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Research article

Indoor-outdoor concentrations of fine particulate matter in school building microenvironments near a mine tailing deposit

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Abstract: Indoor air quality in school classrooms is a major pediatric health concern because children are highly susceptible to adverse effects from xenobiotic exposure. Fine particulate matter ($PM_{2.5}$) emitted from mining waste deposits within and near cities in northern Chile is a serious environmental problem. We measured $PM_{2.5}$ in school microenvironments in urban areas of Chañaral, a coastal community whose bay is contaminated with mine tailings. $PM_{2.5}$ levels were measured in six indoor and outdoor school environments during the summer and winter of 2012 and 2013. Measurements were taken during school hours on two consecutive days. Indoor $PM_{2.5}$ concentrations were 12.53–72.38 μg/m^3 in the summer and 21.85–100.53 μg/m^3 in winter, while outdoor concentrations were 11.86–181.73 μg/m^3 in the summer and 21.50–93.07 μg/m^3 in winter. Indoor/outdoor ratios were 0.17–2.76 in the summer and 0.64–4.49 in winter. $PM_{2.5}$ levels were higher in indoor microenvironments during the winter, at times exceeding national and international recommendations. Our results demonstrate that indoor air quality Chañaral school microenvironments is closely associated with outdoor air pollution attributable to the nearby mine tailings. Policymakers should enact environmental management strategies to minimize further environmental damage and mitigate the risks that this pollution poses for pediatric health.

Keywords: particulate matter; schools; mine tailings

1. Introduction

Air quality in the school environment that has taken on increasing public health importance in recent years. Several studies have reported that school indoor microenvironments are among the most highly contaminated sites, finding high levels of particles, gases, and microorganisms associated with acute and chronic health problems [1-6]. A correlation exists between the concentration of pollutants and health problems in school children. These observed health effects are predominantly respiratory, including asthma, allergies, respiratory infections, chronic obstructive pulmonary disease, and the risk for developing other pulmonary obstructive diseases in adulthood [5,7,8]. These findings are concerning, given that children typically spend 6–10 hours per day in elementary schools, preschools, or nurseries [5,9]. Children are especially susceptible to the adverse effects of air pollution, due to their immature physiological and metabolic systems, their immunological defenses are not fully developed [9-11]. Additionally, children's normal activity patterns tend to stir up dust, increasing exposure to pollutants [12,13]. On the other hand, because of their smaller stature, children are exposed to a higher concentration of inhaled aerosol particles. Because their airways are smaller, children inhale a higher level of air per unit body weight compared to adults. Smaller air particles, such as $PM_{2.5}$ and ultrafine particles, are considered more harmful than larger particles [14-16]. In addition to size, the chemical composition of PM can determine its dangerousness while components such as transition metals (iron, copper, nickel, and chromium) are known to produce severe toxicity on exposed tissues [17-19]. Reactive oxygen species generated during metabolism of air contaminants are responsible for inflammatory processes that occur in response to air pollutant exposure [20].

Mining has been Chile's main economic activity for decades, operating primarily from central and northern regions of the country [21]. Mining provides economic benefits but also creates environmental damage, due to residues left after mineral processing. One such environmental liability is mine tailings of ore processing, containing high levels of toxic metals [22-24].

Chañaral is a coastal city in northern Chile whose main commercial activity is mining and fishing. During the last century, it had a great mining boom which resulted in large beneficial to the country. However, this activity generated a lot of waste that ended up in the Chañaral's bay, embanking and polluting the beach. This massive pollution of the coastline has affected the marine flora and fauna [25-27]. This phenomenon of coastal mining waste pollution has been described in different places of the world [28-31].

In 2011, environmental Chilean authorities identified at least 603 mine tailing deposits, many of which are adjacent to highly-populated areas [32]. The bay of Chañaral in northern Chile is one such area where strong prevailing winds carry dust from the beach towards urban areas during spring and summer [33,34]. The aim of this study is to determine fine particulate matter concentrations in school microenvironments settings and to measure the relationship between indoor and outdoor levels.

2. Materials and Methods

2.1. Study design and schools sampling

We performed a cross-sectional study of a sampling frame of 10 schools in Chañaral, from which we randomly selected six schools distributed throughout the city (Figure 1). Sets of measurements were performed during the summer (December 2012) and repeated during the winter (July 2013). The microenvironments studied were classrooms, offices, and playgrounds on school property. Administrative offices and classrooms were classified as indoor environments and playgrounds as outdoor environments. The characteristics of the sampling areas in preschools (PS) and elementary schools (ES) are described in Table 1.

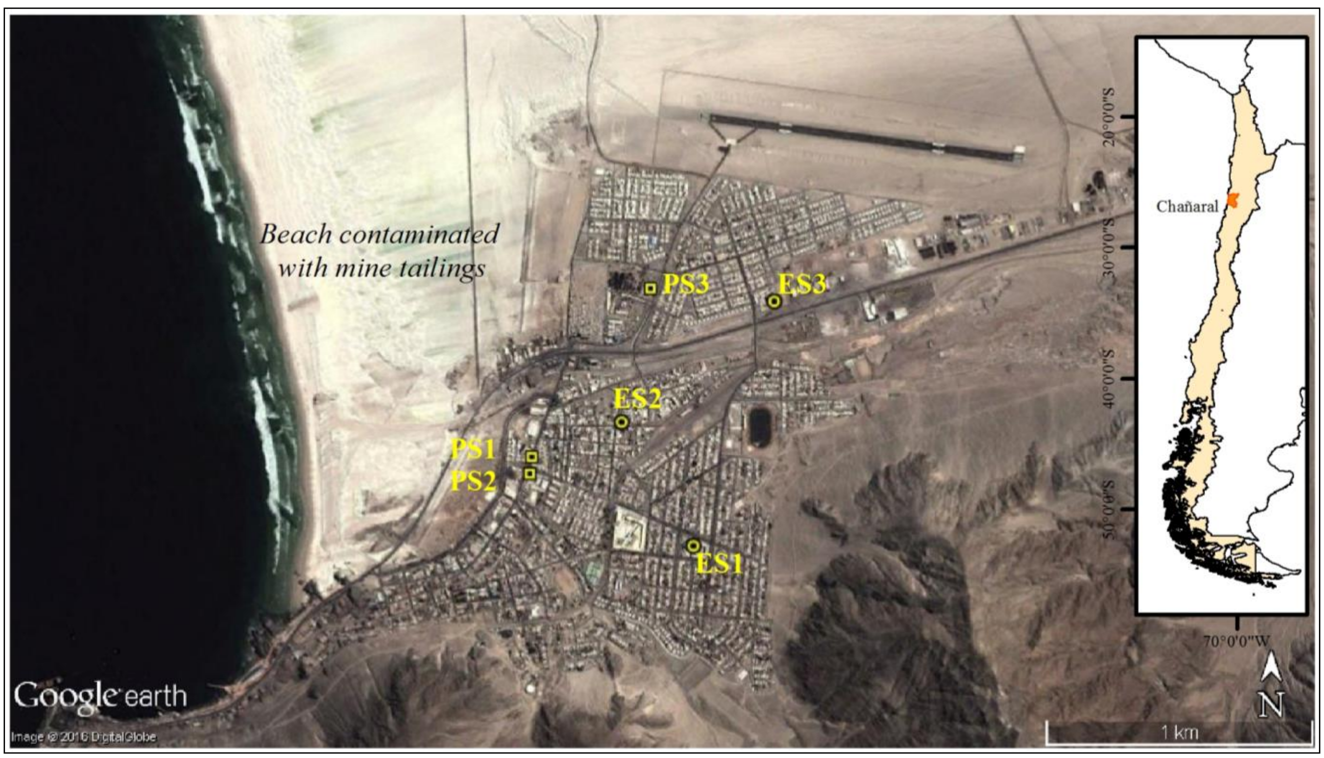

Figure 1. Map of Chañaral, Chile and locations of the participating schools. PS, preschools; ES, Elementary schools.

Table 1. Characteristics of preschool and elementary school sampling areas, Atacama Region, Chile.

ID	Room ventilation	Office ventilation	Indoor floor type	Outdoor floor type	Location(s)	Comments
ES1	Small iron windows to outside closed throughout the process	One aluminum window to exterior, closed throughout the process	Vinyl	Concrete/Ground	Hilltop, near railway line	Elementary school located near train line, farther from beach than most of the other schools. Daily cleanup after school hours
ES2	Small aluminum windows to outside open throughout the process	One aluminum window to exterior, closed throughout the process	Vinyl	Concrete	On main two-way street	School located farther from beach than most of the other schools. Daily cleanup after school hours
ES3	Aluminum windows to outside closed throughout the process	One aluminum window to exterior, closed throughout the process	Vinyl	Concrete/Ground	Near Main Street	Playground remodeling construction activities occurred throughout the process. Daily cleanup after school hours
PS1	Wood windows to outside closed throughout the process	One aluminum window to exterior, closed throughout the process	Vinyl	Ground	On Main Street and adjacent to beach	School located near the beach, adjacent to the municipal greenhouse. Daily cleanup after school hours
PS2	Small aluminum windows to outside open throughout the process	One aluminum window to exterior, closed throughout the process	Vinyl	Concrete	On Main Street and adjacent to beach	School located near the beach, with playground adjacent to a bus station. Daily cleanup after school hours
PS3	Small aluminum windows to outside open throughout the process	One aluminum window to exterior, closed throughout the process	Vinyl	Concrete/Ground	On main two-way street	School located near the beach, in an obviously impacted area, and adjacent to a local mini-zoo. Daily cleanup after school hours

PS: Preschool; ES: Elementary school

2.2. Study area

Chañaral is a northern coastal city with a warm desert climate, abundant clouds, and scarce rain. Chañaral has a narrow thermal amplitude with low contrast, both across seasons and between night and day, and prevailing west-east winds [35]. The ocean currents stir up the tailing mud when the coast is soaked by high tides [26,34].

2.3. $PM_{2.5}$ indoor vs outdoor gravimetric sampling and meteorological parameters

$PM_{2.5}$ mass concentration was measured by gravimetric analysis in Chester LabNet Laboratory, (www.chesterlab.net), a National Environmental Laboratory Accreditation Conference (NELAC) accredited laboratory (Tigard, OR, USA). Personal environmental monitoring system (PEMS)® equipment model 761-203A, SKC, Eighty Four, PA) containing 37 mm pre-weighed Teflon filters was used to collect PM2.5, using a 44XR Universal Sample Pump (SKC Inc, Eight Four, Pennsylvania, USA). A flow of 4 L/min was set, and variation was monitored daily by means of a soap bubble electronic SKC ULTRAFLO® calibrator. $PM_{2.5}$ was measured in indoor and outdoor microenvironments simultaneously. All measurements were performed during school hours on two consecutive days, for eight hours per day, resulting in a total measurement time of 16 hours for each school per season. In indoor environments, particle collectors were placed at a height of one meter and a distance of 50 cm from the wall, in a corner opposite the main windows. In outdoor areas, collectors were placed on the playground, also at a height of one meter. A total of 36 measurements were performed at each site.

Meteorological station equipment with adequate coverage of the target area was used to record wind velocity, temperature, relative humidity, solar radiation, barometric pressure, and precipitation. Meteorological parameters were measured according to established guidelines [36].

2.4. Data analysis

Descriptive and exploratory analyses were performed on the data collected. To compare $PM_{2.5}$ mass concentration between stations and microenvironments two-sample Wilcoxon rank-sum test was used. We also analyzed indoor-outdoor ratios (I/O), with the assumption that I/O values higher than unity (1) would suggest another source of emissions into the studied areas and/or outside infiltration [37,38]. To evaluate indoor and outdoor relationships among offices, classrooms and playground during the sampling period Spearman's correlation coefficient was used, respectively. Statistical analysis was performed using STATA 11.1 software.

2.5. Ethical considerations

The study was conducted as part of FONIS project SA11|2224 and was approved by the ethical committee of the University of Chile School of Medicine [39].

3. Results

3.1. $PM_{2.5}$ levels and indoor-outdoor relationship in schools' microenvironments

Figure 2 shows $PM_{2.5}$ mass concentrations by season and microenvironment. During summer, $PM_{2.5}$ mass concentrations were 12.53–72.38 μg/m^3 within indoor microenvironments and 11.86–181.73 μg/m^3 in outdoor microenvironments. In winter, $PM_{2.5}$ concentrations were 21.5–93.1 and 21.9–100.5 μg/m^3 in outdoor and indoor settings, respectively. No significant differences for indoor and outdoor $PM_{2.5}$ median concentrations for summer (p = 0.6199) and winter (p = 0.2026) were observed, respectively. In summer, the highest indoor value was found in ES2 (office) and the highest outdoor values in PS1 and PS2 playgrounds, respectively. The highest values in winter were found in PS1 (all microenvironments), and PS2, ES3 for classroom, respectively (see supplementary data).

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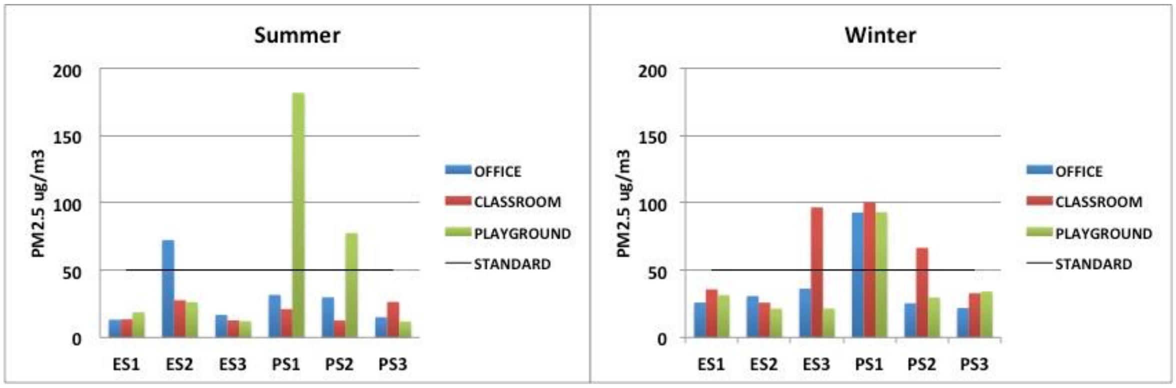

Figure 2. Summer and winter $PM_{2.5}$ concentration and indoor/outdoor ratio in school microenvironments in Chañaral, Chile. PS, preschools; ES, Elementary schools.

When comparing the median concentrations of $PM_{2.5}$ between summer and winter season, not statistically significant differences for offices (p = 0.3367) and playgrounds (p = 0.4233) were observed, respectively. However, the median concentration of $PM_{2.5}$ in classrooms in winter period was significantly higher compared with summer (p = 0.0104).

Table 2 shows indoor vs outdoor $PM_{2.5}$ relationship by season and microenvironment. Summer I/O ratios for offices and classrooms versus playgrounds varied from 0.17 to 2.76 and 0.12 to 2.23, respectively. The relationship between $PM_{2.5}$ levels for offices and classrooms for ES1, PS1, PS2 schools compared with playground was less than unity (1), indicating that during the period sampled, the outdoor levels were higher. In some cases that outdoor concentrations were nearly three to eight times higher than indoor concentrations. This can be explained by any of the following reasons; in ES1 during sampling period, there were works of removal of construction debris outside school, this generated locally resuspension of dust that may have affected the measurement. For PS1 and PS2, it can be explained by its proximity to the area of the deposit of tailings on the beach. In addition, another factor was that the floor of these schools was not completely paved, at least 50% were soil and sand. To ES2 and PS3 I/O relationship was greater than unity (1), indicating higher levels of $PM_{2.5}$ in the microenvironments of offices and classrooms compared with playground. In this preschool, the playground was paved, but there was unpaved area near to the classrooms gate, where it would be entering the dust, which is carried on their clothes and shoes for children and teachers during the school day.

During winter, I/O ratios were 0.17–2.76 for offices vs. playgrounds and 0.12–2.23 for classrooms vs. playgrounds. To classroom vs playground the I/O was greater than 1.0 except in PS3, indicating a higher concentration of $PM_{2.5}$ in the classroom compared with playground. This concentration was up to 4.49 times the outdoor as shown in ES3 (Table 2). This school, the classroom and offices are adjacent to an unpaved area, which could explain these high levels of $PM_{2.5}$. On the other hand, the relationship between offices and playgrounds was around unity (1.0).

Correlation analysis during the sampling period showed no clear relationship between outdoor-indoor $PM_{2.5}$ levels for playground versus classrooms (r = 0.23; p = 0.4705). Instead, the correlation of $PM_{2.5}$ levels in playground versus offices was moderate, near of statistical significance (r = 0.56; $p = 0.0548$).

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Table 2. Indoor/outdoor ratio to PM2.5 concentration in school microenvironments. Chañaral, Chile.

	Summer		Winter	
	Indoor/Outdoor		Indoor/Outdoor	
School	Office/Play	Classroom/Play	Office/Play	Classroom/Play
ES1	0.71	0.72	0.82	1.14
ES2	2.76	1.05	1.44	1.21
ES3	1.38	1.04	1.69	4.49
PS1	0.17	0.12	1.00	1.08
PS2	0.38	0.16	0.86	2.24
PS3	1.27	2.23	0.64	0.97
Median	*1,04*	*0.78*	*0.93*	*1.67*

ES: Elementary Schools; PS: Preschools; Play: Playground.

3.2. Meteorological parameters

Figure 3 demonstrates the direction of the local wind patterns in Chañaral as well as the wind velocity. During 42–56% of the period studied, the prevailing wind direction was West-Northwest (November–March, which are the spring and summer months in South America). During fall and winter (April–June), the wind direction was west, northeast, and east 27, 15 and 20% of the time, respectively (Figure 3a). Wind velocity was more variable during the spring and summer months (December–February) as compared to the fall and winter months (Figure 3b). During this period, 75% of measurements exceeded 4 m/s, and the strongest winds generally occurred between 10:00 and 18:00 hours (see supplementary data).

4. Discussion

This study aimed to determine the concentrations of fine particulate matter ($PM_{2.5}$) at school microenvironments in two different seasons in the coastal city of Chañaral in northern Chile, which bay is heavily polluted with ore waste of copper mines.

The ratio of indoor versus outdoor concentration levels varied by season and were generally high during the winter season. During the summer, there were not significant differences in the median concentrations in indoor compared to outdoor microenvironments. However, concentrations of the two schools closest to the coastline (both preschool level elementary schools) had high concentrations of $PM_{2.5}$. We also did not observe a clear difference in indoor microenvironments. In winter, the median $PM_{2.5}$ concentrations were similar in offices and patios, however, levels in classrooms were higher than in playgrounds. The very high levels seen in outdoor environments during the summer may be associated with atmospheric conditions prevalent during the days we monitored the schools. This weather phenomenon may have influenced the concentrations of particulate matter and dust in suspension in the study area. Some authors have reported that

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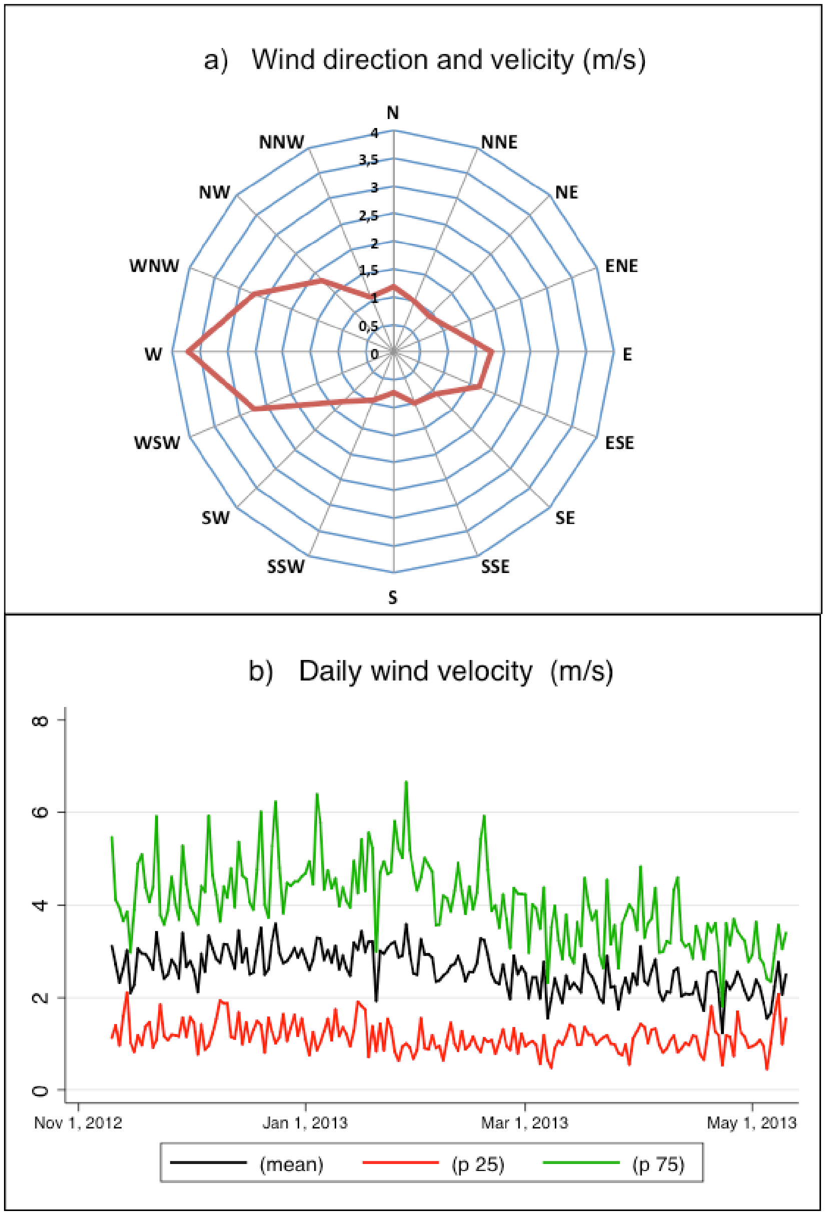

Figure 3. Wind characteristics, November 2013 to May 2013, Chañaral, Chile.

particulate matter concentration is modulated by wind speed, observing lower concentrations for wind speeds under 2 m/s and higher concentrations for stronger winds [40]. Mining waste is amongst the largest generators of dust that pollute the atmosphere. Pollution in coastal areas includes a complex mixture of tailings containing metal, sand, and the effect of sea water, generating particulate matter carried by the wind from surrounding urban areas and communities [24,26,41-44].

This finding may explain the higher particulate matter levels observed in summer, when the wind speed was significantly higher [45,46]. Other authors have reported a similar relationship between wind speed and concentration, albeit with slightly different values, finding, for example, that PM concentrations were higher when wind speeds were above 4 m/s [46-48]. During this study, the 75th percentile of wind velocity measurements was about 4 m/s, with higher speeds in summer vs. winter (Figure 3b). During the study period, no rainfall was recorded. The average relative humidity for the period was 70% (range 34.3–89.9). Barometric pressure and solar radiation were practically constant over the period. Neary and Garcia-Chevesich reported that during spring and summer, local prevailing winds blow towards the coast in this region (west to east), carrying dust from the bay and moving particles towards the urban area of Chañaral [33].

High indoor particulate matter levels in preschools may be attributable to the schools' proximity to the bay polluted with mine tailing deposits, as well as the activity of children in classrooms, which can resuspend particulate matter. During the summer, the preschools closest to the beach kept their windows closed during school hours to prevent dust from entering school offices and classes. This method was relied upon particularly in schools lacking formal ventilation. In the winter, the windows also remained closed most of the time, in this case to keep the classrooms warm, especially in the classrooms where the children spent the most time. The high indoor particular matter levels observed in our study could be explained by infiltration from the outdoor environment and the movement of children during the school day. As it is seen in summer time distribution of $PM_{2.5}$ concentration levels, increase, which would be associated with periods of recess and lunchtime. During these periods of time, children are moving, causing particle resuspension. In preschools (PS), a greater variation in levels of PM compared to basic schools (winter and summer), which could be related to the proximity to the bay were observed. Moreover, the elementary school (ES2) is at higher altitudes and farther from the area contaminated beach.

Seasonal differences were not as apparent in the offices as in the classrooms, suggesting that the variations in classroom levels were attributable to children's activity during school hours. The administrative offices where $PM_{2.5}$ samplers were installed, there were no specific sources of emission of particles, such as photocopying or other equipment. The offices were occupied by school principals and teachers.

Various authors have noted that indoor particulate matter levels are closely related to the presence and activity of students, as well as to levels in outdoor environments [23,49-51]. Several international studies have found results similar to those reported here. Studies performed in England and the Netherlands reported indoor PM concentrations of 19.0–30.0 and 7.7–52.8 μg/m^3, respectively [52,53]. A study by Diapouli et al., which measured $PM_{2.5}$ levels during winter in seven schools, reported indoor concentrations of 22.1–40.3 μg/m^3 and outdoor concentrations of 38.6–99.0 μg/m^3, similar to the values observed in Chañaral (52.7 and 30.9 μg/m^3, respectively) [54]. However, another comparable study by Madureira et al., measuring $PM_{2.5}$ concentration at 11 schools in Porto, Portugal, reported concentrations of 95 μg/m^3 indoors and 115 μg/m^3 outdoors; these values were significantly higher than those measured in Chañaral [55]. A study of six elementary schools in Iran (2013) reported average indoor levels of 29.1–69.1 μg/m^3 during the school day, similar to our results [56]. It is important to note that in the studies described above, the main source of particulate matter was vehicular traffic, a factor that is likely marginal in Chañaral.

Nkosi et al. (2015) conducted a study in 11 South Africa communities, reported an association between proximity to deposits of mine waste and effects on the respiratory health of children and adolescents in 22 primary and secondary schools. The authors concluded the damaging effect of the mine on respiratory health and the proximity of the community to the mine dumps [57]. Studies on the composition of particulate matter in industrial areas of the Atacama region have shown to have a high content of heavy metals in PM_{10} and $PM_{2.5}$ [58-61], which may indicate the potential health risks of the exposed population, especially children, the elderly, and those with concurrent illness.

5. Conclusion

Our results revealed high levels of fine particulate matter during the summer and winter within Chañaral indoor school settings. The highest concentrations were in classrooms, particularly within preschools closest to the mining tailings. Indoor fine particulate matter levels exceeded Chilean and international recommendations, especially during winter months. Outdoor fine particulate matter concentrations also generally exceeded Chilean and international norms during both seasons studied. Children at these schools are exposed to poor air quality, whose main source is from particulate matter from a reservoir of mine tailings present at the Chañaral bay, putting children and other residents at high risk for many health problems. This is the first study of its kind in Chile, whose objective was to measure the concentration of particulate matter in school microenvironments in a polluted area with mine tailing. The composition of metals in particulate matter is urgently needed to clarify the risk of potential adverse effects on the health of the population.

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Conflict of interest

The authors have no conflicts of interest to declare.

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