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Effects of Climatic Conditions, Season and Environmental Factors on CO_2 Concentrations in Naturally Ventilated Primary Schools in Chile

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Abstract: Between the ages of 6 and 18, children spend between 30 and 42 h a week at school, mostly indoors, where indoor environmental quality is usually deficient and does not favor learning. The difficulty of delivering indoor air quality (IAQ) in learning facilities is related to high occupancy rates and low interaction levels with windows. In non-industrialized countries, as in the cases presented, most classrooms have no mechanical ventilation, due to energy poverty and lack of normative requirements. This fact heavily impacts the indoor air quality and students' learning outcomes. The aim of the paper is to identify the factors that determine acceptable CO_2 concentrations. Therefore, it studies air quality in free-running and naturally ventilated primary schools in Chile, aiming to identify the impact of contextual, occupant, and building design factors, using CO_2 concentration as a proxy for IAQ. The monitoring of CO_2, temperature, and humidity revealed that indoor air CO_2 concentration is above 1400 ppm most of the time, with peaks of 5000 ppm during the day, especially in winter. The statistical analysis indicates that CO_2 is dependent on climate, seasonality, and indoor temperature, while it is independent of outside temperature in heated classrooms. The odds of having acceptable concentrations of CO_2 are bigger when indoor temperatures are high, and there is a need to ventilate for cooling.

Keywords: educational building; free-running; carbon dioxide; indoor air temperature; interaction; occupant density; indoor environmental quality

1. Introduction

School classrooms are the indoor spaces where children spend most of the time, other than their homes. According to the 2019 report from Organization for Economic Co-operation and Development (OECD), the compulsory instruction time is between 7360 and 2393 h per year in primary education [1], and most of those hours are spent inside a classroom. These spaces are characterized by high occupant density and low air volume per student [2]. The time spent indoors is mostly in the same classroom, with predefined breaks where they leave the room. At the same time, children, in a traditional classroom, have reduced mobility and, therefore, limited options to adapt or modify their surroundings [3,4]. Indeed, most of the adaptative actions are performed by the teachers, based on their own comfort or requests made by the children [5]. All these factors make it more challenging to provide good indoor air quality (IAQ) in classrooms than other buildings.

The lack of proper indoor air quality is related to asthma, allergies, and other illnesses, sometimes referred to as sick building syndrome (SBS). It is also relevant to note that children are more susceptible to long-term health damage due to low indoor environmental quality (IEQ) [6–9].

Indoor air quality will be affected by various contaminants that can be produced inside or outside the building. Indoor pollutants can have a human origin, like CO_2 from respiration and odors, or be emitted by the building materials. Other indoor contaminants are released by cleaning agents and products used in educational activities [10]. Outdoor sources of pollutants are related to productive activities performed in the school's vicinity, roads' proximity, and local climatic conditions [11].

A common classification scheme of contaminants is based on their origin. Biological pollutants are mold; endotoxins; bacteria; viruses; and allergens, like dust mites, pet hair, or pollen. Chemical pollutants include organic and inorganic gasses, such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO, NO_2), and ozone (O_3), among others. Volatile organic compounds (COVs) are also classified as chemical compounds. Most of the COVs are originated from construction materials, furniture, and cleaning products in school classrooms. The chemical contaminants with the highest presence in classrooms are benzene, toluene, xylene, ethylbenzene, α-pinene, and d-limonene [7,12–16]. The last category is physical pollutants; a common denomination for dust particles is between 0.01–200 μm. Metals can also be classified as physical pollutants when they are present as particles between 0.1 and 30 μm.

Previous research conducted by Chatzidiakou et al. [17,18] found that CO_2 can be used as a proxy for indoor air quality in classrooms, considering that low CO_2 concentration is correlated with the dilution of indoor pollutants and the purge of airborne particles. It is relevant to note that, although a correlation between CO_2 concentration and cognitive performance has been found [19], it is not clear that CO_2 concentration is the cause of the decline in performance [20]; therefore, CO_2 is considered a proxy for indoor air quality [17,18,21–24], not as a contaminant.

In school classrooms, the lack of IAQ can lead, directly or indirectly, to health problems, low productivity [25,26], and absence [4,27–30]. Studies conducted in schools in Washington and Idaho [22] found a correlation between high concentrations of CO_2 and lower attendance. This correlation was further studied for California primary schools [31] and found that increasing the ventilation rates by 1 L/s per person could increase attendance while positively affecting learning outcomes. Haverinen-Shaughnessy and others [32] found that IAQ is related to cognitive function and productivity and that increasing the ventilation rates in classrooms should improve the students' academic achievement. This claim was confirmed by Toftum et al. [33] in a study conducted in Danish Schools. Wargocki et al. [21] present a review of the effects that indoor air quality in classrooms has on students' performance and health. In this study, researchers were able to find a relationship between CO_2 concentration and ventilation rates and learning outcomes, concluding that reducing CO_2 concentrations from 2100 to 900 ppm would increase the performance speed by 12% and accuracy by 2%, while also improving the performance of national tests and school-leaving examinations by 5%. Considering attendance as an indicator of health, they concluded that reducing CO_2 from 4200 ppm to 1000 ppm would increase children's daily attendance by 2.5%. Although the results presented do not apply to every classroom, we can assume that improved performance and health can be expected when indoor air quality is improved.

In naturally ventilated classrooms, this issue is more relevant than in mechanically ventilated ones [34]. Indoor air quality has been related to outdoor conditions, including the location of the school (urban or rural) and climatic conditions (wind speed and direction, outdoor temperatures), as well as window opening behavior and willingness of pupils and teachers to open windows [35]. Korsavi et al. [36] suggest that some factors related to IAQ are occupants' adaptive behavior, occupancy patterns, CO_2 generation rates, and occupant density and highlight the potential of the classrooms to facilitate adaptative behaviors. Based on studying a sample of 29 naturally-ventilated classrooms in the UK during non-heating and heating seasons, they proposed a classification of the main factors affecting ventilation rates, and, therefore, IAQ sorting them into three groups: contextual, occupant-related, and building-related (COB) factors [37].

Although some studies have been done on indoor air quality in Chilean schools since 2011 [38–41], the lack of statistical analysis made it impossible to identify the cofounding factors that affect the IAQ in the context of naturally ventilated schools in a non-industrialized country.

Aim and Contribution of This Study

Considering the proven negative effects that poor air quality in classrooms has on the health and performance of children, this paper's main objectives are as follows: (1) Evaluate CO_2 concentrations in naturally ventilated classrooms and compare them with thresholds. (2) Identify the cofounding factors that will lead to acceptable CO_2 levels, according to EN 13779:2007 [42] and EN16798-3 [43] in naturally ventilated school classrooms under normal occupation conditions. (3) Propose strategies to improve IAQ through design. One of the hypotheses being tested is that the need to conserve heat prevents ventilation in the cold season, having a detrimental impact on air quality. The results of this research can be valuable to building managers and designers of retrofitting strategies, mostly at the government level. The originality of this research is performing a binary logistic analysis to identify the factors that define acceptable CO_2 concentrations. Considering that the variables under study (CO_2 concentration and temperature and humidity) are continuous variables, and Binary Logistic Regression (BLR) was used instead of ANOVA.

This paper's organization is as follows: Section 2 is devoted to the Materials and Methods, which describes the definition of variables under study and data collection. It also describes the data processing and the statistical analysis of the IEQ conditions in the classrooms that would predict IAQ. Section 3 presents the monitoring phase results and the results of the statistical analyses performed to make the association between classroom IEQ and IAQ. Section 4 discusses the findings and the limitations of the study. Section 5 presents the conclusions from this research.

2. Materials and Methods

This paper aims to investigate the cofounding factors that will lead to acceptable CO_2 levels in naturally ventilated school classrooms under normal occupation conditions, considering the local architectural design, materials, and systems, as well as climatic and cultural conditions. The research methodology was defined based on a literature review of similar studies and is organized in steps, as presented in the conceptual framework in Figure 1: (1) Definition of research design. (2) Sample selection. (3) Data acquisition. (4) Evaluation of CO_2 concentration against thresholds. (5) Regression analysis and quality assurance.

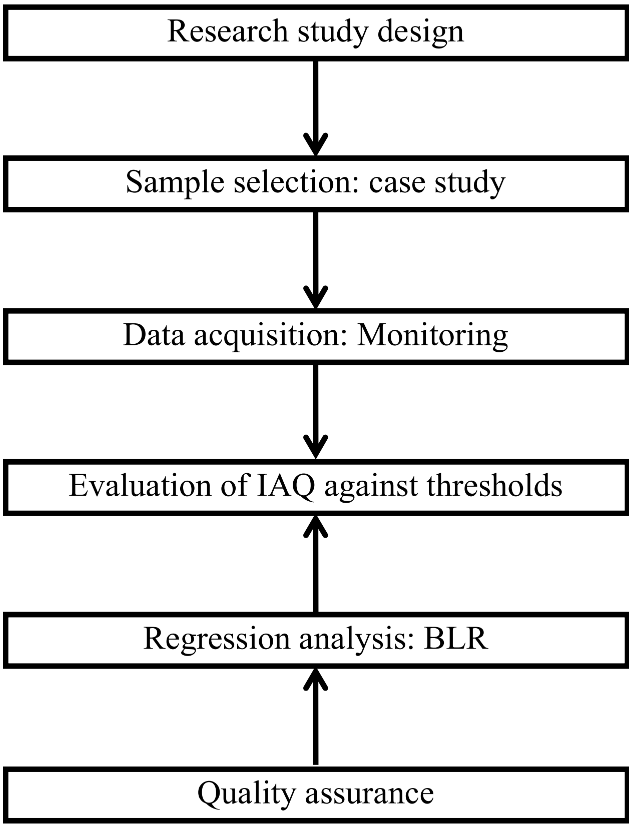

Figure 1. Study conceptual framework.

2.1. Study Variables and Selection of Cases

In this study, the dependent variable will be CO_2 concentration as a proxy for IAQ. In contrast, the independent variables were defined, based on the characterization made by Korsavi [37] and the literature review. The factors under study are contextual factors: season, operative temperature [44–46], outside temperature, and humidity; building-related factors: room's volume and dimensions; and occupant-related factors: occupant density [36].

It is noteworthy that the required threshold for classrooms' indoor environmental quality (IEQ) in Chile is limited to temperatures above 12 °C in classrooms [47], while no requirement is made for IAQ. The only related constraint is a defined percentage of glazing according to latitude, without clarifying if the windows need to be open or not. Occupant density in classrooms must be less than 1.1 m^2/student, and the minimum volume of air is 3 m^3/student, and the minimum height of the rooms is set at 2.2 m [48]. Several standards and certification schemes suggest other requirements for the indoor environmental quality of school classrooms, but they are nonmandatory and are mainly applicable to new buildings [49,50].

The selection of cases had to consider that the school system in Chile categorizes schools based on ownership and type of administration as public, subsidized, and private. It is assumed that the maintenance and operation founding defer between these three categories. This study focuses only on public and subsidized schools, as they are founded and regulated by the Ministry of Education. The criteria for selecting cases were based on availability, and the unit of analysis is defined at the classroom level.

2.1.1. Climate

Considering the diversity of climates in Chile, this study is focused only on two different climatic conditions, each represented in one city. The aim of selecting these two cities is to understand differences between climatic conditions and validate the potential for natural ventilation for air quality in each city and confirm if outdoor conditions affect indoor IAQ [34]. Both cities have clear differences between seasons and each other. Based on the updated Köppen–Geiger climate classification for continental Chile [51], Santiago de Chile (33°27′00″ S 70°40′00″ O) has a Mediterranean climate with warm summer (Csb). The city is located in the foothills of the Andes. It has winter rains and a long dry season. The distance to the sea from the city accentuates the thermal oscillations, which are considered daily and annually. The average temperature in summer is 20.1 °C, with maximum averages over 29 °C and minimum averages over 12 °C, with maximum extremes of 34 °C. In winter, the average temperature is 8.2 °C, with average highs above 15 °C and average lows close to 3 °C, with extreme lows of −2 °C.

On the other hand, Puerto Montt (41°28′18″ S 72°56′23″ O) is classified as Marine West coast climate with warm summer (Cfb). The city is located directly on the coast of the protected northern end of the Reloncaví Estuary. The climate is characterized by abundant rainfall throughout the year, registering an average of 1800 mm per year, which does not define a dry season, despite decreasing considerably in summer. In winter, the average temperature is 6.5 °C, with a maximum of 10.5 °C and a minimum average of 3.9 °C. In summer, the median temperature is 13.9 °C, while the maximum average is 19.6 °C, and the minimum average is 9 °C. The low thermal oscillation, both in the daily and annual regime, the extremely humid environment, and the cloudiness almost permanently define this climate. It is relevant to note that Santiago is the most densely populated city in Chile and concentrates half of the population, making it a relevant case study. On the other hand, Puerto Montt represents the south of the country, where winters are colder and rainy, while also being a regional capital.

2.1.2. Buildings

Most of the schools in Chile are naturally ventilated, and the installation of any form of heating systems is not required by normative; the only requirement is to maintain a temperature above 12 °C [47] in primary and secondary schools from 36°38′12″ S to the south. Therefore, Santiago de Chile's buildings did not include heating systems, while the ones in Puerto Montt had functioning heating systems. The regulation does not require cooling in summer in any part of the country. The selected schools are all public schools that receive funding through the municipal government or subsidized schools that receive funding through the municipal government and fees paid by the students' parents. The cases' selection was made on the schools' directors' availability and willingness to grant access to the researchers.

Data on building characterization was gathered through observation, checklists, and data provided by the Education Ministry. The collected information included microclimate (all of the selected schools are urban), construction characteristics, maintenance and operation of school buildings, occupancy patterns, and socioeconomic data of the students. In Figure 2, pictures of the classrooms are presented: the top row shows the classrooms in Puerto Montt, and the bottom row shows the ones in Santiago.

Figure 2. Classrooms under study.

2.1.3. Occupants

Among the primary school students, the 4th-year elementary class with students between 9 and 10 years old was selected, considering the balance between understanding the questionnaire and a longer permanence in the classroom than older children. The number of students at each school varied between 26 and 42 children per class, and their presence during monitoring further depended on school attendance. The attendance was recorded three times a day at 08:30, 11:30, and 15:00. Therefore, the four blocks of classes were assigned, as per Table 1. Breaks of 15 min were assigned, but the opening of windows during this period was not registered.

Table 1. Schedule and time of the day that the attendance was recorded.

Teaching Schedule	Attendance Log Time
08:30–09:45	08:30
10:00–11:45	11:30
12:00–13:45	11:30
14:00–15:45	15:00

2.1.4. Monitoring

The methodology used for collecting data was the transverse method, collecting data in 8 primary schools located in urban areas across Chile during 3–4 consecutive days in two periods of time. The days selected were representative of that year's winter and spring seasons. Values for temperature, humidity, and solar radiation correspond to the typical values for those periods. The classrooms were of similar size (mean: 52.1 m^2) and housed between 26 and 42 students; see Table 2. It is important to note that the occupant density (according to the number of students enrolled) was between 1.1 and 1.9 m^2 per student, which complies with regulation but is far from international standards [52]. The schools were all located in urban areas; code SCL corresponds to Santiago de Chile, and PMC to Puerto Montt. According to the normative, all of the classrooms had natural ventilation through operable windows, and only cases 5–8, located in Puerto Montt, had heating systems. The occupancy period was from 0900 to 1545 in all classrooms, with two short breaks during the day and a break at lunchtime.

Table 2. Description of case studies.

	SCL 1	SCL 2	SCL 3	SCL 4	PMC 1	PMC 2	PMC 3	PMC 4
Number of students (N)	36	39	41	39	44	35	45	26
Classroom area (m^2)	55.8	56.1	50.8	52.5	49.8	51.9	50.3	49.7
Occupant density (m^2 /student)	1.6	1.4	1.2	1.3	1.1	1.5	1.1	1.9
Classroom volume (m^3)	167.4	151.6	162.7	136.5	149.5	148.2	140.9	139.1
Total of winter working days monitored	4 days	3 days	3 days	3 days	4 days	4 days	4 days	4 days
Total of spring working days monitored	4 days	4 days	4 days	4 days	4 days	4 days	4 days	4 days

2.1.5. Environmental Measurements

Measurements were obtained using a Delta Ohm HD32.3 instrument that registered dry bulb temperature (Ta), globe temperature (Tg), relative humidity (RH), and air velocity (Va) at 5 min intervals during the occupied period (0900 to 1500) in all classrooms. CO_2 concentration was measured with Hobo Carbon Dioxide Logger at the same interval, considering it as a proxy for indoor air quality [17,18,21–24], not as a contaminant. Table 3 summarizes the characteristics of the equipment. As was described in a previous publication [44,53,54], which used the same data collection protocol, teachers and students did not receive any recommendation regarding when to operate windows and did not have control over heating systems, if existing (only cases 5–8, corresponding to Puerto Montt, had a heating system).

Table 3. Summary of the parameters, measurement intervals, and equipment characteristics.

Monitored Parameters	Duration of Measurement	Intervals	Measuring Range	Accuracy	Equipment
Globe Temperature	3–4 school days	5 min.	−10 to 100 °C	±0.1 °C	Delta Ohm HD32.3
Relative Humidity	Idem	Idem	5–98%	±2%	Idem
Carbon dioxide concentration	Idem	Idem	0 to 5000 ppm	±50 ppm	Hobo Carbon Dioxide Logger

2.1.6. Thresholds

Temperature is established as compliant when it is higher than 12 °C, as per Chilean standard [47]. For this study and based on the international requirements and the proposed new regulation for IEQ in schools in Chile (not published), temperatures between 18 °C and 25 °C are desirable. Considering that Chile does not have regulations regarding IAQ, the thresholds used are the categories defined in EN 13779:2007 [42] for indoor CO_2 concentrations.

2.1.7. Statistical Analysis

Before studying the correlation between parameters, we present descriptive statistics. Considering that environmental factors are not normally distributed, mean, median, interquartile range, standard deviation, and maximum concentrations were used to describe each of the parameters of interest at the classroom level.

The collected data had a hierarchical structure (city, season, school, observations), where observations are dependent. Therefore, conventional single level statistical methods were not used.

A binary model using Binary Logistic Regression (BLR) was applied to explore the relationship between acceptable CO_2 concentrations (response variable) and contextual, occupant, and building [37] factors (predictor variables), as shown in Table 4. The threshold values expressed in the table were taken from EN 13779:2007 for CO_2 concentrations, temperature, and humidity thresholds and were defined, based on the proposed new regulation for IEQ in schools in Chile (not published). This method is applicable when the predictor variables are ordinal variables that take only values that have a natural ordering and have more than two categories. The results of this analysis are odds ratios that describe the likelihood of having acceptable CO_2 concentrations when one of the predictor variables is increased by one unit. In contrast, the other variables are kept constant. The odds ratios were then used to rank the parameters regarding their importance for acceptable CO_2 concentrations. Binary Logistic Regression was calculated with SAS/STAT® software, and only the data for occupied periods were used. The Wald Chi-Square test tested the statistical significance of each predictor variable in the regression model.

Table 4. Binary categories.

Binary Category	CO_2 Level	Indoor Temperature	Outdoor Temperature	Indoor RH	Outdoor RH
Acceptable	CO_2 < 1000 ppm	18–24.9	18–24.9	30–50	30–50
Nonacceptable	1000 < CO_2	<18 or >25	<18 or >25	<30 or >65	<30 or >65

3. Results

3.1. Thermal Conditions

Indoor thermal conditions in the classrooms under the study varied between 9.9 °C and 20.1 °C in Santiago (no heating systems) and between 11 °C and 22.6 °C in Puerto Montt (with heating systems) during the occupancy period in winter. In spring, the temperature varied between 18.0 °C and 32.2 °C in Santiago, where cooling is not included in schools, and outside temperatures are high. In Puerto Montt, spring temperatures varied between

10.3 °C and 23.8 °C. More information about thermal perception and comfort for some of the Santiago cases is available in [44].

In winter, schools in Santiago have temperatures lower than 18 °C between 91.78% and 49.32% of the time, while classrooms in Puerto Montt, with a colder climate but compensated with heating systems, had temperatures lower than 18 °C between 0% and 55% of the time.

3.2. CO_2 Concentration

The statistical distributions of CO_2 ppm measurements for all cases in spring and winter are shown in Figure 3. The Figure displays medians below 1500 for all cases in spring, while in winter, most of them rise over this threshold (five of eight). Variability was also bigger in winter, where higher concentrations were observed. This suggests that natural ventilation through windows is being used primarily in spring, but only when the outside temperature is higher. It is not clear if ventilation is due to temperature or to improve IAQ.

During winter, 16.1% of CO_2 measurements in Santiago corresponded to category I ($CO_2 < 800$ ppm), 9.6% to category II ($800 < CO_2 < 1000$ ppm), 22.3% to category III ($1000 < CO_2 < 1400$ ppm), and 52.1% to category IV ($CO_2 > 1400$ ppm). In spring, also in Santiago, 79.8% of CO_2 measurements corresponded to category I ($CO_2 < 800$ ppm), 8.6% to category II ($800 < CO_2 < 1000$ ppm), 8.1% to category III ($1000 < CO_2 < 1400$ ppm), and 3.6% to category IV ($CO_2 > 1400$ ppm).

During winter, 18.6% of CO_2 measurements in Puerto Montt corresponded to category I ($CO_2 < 800$ ppm), 8.1% to category II ($800 < CO_2 < 1000$ ppm), 17.4% to category III ($1000 < CO_2 < 1400$ ppm), and 56.0% to category IV ($CO_2 > 1400$ ppm). In spring, also in Puerto Montt, 29.6% of CO_2 measurements corresponded to category I ($CO_2 < 800$ ppm), 9.7% to category II ($800 < CO_2 < 1000$ ppm), 18.7% to category III ($1000 < CO_2 < 1400$ ppm), and 41.9% to category IV ($CO_2 > 1400$ ppm).

Figure 4 presents the distribution of CO_2 concentrations in four categories, showing that IAQ tends to be better in spring in Santiago, while time under bad conditions (category 4) diminishes in all cases, compared to winter.

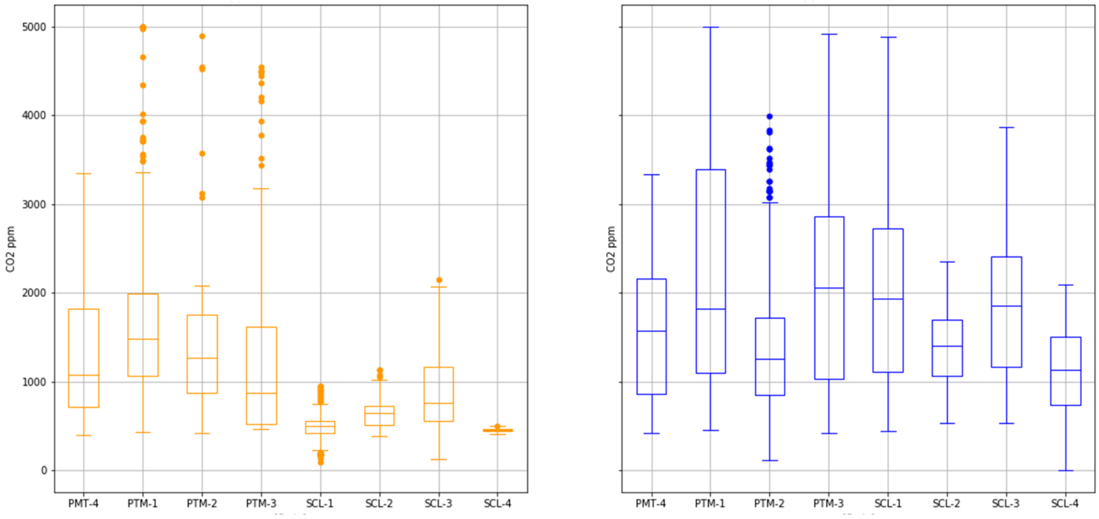

Figure 3. Distributions of CO_2 ppm concentration in each classroom during occupation time for spring in orange and winter in blue.

3.3. Correlation between CO_2, Occupant Density

Occupant density (OD) can be defined as area per occupant (m^2/p) and has been identified in previous studies [36] as correlated with CO_2 concentrations. In the studied classrooms, occupant density was between 1.03 and 2.5 m^2 per student at the time of measure. This OD is much higher than that informed in [36], ranging from 1.7 to 2.6 m^2 per person or 1.8 to 2.4 m^2/person in [55]. Overall, OD in schools is too high, compared to OD in offices, which is around 10 m^2/person [55]. The number of occupants in each classroom was collected, according to the schedule presented in Table 1. The sample size for this analysis was 3270 data points, corresponding to the observations where the number of students in the classroom was recorded.

In Figure 5, OD in area per student is plotted against mean CO_2 levels, showing that mean CO_2 levels will drop if more area is available per person. The variance assigned to the predictor OD is 16.2% (r2 = 0.162), which is similar to the values that appear in [36] that presented a 17% of CO_2 variation explained by occupant density. The significance of the correlation and the linear model are described in Table 5. The *p*-value for the whole model is 0.0004212 (significance established at 0.05), confirming that the model is statistically significant.

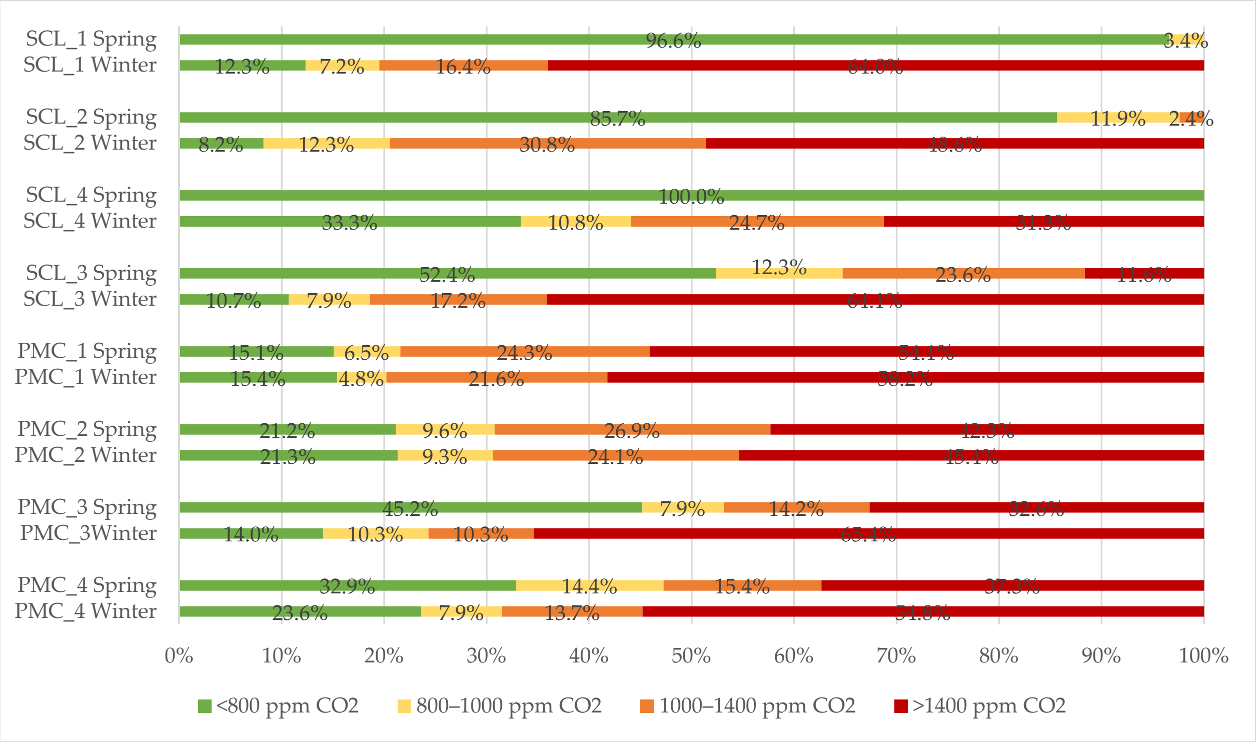

Figure 4. Frequency of CO_2 concentration categorized according to EN 13779:2007.

Table 5. Parameter estimates.

Variable	DF	Parameter Estimate	Standard Error	T Value	Pr > ∣t∣
Intercept	1	2681.3	364.	7.348	<0.0001
Area per student	1	−801.	216.7	−3.701	<0.0001

3.4. Parameters That Determine Acceptable CO_2 Concentrations

Before conducting Binary Logistic Regression (BLR) analysis, an exploratory linear regression analysis was done. It was found that the factor "city" was a strong differencing factor; therefore, Binary Logistic Regression was calculated for each city separately and then used to rank the parameters regarding their importance for acceptable CO_2 concentrations.

Binary Logistic Regression was applied to explore the relationship between acceptable CO_2 concentrations and several predictor variables. The results of this analysis are maximum likelihood estimates (MLE) and odds ratios (OR). Both describe the likelihood of having acceptable CO_2 concentrations when one of the predictor variables is increased by one unit while the other variables are kept constant.

In Puerto Montt (Figure 6), the MLE of having acceptable CO_2 concentrations was 3.75 times bigger during spring than in winter. One interpretation of this data is the hesitancy to open windows when the outside air is too cold and would produce discomfort. The following most critical parameter was low inside temperature versus acceptable inside temperature (OR = 2.08, 95%.CI: 4.288), followed by high indoor temperature versus acceptable indoor temperature. These results suggest that the decision to open a window is based on the need to dissipate indoor gains. Therefore, it will be avoided when the indoor temperature is acceptable. It is important to note that outdoor temperatures in this city are still low in spring (average outdoor temperature: 12.7 °C, with a maximum of 20.4 °C) during the occupancy period. The results show a difficulty to maintain both acceptable temperatures and CO_2 levels, simultaneously, which, in this city, means that the heating systems are not designed or used, considering the losses related to ventilation needed for air quality.

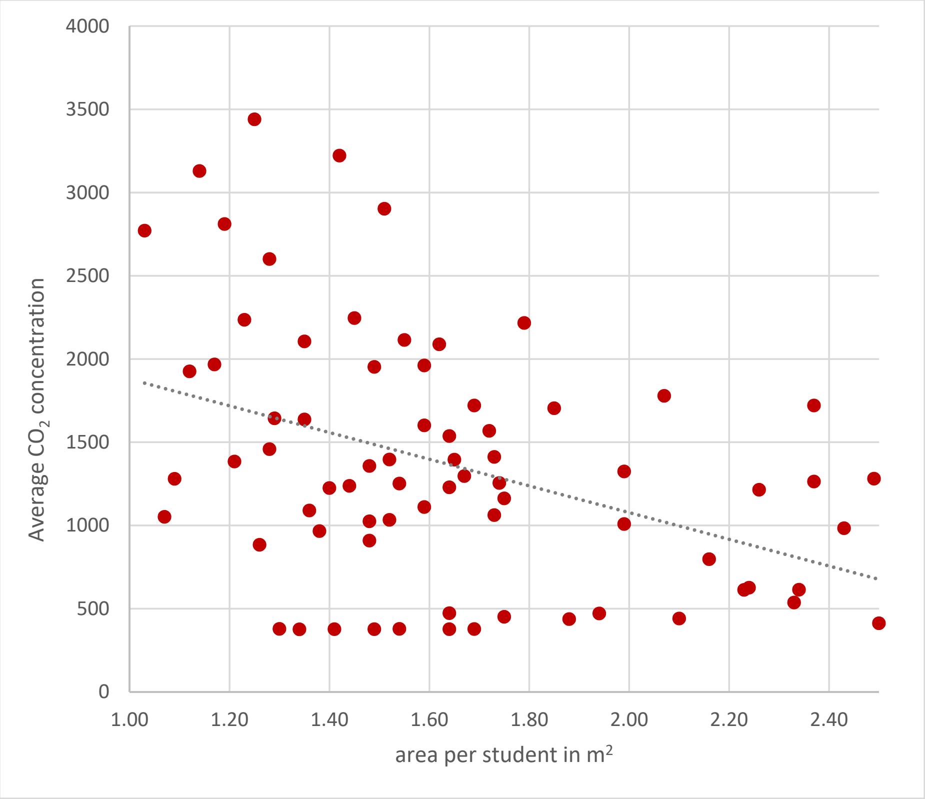

Figure 5. Occupancy density in m^2 per student against measured CO_2 levels.

In Santiago (Figure 7), the MLE of having acceptable CO_2 concentrations was 7.6 times bigger when the indoor air temperature was low than when it was acceptable. It is relevant to note that these classrooms do not have heating devices; therefore, temperatures are low most of the time in winter. The second most relevant factor is seasonality: spring was 2.6 times more likely to have acceptable CO_2 concentrations than winter. The third odd ratio in importance is high indoor temperature, which coincides with the descriptive analysis of the data that showed that the percentage of time with acceptable CO_2 concentrations increased in spring. It is relevant to note that these rooms do not have cooling devices, and that indoor temperatures reached 32.2 °C, demonstrating that, although ventilation strategies managed to lower CO_2 concentration, they could not lower indoor temperatures to the acceptable range.

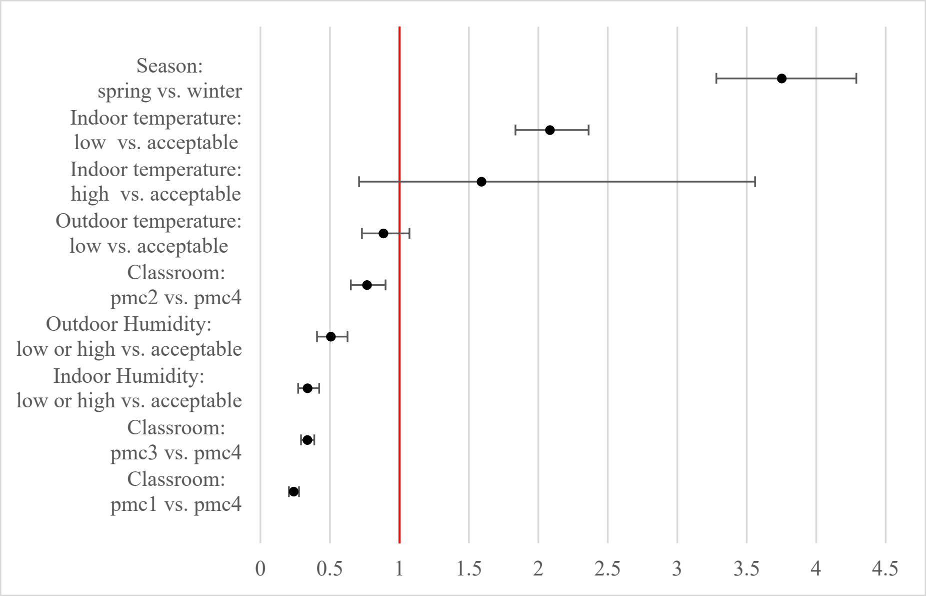

Figure 6. Odds ratios and 95% confidence intervals for acceptable indoor CO_2 concentrations in the heating dominant city Puerto Montt.

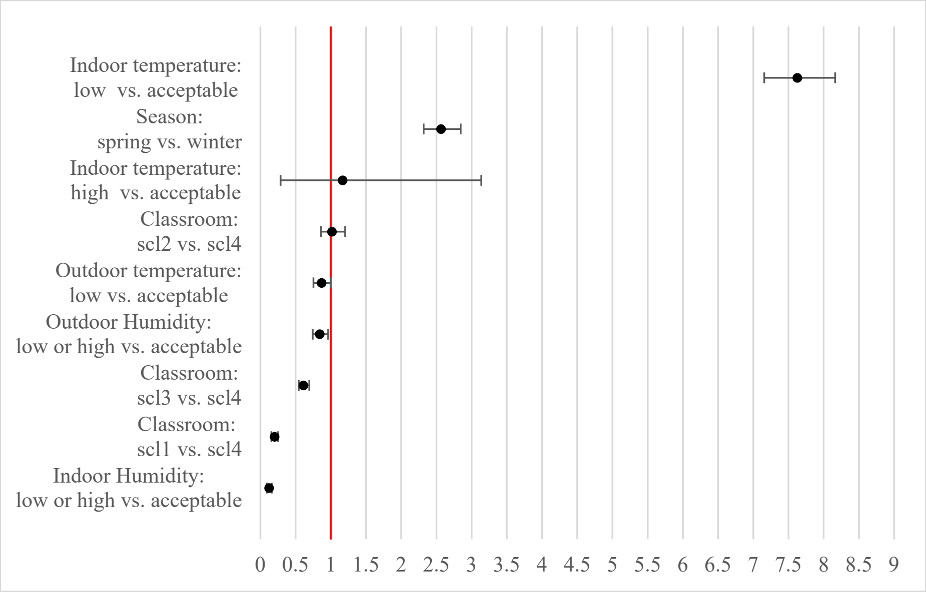

Figure 7. Odds ratios together with 95% confidence intervals for acceptable indoor CO_2 concentrations in the Mediterranean with warm summer city Santiago.

3.5. Statistical Test of Individual Predictors

The statistical significance of individual regression coefficients is tested with Wald chi-square, presented in Table 6. This test confirmed that all variables were significant (p-value < 0.05), except exterior temperature (TempEx), which was not significant in Puerto Montt.

Table 6. Type 3 Analysis of Effects for Puerto Montt and Santiago.

PCM				SCL			
Effect	**DF**	**Wald Chi-Square**	**Pr > ChiSq**	**Effect**	**DF**	**Wald Chi-Square**	**Pr > ChiSq**
Temp	2	131.07	<0.0001	**Temp**	2	1050.95	<0.0001
Temp Ex	1	1.57	0.2099	**Temp Ex**	1	7.14	0.0075
RH	1	91.80	<0.0001	**RH**	1	867.76	<0.0001
RH Ex	1	38.35	<0.0001	**RH Ex**	1	7.82	0.0052
Class	3	450.17	<0.0001	**Class**	3	1623.94	<0.0001
Season	1	374.96	<0.0001	**Season**	1	161.85	<0.0001

3.6. Validation of Predicted Probabilities

The association of the predicted probabilities and observed responses is evaluated by Kendall's Tau-a, Goodman–Kruskal's Gamma, Somers's D, and c statistic. All of these measures of association were provided by SAS and are presented in Table 7. The Gamma statistic for Santiago shows that we can predict that the CO_2 concentration will be acceptable, with 47.0% less error, than using chance, and with 50.8% less error in the case of Puerto Montt. If using the more conservative estimation of Somers's D, we can see how much the prediction of acceptable CO_2 levels can be made, based on the independent variable: 45.3% for Puerto Montt and 46.7% for Santiago. The c statistic shows that, for 73% of all possible pairs of CO_2 concentrations, the model assigned them to the correct category.

Table 7. Association of Predicted Probabilities and Observed Responses.

PCM		**SCL**	
Somers's D	0.45	Somers's D	0.47
Gamma	0.47	Gamma	0.51
Tau-a	0.19	Tau-a	0.22
c	0.73	c	0.73

4. Discussion

4.1. Summary of Main Findings

This research presents the analysis of IAQ through CO_2 concentration in schools and seeks to determine the factors that will allow having good IAQ in naturally ventilated schools in Chile. The analysis showed the following: (1) The climatic conditions are a differentiating factor for CO_2 concentrations. In this case, there is a statistically relevant differentiation between CO_2 concentrations in both cities/climates. (2) Acceptable CO_2 concentrations are determined by the seasonality, increasing the chances of desirable CO_2 concentration (bellow 1000 ppm) in spring over winter for SCL and PMC. (3) Indoor temperature is a relevant factor in predicting CO_2 concentrations. High indoor temperatures are related to lower CO_2 concentrations, presumably due to the opening of windows. Low indoor temperature is linked to high CO_2 concentrations, probably because of the need to conserve heat. (4) CO_2 concentrations will be unacceptable during long periods of time in winter to maintain heat in both cities. (5) In SCL, CO_2 concentrations will be acceptable when ventilation is needed to dissipate indoor heat gains. However, this strategy is not suitable for lowering temperatures to acceptable conditions. It is relevant to note that Wargocki and Da Silva showed that providing mechanical cooling in classrooms will restrict window opening [35], mimicking the behavior observed in winter and having a detrimental effect on IAQ. The factors analyzed do not explain all the variation in CO_2 concentration. Therefore, it is necessary to consider other factors, like occupant interaction with windows, openable windows area, and window-to-wall ratio.

4.2. Design Recommendations

Based on the results of the measurements and the statistical analysis of them, this study recommends the following:

1. Occupant density in classrooms is not as high as designed for (normative allows for 1.1 m^2 per student) but is still high enough to increase concentration after the students arrive at the classroom. Although not demonstrated by the statistical analysis, height, as the third dimension in OD values (m^3/p), has been acknowledged before [36] to have an impact on CO_2 concentrations and should be considered, since the requirements allow for low roofs (minimum height of the rooms is 2.2 m [48]).
2. Heating systems need to be designed considering the need for ventilation. The compromise of air quality over thermal comfort is detrimental to students' learning abilities.
3. Window opening could be a good ventilation strategy for IAQ only when thermal comfort requires the same action. If there is a need to conserve heat, other ventilation approaches should be implemented to ensure IAQ.
4. In the case of a Mediterranean climate with warm summer, cooling strategies should be implemented, while noting that mechanical cooling could hinder window opening, as stated in previous research [34,35].

4.3. Strength and Limitation

This study presents the analysis of the effects of climatic conditions, season, and environmental factors on CO_2 concentrations as a proxy for IAQ in Chilean schools. This is the first study of this kind done in a non-industrialized country and the first one considering the impact of different climatic settings.

The methodology used in this research allowed us to identify parameters that affect ventilation through the evaluation of CO_2 concentration in naturally ventilated classrooms. This methodology can be used with other datasets, regardless of location or climatic conditions. The findings can be generalized to classrooms in the same climatic conditions, occupancy, and ventilation system.

One of the limiting aspects of this research is the lack of information on the students' respiratory comfort and children's adaptative behaviors. This information would allow us to better understand the students' engagement with their own comfort and the level of agency they have. In this sense, the use of logbooks to record the opening of windows should be implemented in future research.

4.4. Future Work

To further understand the correlation between CO_2 levels and temperature in classrooms in use, other factors that could impact CO_2 concentration should be considered.

Occupant interaction should be further investigated by monitoring patterns of window opening, at least through self-reporting with logbooks.

Our dataset needs to be expanded to increase the representativeness of the sample on the national and international level. The sample should allow for climate-based clustering to represent schools in cooling-dominated climates and mixed climates, such as Iquique and La Serena. Additionally, field measurements and campaigns need to take place to monitor indoor air quality in parallel with acoustics, thermal comfort, and visual parameters, to allow for investigating the influence of air quality on overall indoor environmental quality evaluation.

5. Conclusions

All schools in this research suffered from CO_2 concentrations and temperatures outside the thresholds defined during occupied periods. Although this sample is not representative of all school classrooms in Chile, similar results in classrooms designed according to current standards and similar climatic conditions are expected. High occupant density, lack of ventilation design or ventilation systems, and current regulation are systemically related to bad IAQ.

This research aimed to identify the relation between air quality and building-related and occupant-related factors in free-running and naturally ventilated primary schools during typical use. The methodology proposed proved suitable and provided the expected results. This research confirmed the variability of CO_2 concentrations, depending on season and indoor temperature, where IAQ was relegated to second-place relevance by the need to ensure comfortable temperatures. The statistical significance of individual regression coefficients confirmed that all variables were significant (p-value < 0.05) except exterior temperature (TempEx), which was not significant in Puerto Montt. The independent variables in this study were not able to predict all the variation in CO_2 concentration, meaning that there could be others that should be included in further research.

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