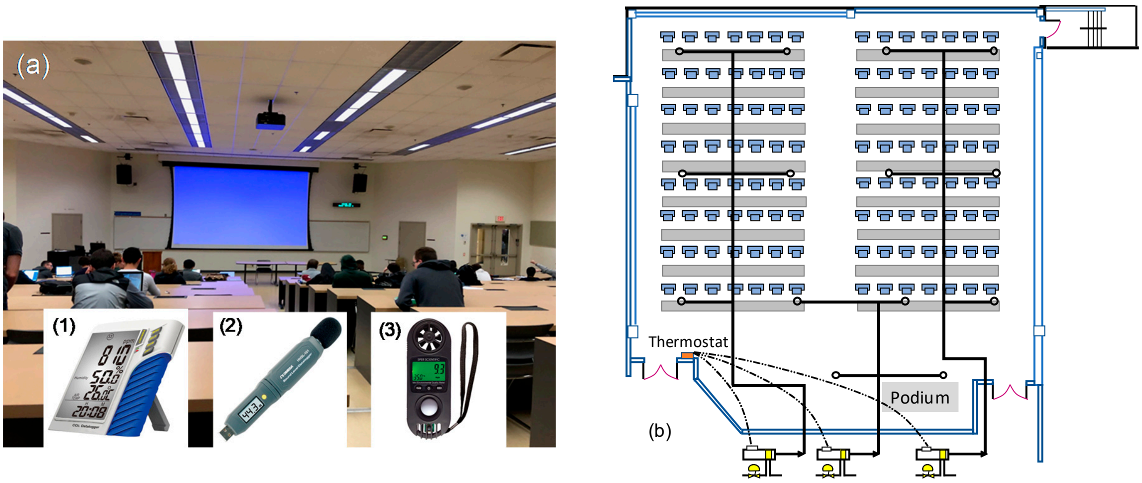

Figure 3. (**a**) Typical lecture hall internal view with testing units: (1) CO_2 meter, (2) sound level data logger, and (3) environmental quality meter). (**b**) Air supply layout in a typical lecture classroom.

2.3. Indoor Environmental Quality Sampling

The field study deployed several IEQ sampling units: An Omega AQM-102 Carbon Dioxide Meter, an Omega HHSL-101 USB Sound Level Data Logger, and a Sper Scientific 850027 Mini Environmental Quality Meter. Table 1 presents the specification of the testing units that were calibrated according to the manufacturer's instructions prior to all measurements. The carbon dioxide sensor continuously measured carbon dioxide levels in parts per million (ppm), temperatures in degrees Celsius (°C), and RH (%) during lectures with a recording interval of 5 s. Background noise measurements were performed using an HHSL-101 sound meter, recording every second when the building was unoccupied. The sound meter also collected the decibel levels in classrooms during lectures to estimate the speech intelligibility index (SII) using software developed by the University of Sydney [49]. It is noted that, for all cases, instructors used electronic sound amplification for lecture delivery in lecture classrooms. The scientific mini environmental quality (SMEQ) meter was responsible for measuring barometric pressure (kPa), illuminance (foot-candle or lux), and airspeed (m/s). In all cases, the room airspeeds were lower than the detection limit (0.1 m/s) of the SMEQ meter, indicating that it is reasonable to assume that indoor air temperature, mean radiant temperature, and the operative temperature are equal to each other [50]. Since most lectures used the projection screen as the educational tool, the light levels were monitored at midlevel lighting status (adjusted to suit students' preferences). Because there were no windows in the lecture classrooms, lighting levels measured did not include daylight contributions.

The locations of testing units in each lecture hall were selected by the investigators to be at least 5 m away from any walls and doors and 0.7 m above ground and varied for all tested classes. At the beginning of a lecture, the carbon dioxide sensor and sound meter were turned on and collected their respective data for the entirety of the lecture. Meanwhile, the SMEQ meter was used to collect pressure, light, and airspeed measurements, respectively, before and after class at random three locations within the classroom. The number of gender- and activity-based occupants (female and male students as well as female or male professors) in the room was visually counted and recorded every 10 minutes. Classroom dimensions were obtained using a laser distance measure. Outdoor climate data (temperature, humidity, wind direction, and wind speed) were collected from the South Campus weather station, 4 km away from the ETLC building. The data were accessible from the government of Canada's website and was synchronized with the time when our measurements were taken. The operational temperature of the CO_2 sensor should be above 0 °C, which did not apply to outdoor measurements in this study. The global ambient CO_2 level currently averages 400 ppm, which was assumed to be a constant value for the outdoor CO_2 concentration [51].

Table 1. Measuring equipment.

Equipment (Serial No.)	Parameter	Range	Resolution	Accuracy
Omega Carbon Dioxide Meter (AQM-102)	CO_2 RH Temperature	0–9999 ppm 0 to 99.9% RH −40 to 85°C	1 ppm 0.1% RH 0.1°C	± 30 ppm + 3% rdg ± 3% RH ± 0.6 °C
Omega USB Sound Level Data Logger (HHSL-101)	Sound Level	30–130 dBA	0.1 dBA	± 1.5 dBA
Scientific Mini Environmental Quality Meter (850027)	Pressure Air Speed Light	1–110 kPa 0.4–20 m/s 0–2200 lux	0.01 kPa 0.1 m/s 1 lux	± 0.2 kPa ± 3% rdg ± 5% rdg

2.4. Metabolism and Air Change Rates

Ventilation and air change rates (ACRs) were evaluated by assuming a one-zone steady-state mass balance model with CO_2 as a tracer gas [23]. The total classroom CO_2 emission rates were calculated as the sum of emissions from students (typically in the range of 20–30 years old) and instructors. The metabolic activity levels of 1.4 and 1.8 MET for students (sitting, listening, writing, and discussing tasks) and instructors (standing, walking around, and talking tasks), respectively, were estimated in this study. Although 1.4 MET exceeded the typically suggested values (1.0–1.2 MET in ASHRAE 55-2017) for a person in a seated status for reading and writing, 1.5 MET for sitting tasks was listed in some documents [52]. Based on the relationship of CO_2 emission rate with variables of metabolic rate, weight, and height of occupants (age and gender) [53], as well as the representative North American statistics on height and weight data for adults [54], the CO_2 emission rates were calculated as 0.407, 0.359, 0.530, and 0.470 L·min-1·person-1 for male students, female students, male instructors, and female instructors, respectively. Due to uncertain activity levels of students prior to classes and occasional latecomers in the first 5 min, 10 min of rest time was estimated from CO_2 measurements (to reach to constant levels) and the first 10 min field-measured CO_2 concentrations in occupied (lecture) periods were not included for the ACRs calculation. ASHRAE 62.1-2016 established that the minimum outdoor air rate for lecture classroom is 4.3 L/s·person [55]; the calculated ACRs from the one zone model were compared with the ASHRAE standard in this study. Although the derived ACRs are approximate due to the accuracy of the steady-state assumption and the representativeness of measurements, ventilation parameters can provide key information to support engineering controls to improve IEQ and reduce energy consumption.

2.5. Data Analysis

The average values of continuously measured IEQ elements during each class were taken into statistical analyses. Distributions of measured average total occupants, indoor temperature, RH, CO_2, and sound and light levels across 99 measurements in four lecture classrooms were visualized using normal quantile–quantile (Q-Q) plots. Differences in IEQ parameters between- and within-lecture classrooms were examined using one-way ANOVA tests with random effects. The room-to-room differences of the median of IEQ parameters were assessed with the paired Wilcoxon signed-rank tests. Indoor and outdoor parameter differences by season (Fall: October–November 2018 and March 2019, Winter: December 2018–February 2019) were examined using one-way ANOVA and Kruskal–Wallis (K-W) tests. The mean and the effect size of the difference was calculated using Cohen's d method [56]. Correlations between key IEQ measurements were calculated using Spearman rank correlation coefficients. Multivariate analysis of variance (MANOVA) was conducted to explore the possibility of interaction effects for IEQ elements as a group. A multilayer perceptron (MLP) artificial neural network (ANN) method was implemented to further examine the complicated inter-relationships. Feedforward backpropagation ANN was developed by participating, training, testing, and holdout at 60%, 20%, and 20%, respectively, for the set of 99 samples. Five covariates (outdoor temperature, outdoor RH, total person, indoor light, and ACR) from the MANOVA analysis were used as input layer units, and three output layer units (indoor temperature, indoor RH, and indoor CO_2) were kept the same as the MANOVA tests. The ANN architecture was set to have two hidden layers, 40 and 20 neurons for each layer with the activation function of a hyperbolic tangent. Associations between outdoor air intake rates and outdoor temperatures were examined using a linear regression model. Statistical analyses and model fitting were performed using Excel (Microsoft 2016, Seattle, WA, USA) and SPSS Statistics v. 25 (SPSS Corporation, Chicago, IL, USA).

3. Results

3.1. Indoor Environmental Quality of Lecture Classrooms

Table 2 contains results on indoor and outdoor environmental variables. The outdoor temperatures were in the range of −25 °C to 12 °C with RHs of 23%–100% during the field study. The mean wind direction was 206° using the vector method with a wind speed of 2–23 km/h during the sampling campaign. The calculated mean wind direction is in compliance with the ASHRAE design dominating wind direction of 210° for Edmonton at a heating season. Indoors, the average 6–36 female students and 34–112 male students were observed in the 99 tested classrooms. The average total occupants were 81 ± 22 in 1676 ± 44 m^3 classrooms. The clothing insulation was not logged but estimated to be around 1.0 clo via field observations. The thermal environment (20–25 °C and 25%–40% RH) was within the thermal comfort zone described in ASHRAE 55-2017 [57]. Across the two seasons, indoor CO_2 concentrations averaged 714 ± 105 ppm (range 550–1055 ppm) with 1% exceeding 1000 ppm, all cases satisfying ASHRAE 62.1-2016 [55]. The background noise level was 26 ± 2 dBA, meeting the maximum background noise of 30 dBA (approximately Noise Criterion-23) defined by NRC-CNRC [58]. The median indoor sound, pressure, and light were 58 dBA, 94 kPa, and 222 lux, respectively. The acoustic control was accomplished with fibrous textiles hung on the walls and ceiling. The calculated SII value was 0.86 ± 0.03, indicating the lecture classrooms satisfied the acoustics requirement for speech rooms (values of SII above 0.75 are recommended for good communication [59]). Usually, 300–500 lux and 150–200 lux are recommended for normal classrooms and auditoria, respectively. Considering the screen-based teaching method was delivered for most lectures, the lighting was dimmed to sufficient darkening to accommodate various projection tasks while still permitting enough light in the seating area for note-taking. Compared with acceptability criteria in Table 2, IEQ investigations indicate that thermal, acoustic, and visual comfort was achieved in the tested lecture classrooms.

Table 2. Indoor and outdoor environment characteristics of classrooms (*N* = 99).

Characteristics.	Range	Median	Mean	Std. Dev.	Recommended Value
Occupants					
Number of students (female)	6–36	13	15	7	—
Number of students (male)	34–112	61	64	16	—
Number of professors (female)	0–1	0	0	0	—
Number of professors (male)	0–2	1	1	0	—
Total occupants (male + female)	44–140	78	81	22	—
Outdoor environment					
Outdoor temperature, °C	−25–12	−4	−6	9	—
Outdoor RH, %	23–100	74	71	19	—
Wind direction, °	10–360	180	206	92	—
Wind speed, km/h	2–23	9	10	5	—
Indoor environment					
Classroom volume, m^3	1621–1732	1648	1676	44	—
Indoor temperature, °C	20–25	24	23	1	20–26 [1]
Indoor RH, %	25–40	33	33	3	0–80 [1]
Indoor CO_2, ppm	550–1055	698	714	105	<1100 [2]
Indoor sound, dBA	50–65	58	58	3	AN [3] < 30 dBA
Indoor pressure, kPa	92–95	94	94	1	—
Indoor light, lux	88–825	222	238	115	—

[1] ASHRAE 55-2017. [2] ASHRAE 62.1-2016. [3] AN: ambient noise level, National Research Council Canada (NRC).

3.2. Indoor Environmental Quality Data Distributions

The normal Q-Q plots in Figure 4 indicate that most measured IEQ parameters, especially indoor temperature and RH, were normally distributed. The distributions of total occupants and indoor CO_2 were light-tailed at two ends, and indoor sound and light data were right-skewed at the beginning. IEQ measurements varied by lecture classroom. For example, the median temperature of R1-017 was higher than other rooms, while the median RH of R1-017 was the lowest (Figure 5). Most of the room-to-room IEQ differences were statistically significant, indicating that IEQ was correlated with internal room operations and characteristics; the tested classrooms were connected to the same central heating, ventilation, and air conditioning (HVAC) system. R1-007 had narrow distributions in indoor RH and illuminance, medium distribution in indoor temperature, acoustics, and pressure, and wide distribution of indoor CO_2 concentration. It is interesting to see that there was no significant room-to-room difference in indoor pressure (Figure 5f).

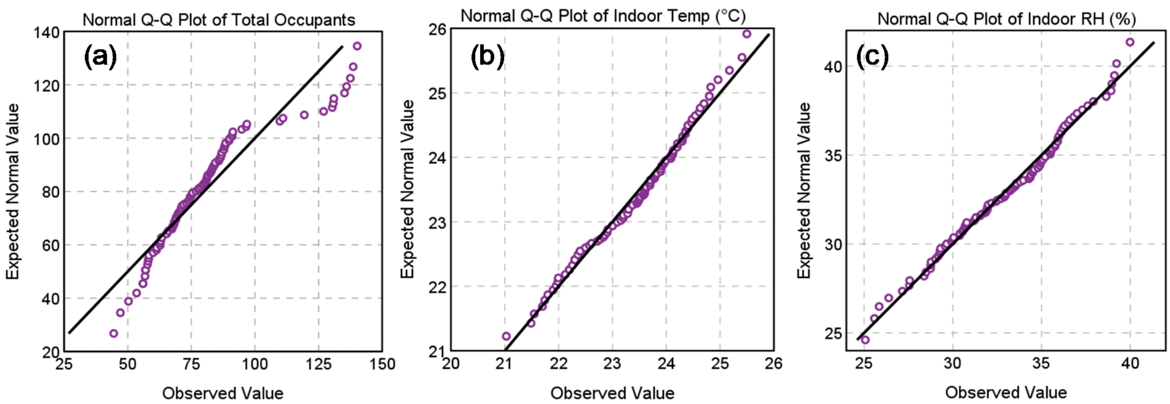

Figure 4. *Cont.*

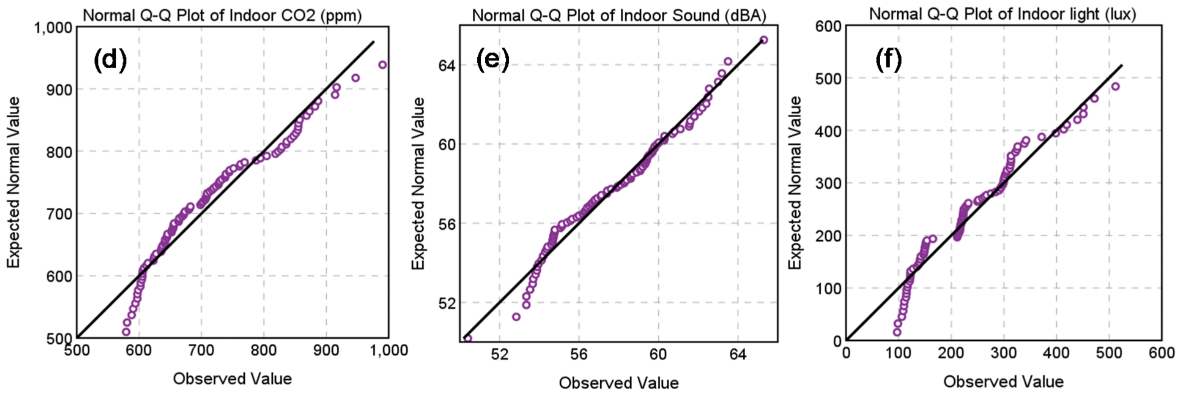

Figure 4. Normal quantile–quantile (Q-Q) plots for (**a**) total occupants, (**b**) indoor temperature, (**c**) indoor relative humidity (RH), (**d**) indoor CO_2, (**e**) indoor sound level, and (**f**) indoor light (n = 99).

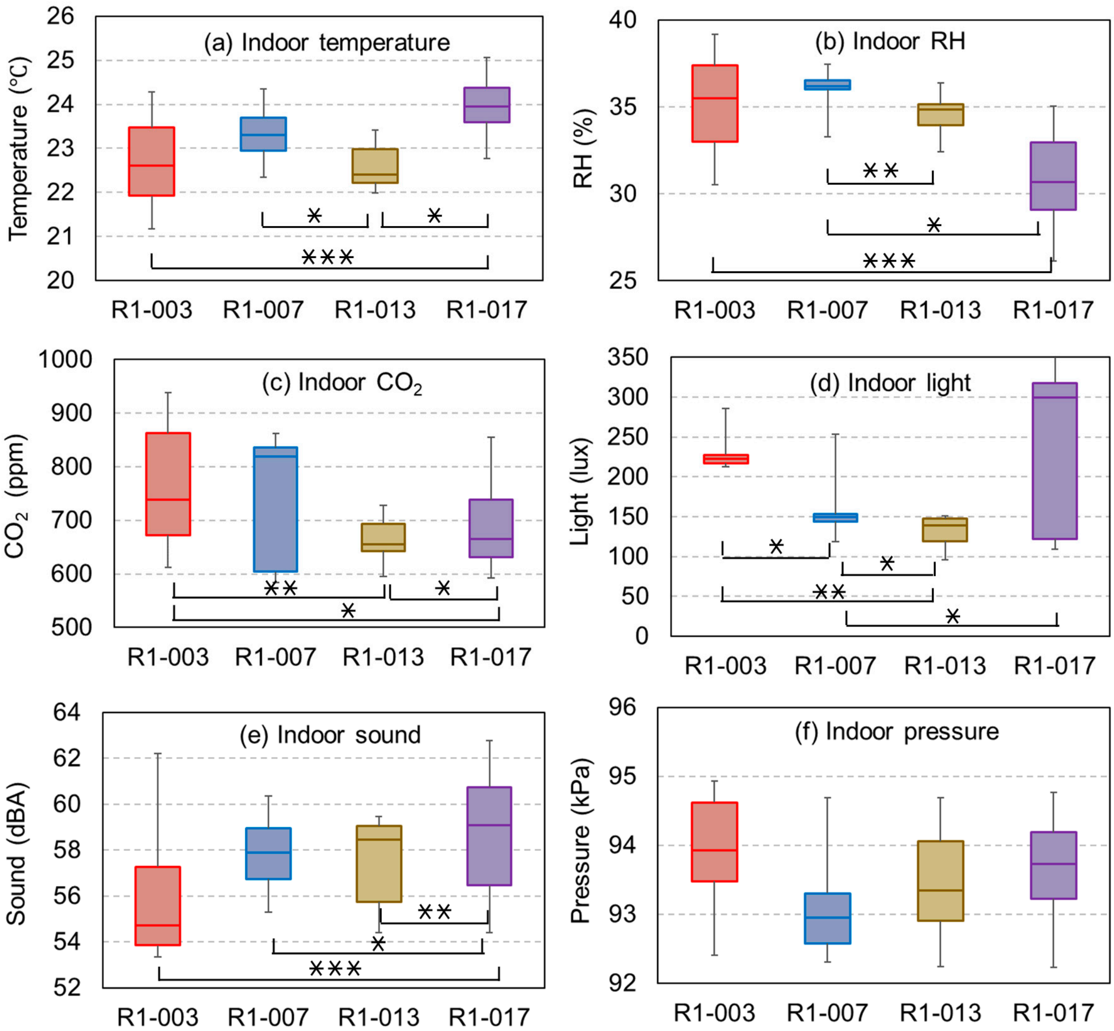

Figure 5. Boxplots for key indoor environmental quality (IEQ) parameters, where the boxes represent the 25th, 50th, and 75th percentiles, and the whiskers represent the 5th and 95th percentiles (statistical significance: * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$).

4. Discussion

4.1. Within- and Between-Classroom Comparisons

The variance analysis indicated that the within-lecture classroom variations in most IEQ parameters exceeded between-lecture classrooms (Table 3). In particular, indoor CO_2, sound, illuminance, and pressure had large within-classroom variations. Within-room variation results from multiple factors: Outdoor environment, HVAC system operation, occupant behavior (number, voice frequency, learning activity), use of indoor facilities (microphone and light system). Low between-classroom variations are attributed to the mixed mechanical system of the central AHU with heating units and similar indoor design. Occupant number difference (latent heat is given off by humans) could be a reason for the slightly higher between-classroom variation in RH than the within-classroom one since only the central AHU had a humidification function. Temperature and RH had almost equal within- and between-classroom variations indicating that the central HVAC system, combined with VAV terminal reheat boxes, provided constant conditioned air to the classrooms, resistant to influence from fluctuations from other indoor and outdoor factors across the heating season. When the between-classroom variance is small, it means that the IEQ evaluation from the selected lecture classrooms can represent the IEQ characterization within the building. For all IEQ elements, the differences between classrooms were statistically significant. Hence, classroom characteristics, internal classroom operation (manual light levels and microphone voice volumes), the VAV system, and occupant behavior play a key role in determining indoor IEQ.

Table 3. Within- and between-classroom variation in indoor environmental quality parameters.

IEQ Parameter	Percent of Variation (%)		*p*-Value [1]
	Within-Classroom	Between-Classroom	
Temperature	54.0	46.0	**0.000**
RH	46.7	53.3	**0.000**
CO_2	89.2	10.8	**0.017**
Sound	78.8	21.2	**0.000**
Illuminance	78.1	21.9	**0.000**
Pressure	91.1	8.9	**0.032**
Number of persons	77.2	22.8	**0.000**
ACR	64.6	35.4	**0.000**

[1] *p*-value test for the IEQ differences between-classrooms. Bold values are statistically significant ($p < 0.05$).

4.2. Seasonal Comparisons

Most indoor and some outdoor parameters varied by season. For example, outdoor temperatures at study classrooms averaged −14.2 ± 5.8 °C in winter, statistically lower than the average temperature in fall by both ANOVA and K-W tests (Table 4). Outdoor RH, wind speed, and wind direction had no statistically significant seasonal differences. Except for acoustics and the number of total persons, all other observed IEQ elements had statistical differences, and the effect sizes of such differences were large (Cohen's d > 0.5). The below-average ACR in winter compared to fall led to an increase in indoor CO_2 concentration in winter. In addition, although the winter heating load was larger than the heat requirement in fall, the mean indoor temperature was higher in winter (23.7 ± 1.1 °C) than in fall (23.1 ± 0.8 °C), indicating that, to save energy, some operation should be adjusted for the thermostats or VAV heat boxes in cold weather.

4.3. Interactions Between Indoor Environmental Quality Parameters

Since HVAC systems work as a bridge to link outdoor and indoor microclimates, IEQ was highly correlated to outdoor environments (Figure 6). For example, indoor RH increased with outdoor temperature (r = 0.336) as humidity ratio (g moisture/kg dry air) increased with outdoor temperature across two seasons. Outdoor temperature was inversely correlated with outdoor pressure due to the higher density of air at the lower temperature (ideal gas law), while indoor pressure was highly dependent on the outdoor pressure (r = 0.995, 0.50 ± 0.06 kPa higher indoors). Thus, the outdoor temperature was negatively correlated with indoor pressure. ACR was linearly correlated with outdoor temperature, possibly due to the energy-saving strategy discussed in Section 4.4, leading to higher indoor CO_2 levels at colder days.

Table 4. Statistics of outdoor and indoor parameters by season.

Parameter		Fall (n = 50)	Winter (n = 49)	Season: Fall and Winter		Cohen's d
				ANOVA [1]	Kruskal–Wallis [1]	
Outdoor	Temperature (°C)	1.7 ± 4.0	–14.2 ± 5.8	**0.000**	**0.000**	3.192
	RH (%)	69 ± 23	74 ± 13	0.174	0.554	0.268
	Wind speed (km/h)	9.0 ± 5.5	10.2 ± 5.1	0.245	0.140	0.226
	Wind direction (°)	210 ± 80	214 ± 96	0.874	0.682	0.045
Indoor	Temperature (°C)	23.1 ± 0.8	23.7 ± 1.1	**0.008**	**0.001**	0.624
	RH (%)	34 ± 3	32 ± 3	**0.000**	**0.000**	0.667
	CO_2 (ppm)	677 ± 81	751 ± 115	**0.000**	**0.001**	0.744
	Sound (dBA)	58 ± 3	58 ± 3	0.742	0.785	0.067
	Illuminance (lux)	206 ± 86	271 ± 131	**0.005**	**0.008**	0.587
	Pressure (kPa)	93 ± 1	94 ± 1	**0.000**	**0.000**	1.000
	Total persons	83 ± 25	79 ± 17	0.326	0.737	0.187
	ACR (1/h)	4.2 ± 1.3	3.4 ± 1.4	**0.005**	**0.005**	0.592

[1] Bold values are statistically significant ($p < 0.05$).

Indoor temperature was positively and significantly correlated with total occupants (r = 0.403), indoor sound (r = 0.313), ACR (r = 0.320), and indoor light (r = 0.283). Occupants and equipment, i.e., light system and sound amplification system, are the internal thermal sources that contribute to indoor temperature. This observation was in line with Yang's finding that the effects of room temperature were significant on the room brightness [60]. Light level was negatively and correlated with RH (r = −0.506) and occupancy number (r = −0.284) because water vapor tended to condense on outer lens of LED lights at high humidity surroundings [61] and occupants were light absorption source, which degraded optical performance. This study has revealed that light performance interacted with its surrounding thermal conditions, which supported the other researchers' finding that light affects human thermal perception also [62]. The stiffness of the acoustic wall panels was temperature-dependent, leading to the lower sound level at lower indoor temperature. In addition, the attenuation of sound in air was affected by RH. Moist air was less dense at a higher temperature as holding more water vapor, thus dry air at low temperature absorbed far more acoustical energy than did moist air at high temperature. Thus, sound passed through hot air easier than through cold air. Different from indoor temperature, indoor RH showed positive correlations with classroom volume and outdoor temperature and was negative to indoor light levels. The ACRs determined for the classrooms were significantly associated with CO_2 concentration (r = −0.740). Table S1 in the Supplementary Material shows all the results of the Spearman tests. It is interesting to note that the complicated correlation of IEQ parameters found here was based on the analysis of local outdoor weather in conjunction with HVAC operations in the building, constrained by indoor operations. For example, the brightness setting of light systems varied significantly.

MANOVA was implemented to indicate that the interaction of outdoor environments (outdoor temperature (p = 0.000) and RH (p = 0.000)), indoor behaviors (ACR (p = 0.000) and illuminance (p = 0.012)) has significant impacts on a linear combination of the indoor dependent variables (indoor temperature, indoor RH, and indoor CO_2) (Table S2). Indoor sound levels did not appear to have a significant effect on indoor conditions. In order to further explore the complicated inter-relationships and importance of independent variables, the ANN model was trained 10 times to generate mean and standard deviation of relative errors and correlation coefficients for three indoor dependent variables (indoor temperature, indoor RH, and indoor CO_2) (Table S3). The trained ANN model had high correlations (R^2 = 0.469–0.928) between measured and predicted three variables. Hence, the established ANN model was able to provide the relative importance of five independent predictors (outdoor RH, outdoor temperature, occupant number, daylight lux, and ACR) in estimating three dependent variables. The normalized importance chart (Figure 7) from 10 ANN model tests shows that the indoor conditions were dominated by the ACR performed (99.0% ± 2.1%), followed by indoor operations (light system (85.1% ± 10.1%), and occupant numbers (79.2% ± 11.9%)), followed distantly by outdoor conditions. Therefore, the HVAC system operation, classroom conditions, and building location play critical roles in determining classroom IEQ.

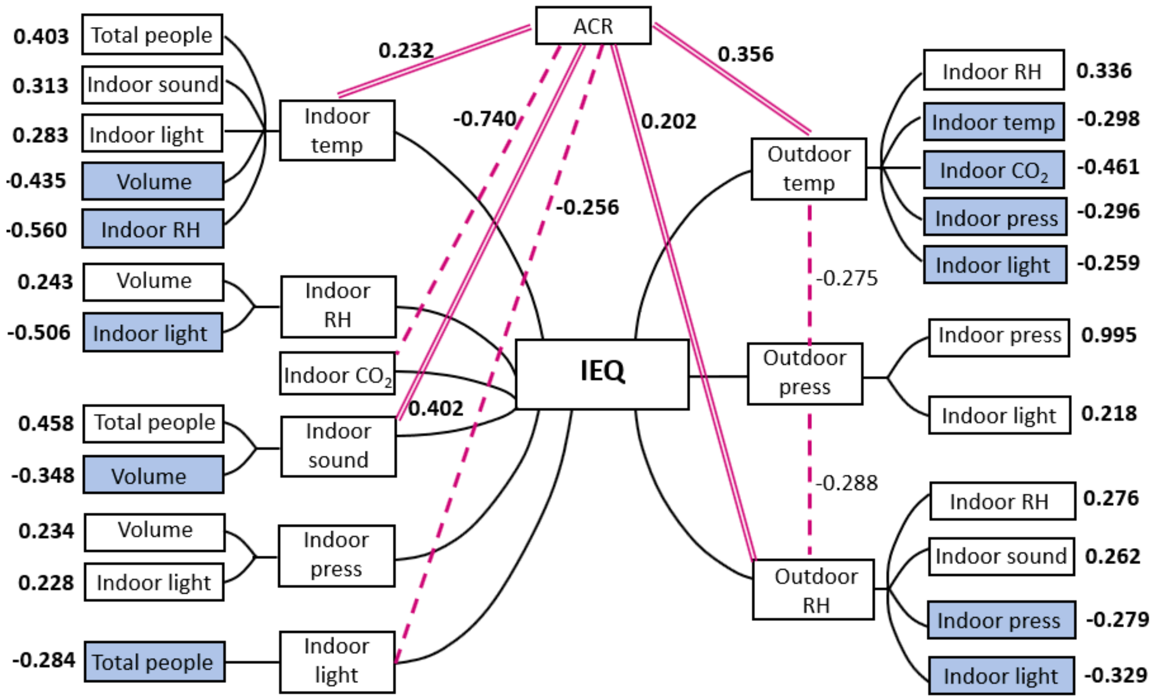

Figure 6. Map of the major associations for indoor and outdoor variables. Positive associations are indicated with white boxes or double lines. Negative associations are indicated with blue boxes or dash lines. Bold values are statistically significant by Spearman rank tests ($p < 0.05$). "Temp" denotes temperature. "Press" denotes pressure.

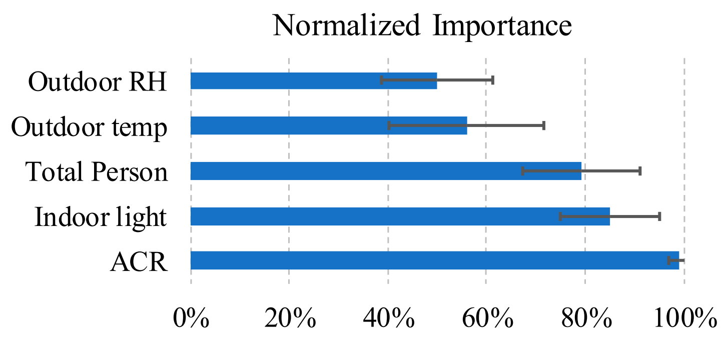

Figure 7. Normalized importance of independent variables.

4.4. Ventilation and Air Change Rate (ACR)

In all cases, ACRs were in the range of 1.3 to 6.5 per hour (4 ± 1 per hour) during lecture periods when the building's HVAC systems commonly operated. The linear regression model in Figure 8a presents the increasing trend of outdoor ventilation rates with outdoor temperatures across all classrooms. Assuming return airflow rates remained the same across seasons, it was highly possible that outdoor air intake rates decreased as outdoor temperature decreased. This engineering ventilation strategy was developed for energy saving with consideration of a significant amount of energy required for air conditioning during extremely cold days. Figure 8b shows that the mean and median ACRs of R1-017 and R1-013 were higher than those of R1-003 and R1-007. ASHRAE 62.1-2016 recommends a minimum outdoor air rate (accounting for both people- and area-related sources) for lecture classrooms of 8 cubic feet per minute (cfm) (4.3 $L \cdot s^{-1}$) per person. The calculated outdoor air rates were 15 ± 6 cfm (7 ± 3 $L \cdot s^{-1}$) per person with default occupant density 65 persons/100 m^2 defined by ASHRAE 62.1 [55], indicating that the adequacy of the ventilation system in the ETLC building was compliant with the standard. If based on actual average occupant density across all measurements, outdoor air rates were 47 ± 15 cfm (22 ± 7 $L \cdot s^{-1}$) per person, much exceeding the recommended ASHRAE values. Hence, smart controls for building systems should be implemented. For example, if occupant sensors are sensitive to the occupant number, they then have the ability to adjust outdoor air intake rates according to the real number of persons in a room to save energy costs.

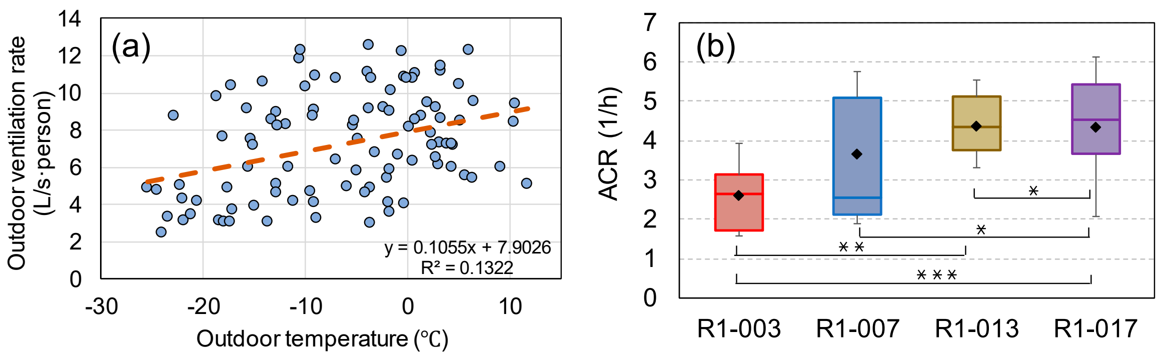

Figure 8. (**a**) The relationship between outdoor ventilation rate and outdoor temperature and (**b**) room-to-room air change rates (ACR) variability (the boxes represent the 25th, 50th, and 75th percentiles, and the whiskers represent the 5th and 95th percentiles; diamonds denote the mean values; statistical significance: * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$).

4.5. Limitations and Future Study

This study repeatedly characterized IEQ in four lecture classrooms housed in the ETLC building for the fall and winter seasons in the climate zone seven. Our results may not apply to other institutional buildings that are older, naturally ventilated, located in other climatic regimes, or accommodated with different HVAC settings. In addition, each lecture classroom was assumed to be a single well-mixed zone with measurements in a single location. Repeated measurements across seasons and random measurement location selection somehow offset the spatial variations. The CO_2-derived ACR was not verified by other methods, like the tracer gas CS_6 method.

Other indoor environmental parameters, such as volatile organic compounds, particulate matter, reverberation time, sound uniformity, and sound intelligibility, were not measured in phase I but will be included in phase II. Some building features, such as building envelop heat resistance values and exposure areas, may need to be involved in the development of the input units of the ANN model to better predict indoor temperature performance. While the data collected appear sufficient to characterize IEQ in lecture classrooms, future studies might use long-term measurements (workdays), repeated measurements at different times in each season, and shift samples between classes that better characterize IEQ in institutional buildings. Moreover, the unoccupied period is of less interest to IEQ research purposes. However, the quantification of IEQ changes during HVAC shut-off periods would provide more evidence to optimize the HVAC control for energy-saving purposes. These topics will be the focus of further studies.

5. Conclusions

Due to the amount of time that young adults and faculty members spend in lecture classrooms, they are vital environments in postsecondary education institutions. To date, however, characterizations of IEQ in these institutions have been limited, and studies comparing IEQ in institutional buildings are not available. Impacts of the institutional environment on the academic performance of students and energy costs to create healthy IEQ motivated this study to better characterize environmental conditions.

This study examines IEQ parameters, including pressure, illuminance level, acoustics, CO_2 levels, temperature, and humidity, with appropriate monitors allocated during a lecture (duration 50 min or 80 min) in four lecture classrooms 1676 ± 44 m^3 repeatedly from October 2018 to March 2019. Outdoor temperature was −25 °C to 12 °C during two-season measurements, while the classroom environment was maintained at 23 ± 1 °C and 33% ± 3% RH. Through a central AHU and VAV terminal boxes, indoor CO_2 had mean concentrations of 550–1055 ppm, indicating the CO_2 concentrations were mostly acceptable. Mean sound and illuminance levels were 58 ± 3 dBA and 235 ± 112 lux, respectively, which imply acoustic and visual comfort was created. Except for RH, within-lecture classroom variations of IEQ elements during the two seasons exceeded between-lecture classrooms. Using the one-zone steady-state box model, the ACRs were configured at 1.3–6.5 per hour based on continuous CO_2 measurements and occupant loads in the lectures. The actual outdoor air intake rates, 47 ± 15 cfm (22 ± 7 $L{\cdot}s^{-1}$) per person, were much higher than the recommended value (8 cfm (4.3 $L{\cdot}s^{-1}$) per person) for lecture classrooms by ASHRAE 62. High-sensitivity occupant sensors would be an option in conjunction with a dynamic CO_2 control sequence to adjust outdoor air intake rates for energy-saving purposes. The results of the IEQ investigation in this study updates the literature by putting the spotlight on the correlations of the building and the HVAC operations, as well as the effects of the outdoor environments on IEQ.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/23/6591/s1, Table S1: Spearman rank correlation coefficients of key IEQ parameters (n = 99), Table S2: Multivariate analysis, Table S3: Relative error and R^2 for the optimal ANN model by five consecutive trainings.

Author Contributions: L.Z. and B.F. conceived and designed the field study; J.Y. performed the data analysis and validation; L.Z. administrated the project, analyzed the data, and wrote the original draft; B.F. reviewed and edited writing.

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Conflicts of Interest: The authors declare no conflict of interest.

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