Air Quality and Teacher Health in the Context of Energy Poverty in Chile

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ABSTRACT: Current research has found evidence of associations between particulate matter, respiratory diseases, and increases in mortality from all causes. However, most of this data comes from developed countries, whereas studies from middle to low-income countries are limited. In Chile, high levels of Energy Poverty (EP) have been identified in the central-southern towns of the country, where the primary means for household heating are wood stoves. They generate periods of high air pollution during the winter and may exacerbate preexisting health conditions that affect vulnerable populations. Air pollution from EP goes beyond residential buildings and impacts public spaces and buildings near residential areas, like schools. This paper presents an analysis of indoor and outdoor air quality along with a survey of self-reported health symptoms of teachers in public schools in Chile, located in areas of energy poverty. During the winter, indoor and outdoor $PM_{2.5}$ and PM_{10} concentrations were monitored for a school week in three schools in the Gran Concepción metropolitan area in Chile. Particulate matter concentrations were compared with the WHO Air Quality Guidelines (AQG) and local air quality regulations. Indoor and outdoor $PM_{2.5}$ surpassed the AQG recommended levels of air pollution, with the highest concentrations occurring in the evenings and nights. In addition, the survey showed that almost a third of teachers ranked the outdoor air quality in the previous week as "bad," but only 13% saw outdoor air pollution as an important health concern. The symptoms teachers reported as being more frequent included those related to teaching, such as hoarse-dry throat, and respiratory health, like irritated, stuffy, or runny nose. This paper portrays the reality and urgency of Chilean classrooms regarding indoor and outdoor air quality during the winter months and discusses the health implications of teaching and learning in the context of energy poverty.

KEYWORDS: Air Quality, Respiratory Health, Energy Poverty, Schools, Chile

INTRODUCTION

Particulate matter (PM) is one of the classic pollutants considered hazardous by the World Health Organization (WHO). Particulate matter is classified according to size, though its chemical and physical composition might be heterogeneous (World Health Organization 2021). Particles less than 10 μm diameter are coarse or inhalable particles and can be hazardous when deposited in the respiratory tract. In comparison, respirable or fine particles are those smaller than 2.5 μm diameter and represent a hazard because they can infiltrate the gas-exchange region of the lungs (Morakinyo et al. 2016). Previous research has associated both $PM_{2.5}$ and PM_{10} with cardiovascular disease, lung cancer, respiratory problems, and mortality from all causes. However, the current evidence on the health effects of $PM_{2.5}$ and PM_{10} includes very limited studies done in low and middle-income countries (Chen and Hoek 2020), where PM pollution is often a problem due to energy poverty.

For instance, in Chile, energy-poor households are those that do not have equitable access to high-quality energy services to cover the basic needs for the human and economic development of its members (Ministerio de Energía 2021). In the south-central region of the country, this has become an enduring problem, with previous studies finding multiple municipalities at high risk of energy poverty due to heating needs (Pérez-Fargallo et al. 2020). In Chile, over 80% of the households in the southern areas of the country rely on firewood for heating (Corporación de Desarrollo Tecnológico (CDT) 2015; Reyes et al. 2019), which generates significant air pollution due to PM during the winter months. In the municipalities of Concepción and San Pedro de La Paz, 43.3% and 57.4% of households use heating with polluting sources, respectively according to official data. In addition, 50.3% of the households in San Pedro de La Paz and 56% in Concepción are thermally inefficient constructions, increasing the need for heating during the winter (Ministerio de Energía et al. 2024). To address this issue, the Chilean government has strived to reduce air pollution by creating programs for people to use dry firewood and replace wood stoves, which are still insufficient and do not fully address the root of the problem (Reyes et al. 2019).

Furthermore, while the primary source of pollution comes from residential wood stove use during the evenings and nights, the overall air quality decreases in these neighborhoods, impacting nearby public spaces and other facilities like schools. In schools, sources of air pollution can come from indoor and outdoor sources, which is particularly relevant for naturally ventilated classrooms. Some of the primary outdoor sources of PM in schools highlighted in previous literature are high traffic density, emissions from industrial areas, and wildfires. In contrast, indoor sources include chalk dust, particle resuspension due to children's activity, indoor combustion sources (heaters, gas, and wood stoves), cleaning, soil dust, new furniture, and smoking where allowed (Sadrizadeh et al. 2022).

There are many local factors affecting PM concentration levels in school buildings. For example, a study found that summer $PM_{2.5}$ and PM_{10} concentrations were up to 3 times lower than winter concentrations in a naturally ventilated school, and the authors attributed this finding to a lack of ventilation during the cold season (Habil and Taneja 2011). Similarly, other studies have found differences between urban and rural, as well as public and private schools, depending on their immediate surroundings and indoor pollution sources (Branco et al. 2019; Alameddine et al. 2022). In addition, studies looking into social variables such as race and socioeconomic status have pointed out that higher air pollutant concentrations are associated with poverty in specific contexts (Cheeseman et al. 2022). Therefore, assessing PM concentrations in schools can be highly context-dependent and convey different results.

Most studies on indoor air quality in schools have concentrated on the student population and its effects on student health and cognitive performance. In contrast, only a few have examined associations between teachers' health and the classroom's indoor environmental conditions (Lin et al. 2017; 2020; Brink et al. 2021). Teachers spend most of their workday in classrooms, constantly exposed to the indoor air pollutants in these spaces. These exposures may affect teachers' ability to teach through various health symptoms, which indirectly affects children's learning ability. This study focuses on teachers as the primary group of interest. The rationale behind this choice is that teachers are influenced by the school environment just as much as students, and they play a crucial role in shaping classroom environmental conditions. Even more, in elementary school classrooms, students often have to ask for teachers' permission to open or close a window or door. Hence, the indoor environmental conditions of classrooms tend to respond to the teachers' preferences instead of those of students (de Dear et al. 2020). In addition, in lower grades, students might be too young to understand questions related to air quality and health, and parents might be reluctant to provide their permission to participate in the study.

This paper analyses indoor and outdoor $PM_{2.5}$ and PM_{10} concentrations in three public schools in Concepción and SanPedro de La Paz in south-central Chile, along with a survey of teachers' perceptions, self-reported health concerns, and health symptoms in areas of energy poverty, and addresses the following questions (1) How is the air quality in Chilean schools during the winter? (2) How do teachers perceive their health and air quality in schools? (3) How does particulate matter concentrations affect teachers' self-reported health symptoms and concerns?

1.0 METHODS

1.1 The schools

The study was conducted in three public schools in south-central Chile, in the neighboring cities of Concepción and San Pedro de la Paz. The cities are located at -36º 46' 22" latitude and -73º 03' 47" longitude, with an average height above sea level of 12 m (39.4 ft) and are geographically separated by the Biobio River. According to the Köppen Geiger classification, the cities have a Csb climate (Warm-summer Mediterranean climate). Their winter spans from May to August, where July is the coldest month, with an average temperature of 48.2°F (9ºC), and the rainiest month is June, with an average rainfall of 145 mm (Climate-Data.org, n.d.). All schools are in urban residential areas with different immediate contexts. School CH-Z is a two-story building that faces a neighborhood park, school CH-I neighbors a small butte and school CH-G is adjacent to a major highway, with heavy traffic and cargo (Figure 1). All the schools are naturally ventilated and have operable windows.

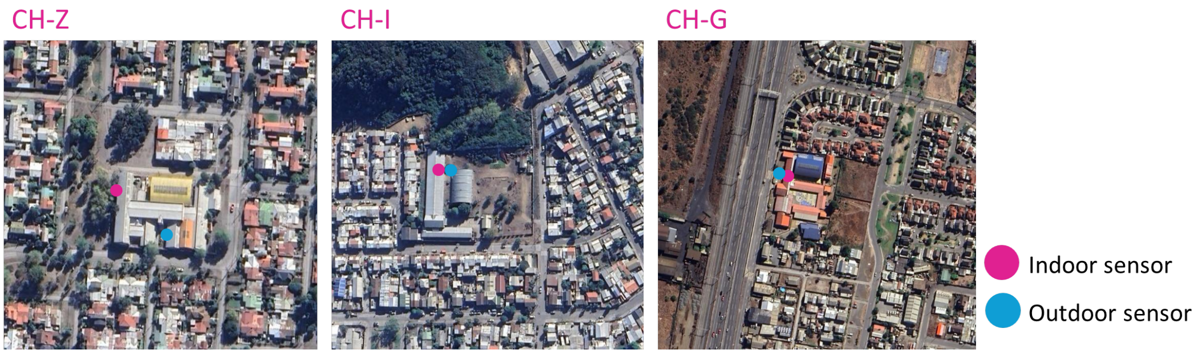


Figure 1. Schools and sensors' location. Indoor sensor (pink) and outdoor sensor. Source: (Authors 2024)

1.2. Physical measurements

Two neighboring first and second-grade classrooms were selected in each school for the study. In elementary schools in Chile, the same teacher imparts most subjects. Teachers stayed in the classroom with the students most of the time, which helped ensure the equipment's safety and the reliability of teachers' perceptions of the classroom. Depending on the available space, the measuring station was placed in the back or front of the classroom to avoid interrupting classes and to prevent children from tampering with the equipment. Each station was placed from Monday through Friday during the winter of 2023 to gather data on a typical academic week (Table 1). Sensors were moved from school to school every week. Classrooms had normal occupancy in all schools during the measuring week, except for school CH-G, where there was a teacher strike on Wednesday and Thursday, so those days measurements were recorded without occupancy.

A Dylos DC1700-PM air quality monitor recorded indoor $PM_{2.5}$ and PM_{10} mass concentrations (μg/m^3) every minute. The sensor was located at 0.9 m (3 ft) in height to stay inside the breathable zone of the students and teachers when they were sitting down. Also, a Purple Air Zen sensor (counting efficiency 50% at 0.3µm & 98% at ≥0.5µm), was installed in an outdoor area of each school during the same week, recording outdoor $PM_{2.5}$ and PM_{10} concentration readings (µg/m^3) every 2 minutes. All data from indoor and outdoor sensors was cleaned and averaged at 10-minute intervals to make it comparable. Due to measurement errors, data from one classroom in school CH-Z and one in CH-G was removed from the analysis. Measurements in the two classrooms in school CH-I were averaged to report and compare them with the results of the classrooms in the other schools.

Table 1: Classroom characteristics and physical measurements summary. Source: (Authors 2024)

School	Dates	Floor	Area m^2 [ft^2]	Max. occupancy	Heating system	Equipment location	
						Indoor	Outdoor
CH-Z	07/17 to 07/21	2	46.5 [500.5]	34	Radiant fan in the back + gas heater (not working)	Front	Interior courtyard façade
CH-I	07/24 to 07/28	1 1	45.0 [484.4] 45.0 [484.4]	25 25	None	Back Back	Side façade to green space
CH-G	07/31 to 08/04	1	37.2 [400.4]	32	Radiant fan in the front + gas heater next to the teacher	Back	Main façade adjacent to the highway

Physical measurement data was analyzed in four different ways. First, statistical tests were conducted using R studio to understand the influence of the immediate context on the school's outdoor PM concentrations. Since the data was not normally distributed, differences between the schools were tested using non-parametric Kruskall-Wallis tests. The following pairwise comparisons were developed using the Dunn procedure, with p-values adjusted with the Bonferroni correction. Second, Kendall tau correlations were used to evaluate the association between outdoor air quality (AQ) and indoor air quality (IAQ) in each school. Third, to assess the indoor air quality of each school, the 24-hour average $PM_{2.5}$ and PM_{10} concentrations were compared with international and local standards. Finally, physical measurements were grouped into three 8-hour occupancy periods to assess daily differences in PM concentrations, which represented (1) normal occupancy (class) from 8 am to 3 pm, (2) evening/unoccupied (pm) from 3 pm to midnight, and (3) early morning/unoccupied (am) from midnight to 8 am.

1.3. Surveys

An online questionnaire was distributed to teachers in all schools during the same week of the physical measurements. The questionnaire was based on the MM-040 questionnaire from the Örebro Model (Andersson 1998) and adapted from the long-term thermal comfort assessment survey of the ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy (American Society of Heating, Refrigerating, and Air-Conditioning Engineers 2023) to fit the purpose of this study. In this paper, we only report the results of questions related to teachers' perceptions regarding long-term (last year) and short-term (last week) indoor and outdoor air quality, health concerns, and self-reported health symptoms in the last three months (Table 2). The sample of teachers in each school varied depending on the school's size and the teachers' availability at the time of the survey. A total of 78 responses were received from teachers in the three schools: 36 from school CH-Z, 16 from school CH-I, and 26 from school CH-G, with nine incompletes.

Table 2: Survey questions and measures. Source: (Authors 2024)

Health	Question type	Measure
What do you think of the overall outdoor air quality surrounding the school in the last school year?	5-point acceptability scale	Outdoor air long-term acceptability
How frequently do you find the outdoor air surrounding the school is not acceptable?	5-point frequency scale	Outdoor air acceptability frequency
What do you think of the outdoor air quality surrounding the school in the last week?	5-point acceptability scale	Outdoor air short-term acceptability
What do you think of the indoor air quality of your classroom in the last week?	5-point acceptability scale	Indoor air short-term acceptability
For each of the following potential issues, please rate how much of a concern it is for you in the classroom where you teach.	Matrix - 4-point assessment scale	Health concerns
Have you ever had any of the following respiratory issues?	Matrix - Multiple choice	Previous respiratory health problems
Do you smoke?	Multiple choice	Previous respiratory health influence
During the last 3 months, have you had any of the following symptoms?	Matrix - Multiple choice	Health symptoms & frequency

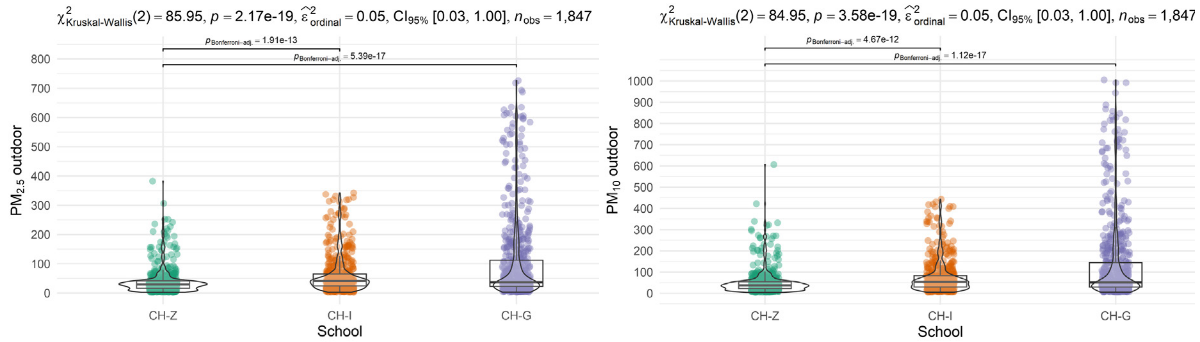
2.0 RESULTS

2.1. Indoor and outdoor air quality in Chilean classrooms

Upon visual examination of outdoor $PM_{2.5}$ and PM_{10} measurements, it was apparent that the data did not follow a normal distribution. Therefore, non-parametric Kruskall-Wallis tests were used to assess differences between the schools, which revealed significant differences in the distributions of $PM_{2.5}$ and PM_{10}. In addition, pairwise comparisons revealed that these differences occurred in all pairings, except for the pair between CH-I and CH-G, even when these two schools have different neighboring contexts (Figures 2 & 3). In all schools indoor PM concentrations were higher than outdoor concentrations, as indoor/outdoor concentration ratios for $PM_{2.5}$ the schools were 1.3 for CH-G, 1.1 for CH-I, and 1.4 for CH-Z. For PM_{10} these were 1.7 for CH-G, 1.6 for CH-I, and 1.9 for CH-Z. In addition, when assessing the correlation between indoor and outdoor air quality, Kendall tau correlations showed that the strength and direction of association between indoor and outdoor $PM_{2.5}$ and PM_{10}

concentrations were positive and significant at the $p < 0.001$ level. Therefore, outdoor AQ had a substantial influence on classroom IAQ.

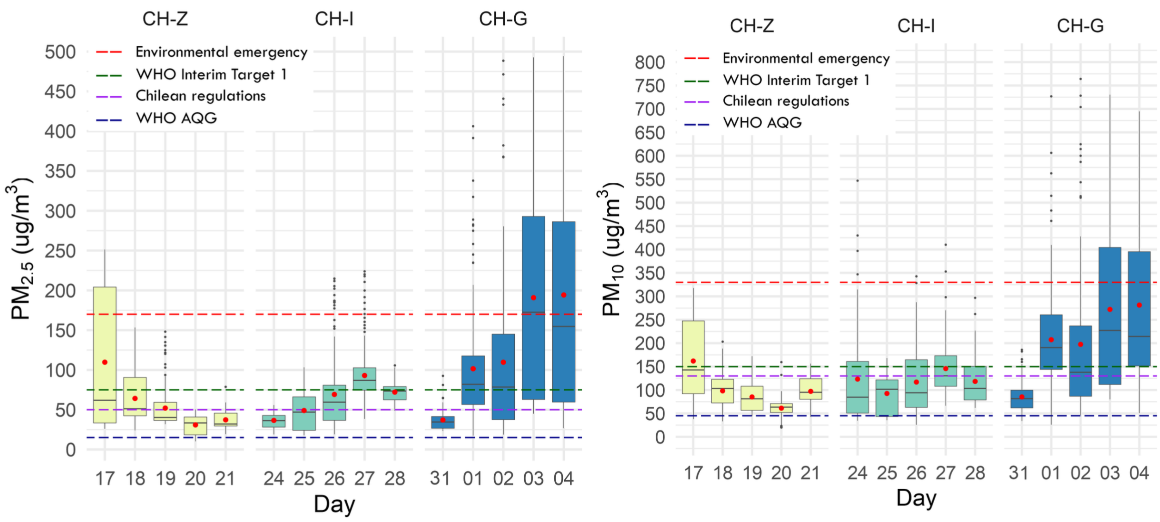
Following these tests, 24-hour averages of indoor $PM_{2.5}$ and PM_{10} concentrations were compared with international and local air quality standards. The latest air quality guidelines (AQG) from the WHO recommended short-term 24-hour exposures to $PM_{2.5}$ at concentrations no larger than 15 µg/m^3 and 45 µg/m^3 for PM_{10}. In addition, the same document establishes interim targets for highly polluted places, with the least stringent being Interim Target 1, with limits of 75 µg/m^3 for $PM_{2.5}$ and 150 µg/m^3 for PM_{10} (World Health Organization 2021).On the other hand, the Chilean Ministry of the Environment defined the Primary Environmental Quality Standard for $PM_{2.5}$ and PM_{10} concentrations in the Decree 12 of 2011 and 2022. The regulation establishes the limits for 24-hour exposures of $PM_{2.5}$ as 50 µg/m^3 and 130 µg/m^3 for PM_{10} (Ministerio de Medio Ambiente 2011; 2022). In addition, the Chilean regulations consider a state of environmental emergency when 24-hour mean PM concentrations are above 170 µg/m^3 for $PM_{2.5}$ and 330 µg/m^3 for PM_{10}.



Figures 2 and 3: Differences in $PM_{2.5}$ and PM_{10} outdoor concentrations for the three schools, respectively. Source: (Authors 2024)

All schools exceeded the most stringent 24-hour AQG of the WHO for $PM_{2.5}$ and PM_{10}, both indoors and outdoors. Since the Chilean local regulations and the Interim Target 1 from the WHO are less strict than the AQG, the schools complied with these standards more often, but not every day (Figures 4 and 5). Even more, the average concentrations of indoor $PM_{2.5}$ recorded in 2 days in school CH-G fell into the environmental emergency category of the Chilean regulations. Interestingly, the school was empty due to the teacher strike on one of those days, meaning that the high $PM_{2.5}$ concentrations were unrelated to any school activities.

When comparing different moments of the day, the average $PM_{2.5}$ concentrations in all schools were lower during class times (Table 3). In addition, in CH-I and CH-Z, the highest average $PM_{2.5}$ concentrations occurred during the evenings, while in CH-G this happened in the early hours of the day. Regarding PM_{10}, in CH-I and CH-Z, the lowest average concentrations occurred in the early morning, while for CH-G, this occurred during class time. The highest average PM_{10} concentrations occurred at different times in each school: in the early morning for CH-G, during class for CH-I, and in the evenings for CH-Z. Even with the occupancy groupings, all schools failed to comply with the WHO AQG while the school was in session. Additionally, CH-G failed to comply with the local regulations during class time, and the average concentration in the early morning fell into the environmental emergency category.



Figures 4 and 5: Daily distribution of indoor $PM_{2.5}$ and PM_{10} measurements in comparison to local and international guidelines. Red dots represent averages. Source: (Authors 2024)

Table 3: Indoor and outdoor $PM_{2.5}$ and PM_{10} average concentrations during different occupancy periods. Source: (Authors 2024)

	Indoor $PM_{2.5}$				Outdoor $PM_{2.5}$			
School	am	class	pm	24-h	am	class	pm	24-h
CH-Z	49.3	38.4	82.3	55.8	27.1	24.2	68.7	39.3
CH-I	64.4	54.1	81	66.2	41.2	34.4	106.1	59.9
CH-G	178.8	76.7	155.8	134.3	119.4	37	149.1	100.8
	Indoor PM_{10}				Outdoor PM_{10}			
CH-Z	74.2	98.8	111.5	95	36.1	31.5	89.2	51.3
CH-I	82	144	128.9	119	54.7	43.8	130.9	75.6
CH-G	262.4	169.9	233.4	219.3	161.4	48.7	190.4	131.8

2.2. Teacher outdoor and indoor air quality perceptions

The first three survey questions inquired about outdoor air quality (AQ), and the fourth inquired about indoor air quality (IAQ) perceptions. Of all the surveyed teachers, 41.3% deemed outdoor AQ acceptable in the last year. Nonetheless, there were differences between the perceptions in each school. In school CH-G teachers had more negative perceptions, with 52.9% perceiving it as either bad or very bad, while in schools CH-I and CH-Z, this only occurred with 6.25% and 20% of teachers, respectively. On the other hand, in school CH-I, 62.5% of the teachers perceived AQ in the last year as good or very good, while this only occurred in 24% of CH-Z and 11.8% of CH-G teachers. Finally, 56% of teachers in school CH-Z, 31.25% in CH-I, and 35.3% in CH-G thought AQ was acceptable.

A total of 37.3% of all teachers reported not finding AQ acceptable either once a month or during a specific period of the year. Nonetheless, following a similar pattern as the previous question, in school CH-G this occurred for 40% of teachers at least once a week. In comparison, in school CH-I, 50% of teachers never or rarely found AQ to be unacceptable. Finally, in CH-Z, 45.8% of teachers found AQ was not acceptable only occasionally.

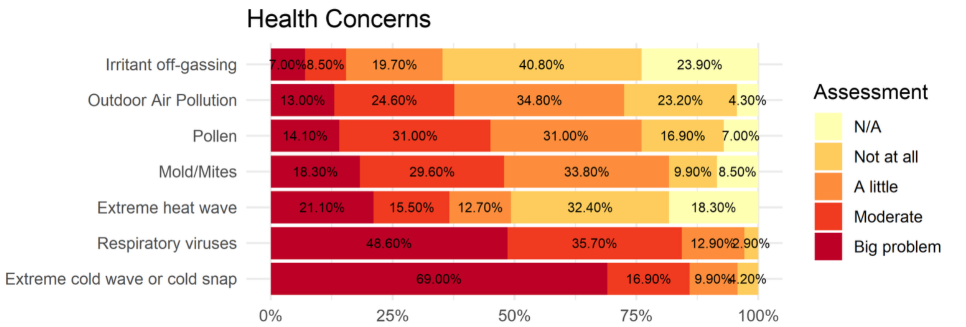
Perceptions about AQ during the week of measurements rendered similar results as general AQ perceptions. Overall, 26.7% of teachers thought AQ was good or very good, 41.3% thought it was acceptable, and 32% thought it was bad. Teachers in school CH-G had the worst perceptions overall, as 52.9% stated AQ was bad during that week, while in schools CH-Z and CH-I, this only occurred with 20% and 6.25% of respondents, respectively. On the contrary, 50% of teachers in school CH-I evaluated AQ in the last week as good or very good, while this only happened with 28% and 14.7% of respondents in schools CH-Z and CH-G. Finally, 52% in CH-Z, 43.7% in CH-I, and 32.35% in CH-G thought AQ was acceptable.

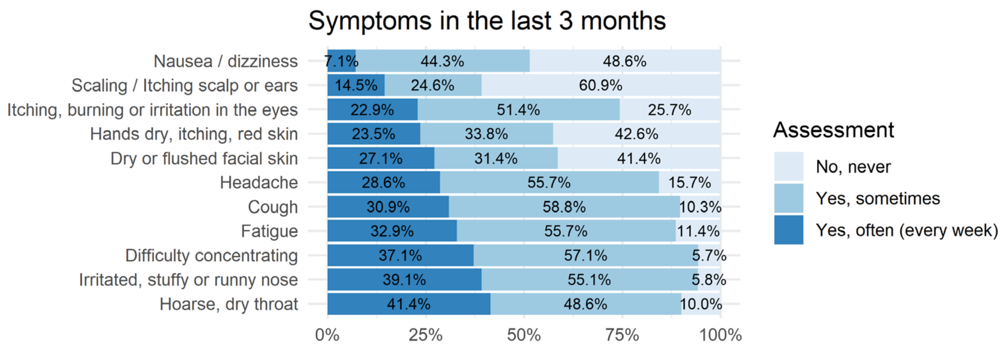
Regarding indoor air quality (IAQ) in the classroom, 42.7% of all teachers considered it acceptable, 38.7% said it was bad, 13.3% very bad, and only 5.3% thought it was good. In this case, teacher perceptions in all schools were more negative than with outdoor air quality. Nearly half the teachers in each school considered IAQ in the classrooms bad or very bad. This perception was distributed among the schools like this: 62.5% in CH-I, 50% in CH-G, and 48% in CH-Z. Nonetheless, a large portion of respondents thought the IAQ was acceptable: 44% in CH-Z, 31.25% in CH-I, and 47.06% in CH-G, while only a small percentage considered the IAQ good: 8% for CH-Z, 6.25% for CH-I, and 5.33% for CH-G.

2.2. Teacher health concerns and symptoms

The main health concerns among teachers were extreme cold waves or cold snaps, as 69% of all respondents considered them a big problem, with similar trends for all schools. Similarly, respiratory viruses were the second health hazard that concerned teachers the most in all schools (48.6%). Also, 21% of all teachers listed heat waves as a big problem, making it the third most frequent response. Interestingly, most of these responses came from school CH-I (40%), while in schools CH-G and CH-Z, heat waves were a problem only for 18.8% and 12.5% of respondents. In addition, heat waves were not a problem for 34.4% of teachers in CH-G and 37.5% in CHZ, while this only occurred for 20% in school CH-I. Therefore, the origin of this concern might be related to a unique characteristic of school CH-I.

Other IAQ problems such as mold or mites, pollen, allergies, outdoor air pollution, or irritant off gassing from paint or other materials were only big problems for under 20% of all respondents. Interestingly, only 13% of respondents considered outdoor air pollution a big problem. Moreover, 34.78% and 46.67% of teachers in schools CH-Z and CH-I did not consider it a problem at all (Figure 6). In addition, 62% of respondents in all schools had never had asthma, but 24% had had it, including the last year. This accounted for 25% of respondents in schools CH-Z and CH-G, while in CH-G, it was only 20%. Regarding hay fever, 54.3% of respondents reported having it during the last year (65.3% in CH-G, 43% in CH-I, and 45.8% in CH-Z). In addition, 60% of respondents reported never having dermatitis, and only 30% reported suffering it during the last year. Finally, 18.3% of teachers reported smoking often, 18.31% smoking occasionally, and 12.68% reported that they used to smoke but did not do it anymore.





Figures 6 and 7: Teacher's health concerns and self-reported health symptoms in the last three months. Source: (Authors 2024)

The most prevailing and frequent health symptoms among teachers in all schools were hoarse or dry throat (41.4%), closely followed by a stuffy, irritated, or runny nose (39.1%), and difficulty concentrating (37.1%), with all schools following similar patterns. On the other hand, the least self-reported symptoms in the last three months were nausea or dizziness (7.1%), scaling or itching of the scalp or ears (14.5%), and itching, burning, or irritation of the eyes (22.9%) (Figure 7).

DISCUSSION

The location of the schools proved to have an influence on daily PM measurements. School CH-G had the highest $PM_{2.5}$ and PM_{10} concentrations, likely due to its location near a major highway. Nonetheless, the lack of significant differences between the distribution of PM concentrations in school CH-I and CH-G revealed that other sources of pollution are ubiquitous in both cases. In the case of Concepción and San Pedro de la Paz, this can be explained by the prevalence of firewood stoves in both cities, which generates PM pollution during the colder moments of the day all over the city.

Indoor and outdoor air quality were significantly correlated, indicating that outdoor PM has a major influence on IAQ. All the schools included in this study are naturally ventilated, have leaky envelopes, and have old windows that sometimes do not close properly, making indoor and outdoor conditions highly correlated. What is problematic though, is that outdoor air conditions surpassed the WHO guidelines and, on occasion, reached environmental emergency conditions. Public schools in these cities do not have on-site tools to monitor indoor and outdoor air quality. Therefore, they must rely on the few governmental stations available, which might not account for localized conditions. Consequently, schools cannot keep records of their air quality and do not have the tools to take any action towards improving it.

Data analysis using 8-hour periods allowed us to address differences in PM concentrations at different moments of the day. Average $PM_{2.5}$ and PM_{10} concentrations were higher indoors than outdoors during class time. Teachers kept the door, and most windows closed to preserve the warmth inside and avoid noise coming from outside, which can cause the resuspension of PM inside the classroom and a lack of air renovation during the day. In addition, some classrooms used a radiant fan for heating for a couple of hours in the morning, which might increase PM resuspension and decrease IAQ.

Class periods represented the lowest average $PM_{2.5}$ concentrations in every school. In contrast, evening periods had the highest $PM_{2.5}$ concentrations in CH-I and CH-Z, corresponding with the moments when residential areas turn on the woodstoves for heating. In contrast, in school CH-G, the highest $PM_{2.5}$ average concentrations occurred in the early morning, possibly due to early morning traffic on the highway. In addition, the average $PM_{2.5}$ concentration in CH-G in the evenings was still higher than that of the other two schools, and reached pre-emergency levels according to Chilean regulations (Ministerio de Medio Ambiente 2011; 2022). These results show how PM impacts come mainly from neighboring sources, including the highway and the residential areas adjacent to the schools. The high evening PM records correspond with issues related to city-wide energy poverty. Even when occupants' exposure to $PM_{2.5}$ is lower during regular class times, they are likely still exposed to high pollution levels when not at school.

Teachers' general outdoor AQ perceptions showed differences between schools. While over half the teachers in school CH-G perceived it as mostly negative in the last year and last week, for school CH-I, general perceptions were mainly positive. However, the physical measurements presented a different story, showing that while the AQ in CH-G was worse than CH-I, it was not ideal either in CH-I, given the overarching impact of wood burning in the area, especially during the evenings. In this case, these perceptions might be related to the school having a large green area and neighboring a butte instead of a major highway. Teachers might associate seeing greenery next to the school with perceiving good AQ.

Indoor air quality perceptions proved to be more negative than outdoor AQ perceptions in all schools. In this case, responses in all schools rendered very similar results despite the differences in PM concentrations evidenced by physical measurements. Even in CH-Z, where the indoor PM concentrations were lower compared with the other two schools, almost half the teachers considered the air quality as bad or very bad. In this case, teachers' perceptions might be coming from a different origin. Since the project was developed during the winter, the most concerning health hazards reported were cold snaps and respiratory viruses. Therefore, teachers might have been associating IAQ with cold indoor air temperatures in the classroom and viruses due to crowdedness, instead of PM concentrations.

General health questions and self-reported health symptoms had similar response trends in all schools. The most frequently reported symptoms were related to teaching, such as hoarse and dry throat, which corresponds with previous findings (Brink et al. 2021). Respiratory symptoms were also reported as being frequent, which might be related to the overall poor air quality in the city and the low temperatures during the winter. Since the study only covered the teacher's time at school, it was not possible to assess other influences they were exposed to during other periods, which might be the most critical for PM exposure times, as shown by the physical measurements.

CONCLUSIONS

The study analyzed PM pollution concentrations on air quality in school facilities in Concepcion and San Pedro de La Paz. The results showed high indoor and outdoor PM concentrations, evidencing the prevalence of energy poverty in south-central Chile. The use of wood stoves for heating in residential areas neighboring the schools was the main source of PM pollution, as concentrations spiked during the evenings and nights. These results highlight the urgency to improve current energy sources. The current Plan for Prevention and Atmospheric Decontamination (PPDA) of the Concepcion Metropolitan region, includes actions such as improving the type of wood for heating, upgrading heating devices, and enhancing the energy efficiency of dwellings (Ministerio del Medio Ambiente 2019). Despite the formulation of the plan years before the development of this research, our results show that the efficacy of its execution is not yielding visible results yet. Studies like this one provide further proof to a call for action on this matter to bring this forward to the political scene.

Future research could further investigate low-cost sustainable technologies and strategies suitable to the local context to replace the current wood burning stoves, as well as affordable ways to increase the energy efficiency of the existing residential building stock. For instance, studies have shown that for low and middle income households, retrofitting traditional woodstoves can improve their performance and reduce emissions (Carvalho et al. 2018). Also, modern woodstoves or pellet stoves have been found to emit lower quantities of particulate material than traditional woodstoves (Bäfver et al. 2011), when other heating sources are not economically feasible.

The research also showed that teachers' perceptions of air quality did not always correspond with the physical measurements. A high percentage of the sample did not consider outdoor air pollution a significant health hazard. Teachers are accustomed to living in the same polluted conditions every winter, so they may not perceive it as a risk. As the health effects of air pollution occur only after chronic long-time exposure, people might not consider it an imminent threat. Nonetheless, Chile suffers approximately 4000 premature deaths every year due to air pollution (United Nations Environment Programme 2017), and the prevalence of energy poverty makes it an even more pressing situation.

These results provide a general idea of the indoor and outdoor air quality conditions in the south-central region of Chile and unveil the existing disconnect between air quality conditions and air quality perceptions. The study was limited by only exploring teacher's exposures during their time at school and a short measuring period, so it was not possible to define a clear relationship between PM exposures and self-reported health symptoms. Nonetheless, since high PM pollution occurs all over the city, teachers are likely exposed to high PM concentrations outside school hours. Future research using mobile sensors could shed more light on the effects of daily PM exposures on personal health.

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REFERENCES

Alameddine, I., K. Gebrael, F. Hanna, and M. El-Fadel. 2022. "Quantifying Indoor PM2.5 Levels and Its Sources in Schools: What Role Does Location, Chalk Use, and Socioeconomic Equity Play?" *Atmospheric Pollution Research* 13 (4): 101375. https://doi.org/10.1016/j.apr.2022.101375.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). 2023. "ANSI/ASHRAE Standard 55-2023 Thermal Environmental Conditions for Human Occupancy." Atlanta, GA: ASHRAE.

Andersson, Kjell. 1998. "MM Questionnarie - Form MM 040." http://www.mmquestionnaire.se/mmq/mmq.html.

Bäfver, Linda S., Bo Leckner, Claes Tullin, and Morten Berntsen. 2011. "Particle Emissions from Pellets Stoves and Modern and Old-Type Wood Stoves." *Biomass and Bioenergy*, Proceedings of a workshop of IEA bioenergy task 31 on 'Sustainable Forestry Systems for Bioenergy: Integration, Innovation And Information,' 35 (8): 3648–55. https://doi.org/10.1016/j.biombioe.2011.05.027.

Branco, P. T. B. S., M. C. M. Alvim-Ferraz, F. G. Martins, and S. I. V. Sousa. 2019. "Quantifying Indoor Air Quality Determinants in Urban and Rural Nursery and Primary Schools." *Environmental Research* 176: 108534. https://doi.org/10.1016/j.envres.2019.108534.

Brink, Henk W., Marcel G.L.C. Loomans, Mark P. Mobach, and Helianthe S.M. Kort. 2021. "Classrooms' Indoor Environmental Conditions Affecting the Academic Achievement of Students and Teachers in Higher Education: A Systematic Literature Review." *Indoor Air* 31 (2): 405–25. https://doi.org/10.1111/ina.12745.

Carvalho, Ricardo L., Estela D. Vicente, Luís A. C. Tarelho, and Ole M. Jensen. 2018. "Wood Stove Combustion Air Retrofits: A Low Cost Way to Increase Energy Savings in Dwellings." *Energy and Buildings* 164 (April):140–52. https://doi.org/10.1016/j.enbuild.2018.01.002.

Cheeseman, Michael J., Bonne Ford, Susan C. Anenberg, Matthew J. Cooper, Emily V. Fischer, Melanie S. Hammer, Sheryl Magzamen, et al. 2022. "Disparities in Air Pollutants Across Racial, Ethnic, and Poverty Groups at US Public Schools." *GeoHealth* 6 (12). https://doi.org/10.1029/2022GH000672.

Chen, Jie, and Gerard Hoek. 2020. "Long-Term Exposure to PM and All-Cause and Cause-Specific Mortality: A Systematic Review and Meta-Analysis." *Environment International* 143 (June): 105974. https://doi.org/10.1016/j.envint.2020.105974.

Climate-Data.org. n.d. "Clima Concepción: Temperatura, Climograma y Tabla Climática Para Concepción." Climate Data. Accessed January 13, 2024. https://es.climate-data.org/america-del-sur/chile/viii-region-del-biobio/concepcion-3984/.

Corporación de Desarrollo Tecnológico (CDT). 2015. "Medición Del Consumo Nacional de Leña y Otros Combustibles Sólidos Derivados de La Madera."

de Dear, R., J. Xiong, J. Kim, and B. Cao. 2020. "A Review of Adaptive Thermal Comfort Research since 1998." *Energy and Buildings* 214:109893. https://doi.org/10.1016/j.enbuild.2020.109893.

Habil, Mahima, and Ajay Taneja. 2011. "Children's Exposure to Indoor Particulate Matter in Naturally Ventilated Schools in India." *Indoor and Built Environment* 20 (4): 430–48. https://doi.org/10.1177/1420326X11409455.

Lin, Shao, Wayne R. Lawrence, Ziqiang Lin, Melissa Francois, Iulia A. Neamtiu, Qiaoxuan Lin, Eva Csobod, and Eugen S. Gurzau. 2017. "Teacher Respiratory Health Symptoms in Relation to School and Home Environment." *International Archives of Occupational and Environmental Health* 90 (8): 725–39. https://doi.org/10.1007/s00420-017-1235-x.

Lin, Shao, Emily Lipton, Yi Lu, and Christine Kielb. 2020. "Are Classroom Thermal Conditions, Lighting, and Acoustics Related to Teacher Health Symptoms?" *Indoor Air* 30 (3): 544–52. https://doi.org/10.1111/ina.12640.

Ministerio de Energía. 2021. "Acceso Equitativo a La Energía Sostenible. Políticas Públicas Para Combatir La Pobreza Energética En Chile." Ministerio de Energía. https://energia.gob.cl/pobrezaenergetica%2520/pe-documentos.

Ministerio de Energía, BID, Centro de Inteligencia Territorial, and EBP. 2024. "Plataforma de Pobreza Energética." Plataforma de Indicadores de Pobreza Energetica. 2024. https://vipe.minenergia.cl/.

Ministerio de Medio Ambiente. 2011. "Decreto 12. Establece Norma Primaria de Calidad Ambiental Para Material Particulado Respirable MP2,5." Biblioteca del Congreso Nacional de Chile.

———. 2022. "Decreto 12. Establece Norma Primaria de Calidad Ambiental Para Material Particulado Respirable MP10." Biblioteca del Congreso Nacional de Chile.

Ministerio del Medio Ambiente. 2019. "Decreto 6. Plan de Prevención y de Descontaminación Atmosférica Para Las Comunas de Concepción Metropolitano." Biblioteca del Congreso Nacional de Chile.

Morakinyo, Oyewale Mayowa, Matlou Ingrid Mokgobu, Murembiwa Stanley Mukhola, and Raymond Paul Hunter. 2016. "Health Outcomes of Exposure to Biological and Chemical Components of Inhalable and Respirable Particulate Matter." *International Journal of Environmental Research and Public Health* 13 (6): 1–22. https://doi.org/10.3390/ijerph13060592.

Pérez-Fargallo, Alexis, David Bienvenido-Huertas, Carlos Rubio-Bellido, and Maureen Trebilcock. 2020. "Energy Poverty Risk Mapping Methodology Considering the User's Thermal Adaptability: The Case of Chile." *Energy for Sustainable Development* 58: 63–77. https://doi.org/10.1016/j.esd.2020.07.009.

Reyes, René, Alejandra Schueftan, Cecilia Ruiz, and Alejandro D. González. 2019. "Controlling Air Pollution in a Context of High Energy Poverty Levels in Southern Chile: Clean Air but Colder Houses?" *Energy Policy* 124:301–11. https://doi.org/10.1016/j.enpol.2018.10.022.

Sadrizadeh, Sasan, Runming Yao, Feng Yuan, Hazim Awbi, William Bahnfleth, Yang Bi, Guangyu Cao, et al. 2022. "Indoor Air Quality and Health in Schools: A Critical Review for Developing the Roadmap for the Future School Environment." *Journal of Building Engineering* 57 (October). https://doi.org/10.1016/J.JOBE.2022.104908.

United Nations Environment Programme. 2017. "Chile Takes Action on Air Pollution." UNEP. November 16, 2017. http://www.unep.org/news-and-stories/story/chile-takes-action-air-pollution.

World Health Organization. 2021. "WHO Global Air Quality Guidelines." World Health Organization. https://iris.who.int/handle/10665/345329.