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Air Pollutants Behavior During the COVID-19 Pandemic in more Polluted Cities in Central and Southern Chile

Giovanni Salini[1,*], Evelin Medina[2]

[1] Departamento de Matemática y Física Aplicadas, Facultad de Ingeniería, Universidad Católica de la Santísima Concepción
Concepción, Chile
**Corresponding author's email*: *gsalini* [AT] *ucsc.cl*

[2] OTB Luis Espinal-Zona Abra
Cochabamba, Bolivia
Email: evelinmedinamitma [AT] gmail.com

ABSTRACT— ***This article studies air quality in some of the most polluted medium-sized cities in Central and Southern Chile, which have experienced high levels of coarse and fine particulate matter pollution in recent years. Since air quality is much better in spring and summer, the study focused on the winter period (from April 1 to August 31) and between 2018 and 2023, corresponding to the pre- and post-COVID-19 pandemic. We analyzed the effect of the COVID-19 lockdown on air quality in ten urban areas declared saturated by air pollution. Elsewhere in the world, and during the same period, air quality improved due to a recession or decrease in human activity. This was due to the quarantine imposed on the global population when the WHO declared the SARS-CoV-2 pandemic. However, this study detected a possible increase in environmental pollution between 2020 and 2022 in all the cities studied. The possible causes of this phenomenon are investigated. Finally, it was observed that the population was exposed to poor air quality throughout the study period in the different cities studied, which could have had very detrimental effects on the population's health.***

Keywords— SARS-CoV-2, Firewood Pollution, Health Impacts, Particulate Matter.

1. INTRODUCTION

In 2019, more than 90% of the world's population lived in areas where particulate matter concentrations exceeded the World Health Organization reference levels [1] established in 2005. The EPA [2] classifies particulate matter pollution as "coarse particulate matter" ($PM_{10\text{-}2.5}$), which ranges in diameter from 2.5 to 10 micrometers (known as PM_{10}), which includes all particles smaller than 10 microns. And "fine particulate matter" (or $PM_{2.5}$), which is less than 2.5 microns in diameter. For health purposes, PM is generally defined by its size, with the smallest particles having the greatest negative impact on human health. The sources of fine particulate matter are diverse, but this document focuses on those derived from the use of wet wood for heating, as well as mobile sources. $PM_{2.5}$ particles are called "primary" if they are emitted directly into the air as solid or liquid particles, and "secondary" if they are formed by chemical reactions of gases in the atmosphere. The main sources of primary fine particulate matter are cars and trucks (especially those with diesel engines), open burning, wildfires, fireplaces, wood stoves, wood cooking, road dust, agricultural operations, and boilers that burn coal and oil. WHO [1] recommends a limit for coarse particulate matter (PM_{10}) of 20 $\mu g/m^3$ for the annual average and 50 $\mu g/m^3$ for the 24 h average. For fine particulate matter ($PM_{2.5}$), the annual average is 10 $\mu g/m^3$ and the 24 h average is 25 $\mu g/m^3$. The Chilean primary air quality standard for fine particulate matter ($PM_{2.5}$) is 38 $\mu g/m^3$ as a 24 h concentration and 15 $\mu g/m^3$ as an annual concentration. Table 1 presents a summary of the Chilean and international standards [2, 3].

Table 1. Air Quality Standard for $PM_{2.5}$ and PM_{10}

AQS	$PM_{2.5}$ Annual $\mu g/m^3$	$PM_{2.5}$ Mean (24 h) $\mu g/m^3$	PM_{10} Annual $\mu g/m^3$	PM_{10} Mean (24 h) $\mu g/m^3$
WHO	5	15	15	45
US EPA	9	35	revoked	150
EU	10	25	40	50
Chile	20	50	50	130

Today, air pollution is one of the biggest environmental threats to population health and can travel to different locations, even carrying viruses such as SARS-CoV-2 [4, 5]. For a 2002 study [6], controlling fine particle pollution results in an annual reduction of thousands of premature deaths. The size of the particles is directly related to their potential to cause a wide range of diseases, significantly reducing life expectancy [7, 8, 9, 10, 11]. According to [12], fine particles were the main environmental risk factor in Nordic cities and the main contributor to the disease burden, which was dominated by mortality. Furthermore, the health impact of fine particles from poor wood combustion in homes in some European cities was assessed [13].

In 2014, Salini [14] presented a study on air quality in medium-sized cities in southern Chile, where he stated that the incomplete combustion of wet, low-quality wood for domestic use releases particulate matter harmful to human health, which penetrates the respiratory tract, causing episodes of poor air quality in winter [15, 16]. This emission of fine particles is the best indicator of health risk. The relationship between ultrafine particles and medical visits has been estimated in Temuco [17, 18], and the elderly population was found to have the highest relative risk. Reyes [19] observed high $PM_{2.5}$ concentrations on winter nights in Temuco, as well as episodes of high pollution caused by biomass combustion and poor mixing [20]. Yáñez and colleagues [21] evaluated the effect of meteorological variables on fine and coarse particulate matter in eight cities in the south-central valley of Chile. They found that the southernmost cities have higher $PM_{2.5}$ pollution and those in the north have higher PM_{10} pollution. Molina and colleagues [22] conducted a study in 18 medium-sized cities in south-central Chile. They found that the highest concentrations of fine and coarse particulate matter occurred during the cold season and at night, when temperatures are lowest and dispersion conditions are very unfavorable. Furthermore, the use of firewood for cooking and heating consistently exceeded the limits established by the WHO and the Chilean standard. In all these cities, the population has been exposed to concentrations of particulate matter that negatively affect their health. Jorquera and colleagues [23] found that the main source of fine particulate matter is wood smoke in two cities (Valdivia and Molina). In another paper, Reyes shows that firewood is the main fuel used for heating in the city of Valdivia, Chile. However, due to its intensive and inefficient use, it produces severe episodes of air pollution [24]. One of the most polluted cities in southern Chile is Coyhaique, whose average annual concentration exceeds national and international air quality standards. The days of highest pollution have been associated with low temperatures and the intensive use of wet firewood for cooking and residential heating [25, 26]. Other studies conducted in medium-sized cities in Southern Chile [14, 27] have shown that their inhabitants' health has been impaired by the burning of wet residential wood. This, in turn, has led to severe episodes of air pollution in winter, deteriorating urban air quality with high concentrations of fine particulate matter. Again, one of the main causes would be the excessive use of very wet firewood for cooking and heating [28].

Furthermore, these events have been correlated with periods of low temperatures, low wind speeds, and high surface pressure. However, at higher altitudes, a thermal inversion occurs that prevents the dispersion of atmospheric pollutants. Air pollution in cities and indoor spaces is a health threat, as it can cause serious illness. Its effects are also evident in high-altitude cities [29].

Various governments around the world, including Chile, had to implement extraordinary measures to mitigate the direct and indirect effects of the SARS-CoV-2 virus following the WHO's declaration of the COVID-19 pandemic. These effects included mandatory mask use, frequent handwashing, social distancing, quarantine, and more. The population was greatly fearful of contagion, which restricted their outings and even their travel on public transportation. It is worth noting that [4] presented a possible relationship between the spread of the COVID-19 pandemic and aerosols present in urban air contaminated with respirable particles.

This study seeks to investigate the possible causes of the apparent increase in particulate matter during the COVID-19 quarantine period, in the fall and winter of 2020 and 2022. To this end, eight medium-sized cities in south-central Chile, comprised of 16 monitoring stations, were considered. Furthermore, the daily exposure of their inhabitants to this particulate matter during this period was analyzed, confirming that the current Chilean standard was constantly exceeded, which undermined their health.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 The study area

The economy of the central and southern regions of Chile is primarily based on agriculture and livestock. These are complemented by the exploitation of resources from the forestry and fishing sectors, and the production of exportable agricultural products, which contribute to $PM_{2.5}$ emissions through biomass burning and vehicular traffic. Figure 1 shows the study area for medium-sized cities located in central and southern Chile. Table 2 summarizes the geopolitical information of these cities. The geographic and meteorological conditions of these cities—located in the middle basin of south-central Chile, between the Andes and the Coastal Mountains—make them exposed to environmental pollution. Low temperatures and recurring inversion layers during the fall-winter season are also significant factors [18]. Talca, Linares, and other cities developed geographically in basin areas. That is, these cities are located on corners, not in high areas. In fact, Table 2 shows the low altitude at which Talca is located, making it one of the lowest-lying cities, with higher surroundings forming a kind of funnel. All cities under study have been declared saturated by air pollution, due to the constant exceedance of the $PM_{2.5}$ particulate matter standard in force in Chile during the most critical period of fall-winter and, lately, every year (Table 2).

Due to the climatic, geographical and topographical conditions of these cities under study, an adverse effect originates from environmental pollution, mainly in the fall–winter period. This, in turn, makes the dispersion of pollutants very complex. Air pollutants emitted by various sources (fixed or mobile) tend to concentrate within the valley area under thermal inversion conditions (a layer of colder air is trapped by a layer of warmer air, preventing any dispersion of pollutants). In turn, the low wind speed within this inversion layer causes a stagnation of air pollutants, generating a serious health problem for the population in these cities. Thermal inversions are usually observed in urban areas surrounded by mountain ranges, causing serious air pollution problems.

Table 2. Geopolitical information of cities in Central and Southern Chile.

City	Latitude	Longitude	Region	Altitude (masl)	Population	Surface km^2
Rancagua	34° 10' 15" S	70° 44' 40" W	O´Higgins	572	274,407	260
San Fernando	34° 35' 02" S	70° 59' 21" W	O´Higgins	89	81.117	2.441
Talca	35° 26' 0" S	71° 40' 0" W	Maule	102	242,344	232
Chillán	36° 36' 24" S	72° 6' 12" W	Ñuble	124	184,739	511
Los Ángeles	37° 28' 15" S	72° 21' 6" W	Bío Bío	139	223,751	1,748
Temuco	38° 44' 0" S	72° 36' 0" W	Araucanía	122	309,696	464
P. Las Casas	38° 46' 0" S	72° 36' 0" W	Araucanía	86	85,373	465
Valdivia	39° 48' 51" S	73° 14' 45" W	Los Ríos	14	166,460	1,016
Osorno	40°34’ 0” S	73° 09’ 0” W	Los Lagos	39	182,338	951
Coyhaique	45° 34' 16" S	72° 04' 7" W	Aysen	302	57,818	7,290

2.2 The data

Hourly particulate matter concentrations ($PM_{2.5}$) may be obtained from stations belonging to the Chilean official monitoring stations network. This network consists of 58 monitoring stations distributed from O’Higgins region to Aysen region. The Chilean National Air Quality Information System [27] website can be accessed via a website maintained by the Chilean Ministry of the Environment [3, 30]. This information comes from public and private stations administered by the state (mainly by the MMA [2]). The hourly data raw on the air pollutant, PM_{10} and $PM_{2.5}$, — in cities in Central-Southern Chile —, cover the period from April 2018 to August 2023. These databases were collected during the fall-winter period (cold season), and recorded at 17 automated public monitoring stations, available in the National Air Quality Information System [30] dependent on the Ministry of the Environment of Chile (MMA), located in 10 cities in Central and Southern Chile. These cities are Rancagua, San Fernando, Talca, Chillán, Los Ángeles, Temuco, Padre Las Casas II, Valdivia, Osorno and Coyhaique (Figure 1).

Figure 1: Map of the cities involved in this study, from central and south of Chile. Source: own elaboration.

2.3 Statistical Analysis

A total of 705,024 hourly observations recorded between 2018 and 2023 were analyzed. Descriptive statistics (mean, standard deviation, coefficient of variation, maximum, skewness, and kurtosis) were used for the analysis.

Figure 2 shows the hourly average of $PM_{2.5}$ concentrations over a year at the 21 de Mayo monitoring station, which consists of 8,760 data points. Figure 3 shows the hourly average of $PM_{2.5}$ for the fall-winter period of the same year, consists of 22,032. Seasonal variation is evident when comparing Figures 2 and 3. Since mid-sized cities are located in the Southern Hemisphere, fall begins in March and winter ends between August and September. Hourly average concentrations are significantly higher between April and August, a period during which more episodes of high $PM_{2.5}$ concentrations are observed, than during the rest of the year. The statistical properties of the $PM_{2.5}$ time series for the years 2018 to 2023 are shown in Table 3, for the period from April to August. Table 4 shows the statistics for PM_{10} for the same period, corresponding to the season with the worst air quality. From here, the difference between the cold season and the rest of the year becomes evident again. The high standard deviations suggest that prediction is not easy. Skewness indicates the symmetry of the probability density function (PDF) of a time series. A time series with an equal number of large and small values has a skewness of zero. Positive skewness values in Tables 3 and 4 indicate that there are relatively fewer high concentrations of $PM_{2.5}$ in all series. This will be difficult for the construction of accurate statistical prediction models, since the parameters in them are calculated from historical cases, and an underrepresentation of high concentration cases will generally imply a tendency to underestimate extreme values. From an operational perspective, detecting high concentrations is particularly important for air quality management in a city. In medium-sized cities, we observed significant differences in kurtosis between monitoring stations. Not surprisingly, the highest kurtosis corresponds to the 21 de Mayo station (54.49, Table 3), where the highest concentrations are observed within the city during these episodes, and where, under unstable atmospheric conditions, the lowest concentrations are observed.

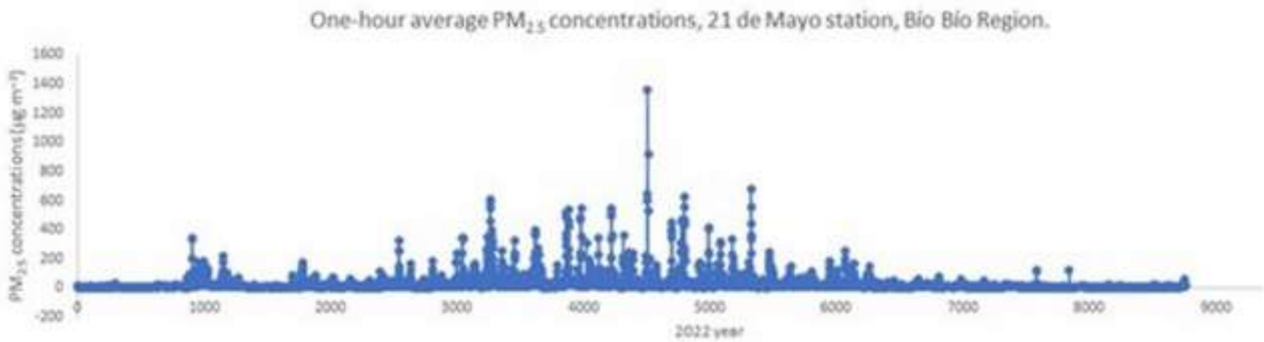

Figure 2: $PM_{2.5}$ concentration at the monitoring station, 21 de Mayo, during the year 2022.

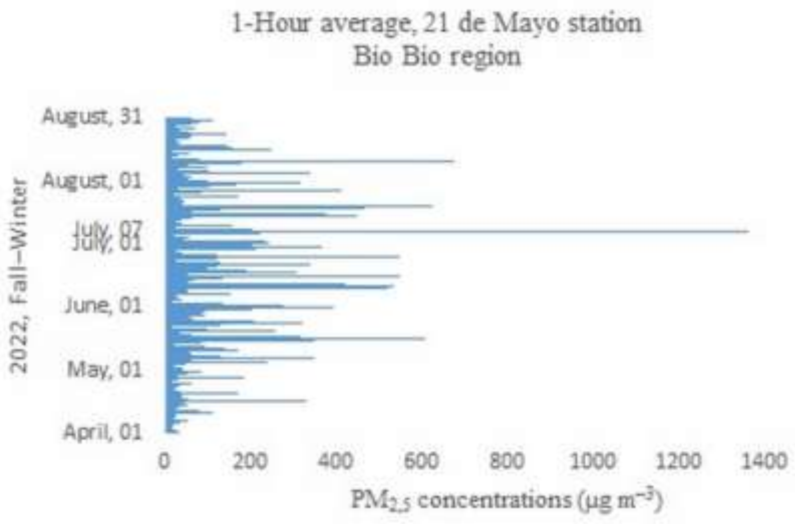

Figure 3: $PM_{2.5}$ concentration at the monitoring station, 21 de Mayo, during the Fall-Winter period of 2022.

Table 3. Basic statistics for $PM_{2.5}$

$PM_{2.5}$ Year	Maximum $\mu g/m^3$	Average $\mu g/m^3$	St. Dev. $\mu g/m^3$	CV	Skewness $\mu g/m^3$	Kurtosis $\mu g/m^3$
Rancagua 2						
2018	438	46.64	44.95	93.38	2.84	11.81
2019	315	44.12	36.89	83.61	2.46	8.66
2020	396	39.44	36.29	92.01	2.99	14.25
2021	351	**43.49**	42.47	97.65	2.49	9.10
2022	423	46.39	39.65	85.47	2.51	10.70
2023	360	34.37	32.50	94.56	2.67	12.27
La Florida						
2018	723	55.93	71.60	128.02	3.33	15.90
2019	557	43.84	55.68	127.01	2.96	12.79
2020	726	48.05	64.45	134.13	3.37	15.94
2021	659	**55.06**	72.95	132.49	3.13	12.73
2022	488	43.44	55.86	128.59	3.12	12.64
2023	553	41.71	55.50	133.06	3.26	14.69
Puren						
2018	1164	72.53	108.96	150.23	3.74	18.14
2019	857	57.96	83.59	144.22	3.90	21.43
2020	854	48.19	77.24	160.28	4.36	25.34
2021	971	**54.00**	84.23	155.98	4.19	23.63
2022	1106	78.19	112.75	177.33	3.36	14.80
2023	876	46.56	70.31	151.01	4.09	23.38
21 de Mayo						
2018	1019	67.17	107.44	159.95	3.98	2.07
2019	1147	51.58	83.87	162.60	5.15	37.52
2020	846	46.58	74.52	159.98	4.66	29.03
2021	1383	**47.89**	85.12	177.74	5.77	49.98
2022	1360	41.24	72.92	176.82	**5.89**	**54.40**
2023	782	41.28	70.63	171.10	4.50	27.05
P. Las Casas II						
2018	1260	92.01	125.91	136.84	3.38	14.97
2019	769	65.97	92.55	140.29	3.28	13.05
2020	928	64.42	88.64	137.60	3.31	14.18
2021	818	**67.66**	91.06	134.58	3.25	12.84
2022	840	65.67	85.61	130.36	3.30	14.57
2023	670	59.66	85.34	143.04	3.08	11.02
Valdivia I						
2018	971	67.05	89.93	134.12	3.58	18.20
2019	1083	51.27	76.33	148.88	4.13	26.54
2020	786	**53.17**	71.80	135.04	3.24	14.50
2021	843	48.08	71.97	149.69	3.72	19.34
2022	742	52.03	72.40	139.15	3.47	16.60
2023	441	39.11	50.70	129.63	3.02	11.67
Osorno						
2018	1284	78.77	114.38	145.21	3.70	19.29
2019	1068	61.77	101.95	165.05	3.78	18.63
2020	904	61.25	95.29	155.58	3.75	18.44
2021	1110	**65.85**	108.14	164.22	4.02	21.27
2022	1272	72.84	115.15	158.09	3.45	15.87
2023	871	52.72	85.28	161.76	3.97	20.75
Coyhaique I						
2018	1437	99.50	148.80	141.51	3.54	16.73
2019	754	70.02	93.14	133.02	3.11	12.78
2020	1132	**72.10**	94.49	131.05	3.49	18.58
2021	1027	64.30	104.86	163.08	4.25	22.97
2022	928	70.35	105.95	150.60	3.43	14.52
2023	869	63.26	84.13	132.99	3.29	16.36

Table 4. Basic statistics for PM_{10}

PM_{10} Year	Maximum $\mu g/m^3$	Average $\mu g/m^3$	St. Dev. $\mu g/m^3$	CV	Skewness $\mu g/m^3$	Kurtosis $\mu g/m^3$
Rancagua 2						
2018	463	69.48	55.05	79.23	2.39	8.23
2019	489	65.10	50.83	78.08	2.63	11.03
2020	397	55.31	39.97	72.27	2.56	11.01
2021	459	**64.57**	48.35	74.88	2.29	8.67
2022	441	57.92	41.99	72.50	2.55	11.48
2023	480	54.99	46.87	85.23	2.74	12.11
La Florida						
2018	862	63.53	77.67	122.26	3.56	18.11
2019	668	60.54	65.11	107.55	3.13	14.56
2020	727	54.95	65.05	118.38	3.26	15.26
2021	758	**65.94**	83.80	127.09	3.22	13.25
2022	500	32.33	59.98	114.62	2.95	11.06
2023	677	53.05	67.03	126.35	3.26	14.93
Puren						
2018	1192	83.58	115.41	138.08	3.69	17.66
2019	1002	73.69	95.14	129.11	3.85	22.16
2020	896	57.28	80.81	141.08	4.37	26.16
2021	972	**62.95**	87.53	139.05	4.10	22.82
2022	799	54.07	75.77	140.13	4.62	29.69
2023	877	57.48	75.33	131.05	3.81	20.34
21 de Mayo						
2018	1124	83.54	120.41	144.13	3.93	19.78
2019	2000	66.28	94.88	143.15	6.18	71.01
2020	908	57.07	82.87	145.21	4.47	25.97
2021	1384	**57.09**	92.10	141.32	5.30	40.80
2022	1394	48.84	78.90	161.55	5.47	45.90
2023	816	54.12	79.75	147.36	4.12	22.75
P. Las Casas II						
2018	1338	104.86	135.92	129.62	3.31	14.10
2019	770	72.19	92.72	128.08	3.25	12.80
2020	929	69.52	89.19	128.29	3.33	14.40
2021	843	**74.47**	97.26	130.60	3.28	12.98
2022	841	69.24	87.26	126.03	3.27	14.18
2023	713	70.73	90.43	127.85	3.01	10.63
Valdivia I						
2018	972	76.96	95.21	123.71	3.45	16.66
2019	1084	57.25	80.06	139.84	3.96	23.73
2020	787	**58.68**	74.00	126.21	3.20	13.76
2021	844	53.02	71.97	135.74	3.72	19.34
2022	743	55.40	72.96	131.70	3.42	15.93
2023	498	47.72	56.26		3.08	12.12
Osorno						
2018	1441	87.30	122.77	140.63	3.63	18.29
2019	1132	76.79	119.17	155.20	3.59	16.16
2020	905	65.30	96.27	147.43	3.79	18.82
2021	1111	**68.89**	108.31	157.22	4.02	21.22
2022	1273	77.34	116.35	150.44	3.50	15.99
2023	776	54.94	80.16	146.40	3.84	19.38
Coyhaique I						
2018	1830	130.05	170.28	130.93	3.54	17.68
2019	769	80.57	95.20	118.16	3.06	12.49
2020	1133	**82.27**	98.66	119.92	3.35	16.93
2021	1028	77.59	112.43	144.90	4.15	21.80
2022	1144	92.12	125.60	136.34	3.45	15.32
2023	1029	76.35	91.11	119.33	3.23	15.55

3. RESULTS AND DISCUSSION

3.1 Descriptive Statistics

Table 3 shows the statistics obtained for $PM_{2.5}$ for all stations studied. The first four moments were: mean, variance, skewness, and kurtosis. Missing data did not exceed 5%, and standard methodology was used for filling missing data [31, 32, 33, 34, 35]. The two types of skewness are right and left. Kurtosis is the weight of the tails in a histogram. Table 4 shows the PM_{10} statistics for all stations studied. Similar to fine particulate matter, the four moments were mean, standard deviation, skewness, and kurtosis. During the COVID-19 pandemic lockdown (2020-2022), Tables 3 and 4 show that the highest average concentrations of $PM_{2.5}$ and PM_{10} were recorded in 2021, followed by 2020, and finally 2022. In two recent articles [36, Fig. 2, p. 12]; [37, Fig. 3], the authors show the concentration of $PM_{2.5}$, among other pollutants, in three different locations: Mongolia, China, and India. These articles show that, between 2020 and 2021, pollution decreased as expected and in accordance with the restrictions suggested by the WHO.

Tables 3 and 4 show the coefficient of variation (CV) between fine and coarse particulate matter. This is defined as:

$$CV = \frac{Standard\ desviation}{Mean} \times 100 \qquad (1)$$

It is observed that this parameter is above 70% in both tables. This means that fine particles are the most abundant respirable particles. This could indicate greater instability in pollution conditions. Furthermore, this high value indicates that the sources of environmental pollution are highly variable and may be located close to the monitoring area. This also indicates a significant share of fine particles at the sampling sites, represented by an average percentage above 50% of total respirable particles at most of the stations studied. Table 4 shows that the pollutant PM_{10} also has high CV values. This situation is worrisome because it poses a high risk to the health of the population, especially children and the elderly. As we saw in the introduction, this area of the country relies heavily on wet firewood for heating and cooking. Thus, high CV values for PM_{10} and $PM_{2.5}$ indicate great variability in the emissions of these particles. This may be due to incomplete combustion that generates large amounts of smoke and particles inefficiently.

3.2 $PM_{2.5}$/PM_{10} Ratios

Tables 5 through 12 show the ratio of fine to coarse particulate matter ($PM_{2.5}/PM_{10}$). The sampling station with the highest $PM_{2.5}/PM_{10}$ ratio was Purén station in 2022 (Table 9). However, all tables show high value for this quotient in each region. This means that fine particles are the most abundant respirable particles. This high ratio may be due to the strong influence of wet firewood burning at these sampling sites. Additionally, the highest values for each monitoring station are indicated in bold in each table. Episodes of high pollution can be unpredictable, posing a risk to the health of residents in the cities under study.

Table 5. Basic statistics for $PM_{2.5}$ and PM_{10}: O'Higgins Region[a].

Monitoring Station Years	$PM_{2.5}$ Average µg/m^3	PM_{10} Average µg/m^3	$PM_{2.5}/PM_{10}$
Rancagua 1			
2018	36.29	70.72	0.513
2019	41.02	**75.11**	0.546
2020	35.13	66.32	0.530
2021	**42.24**	66.59	0.634
2022	39.43	67.12	0.587
2023	35.76	73.73	0.485
T. A. Ave.	38.31	69.93	0.550
Rancagua 2			
2018	**46.64**	**69.48**	0.671
2019	44.12	65.10	0.678
2020	39.44	55.31	0.713
2021	43.49	64.57	0.674
2022	46.39	57.92	0.800
2023	34.37	54.99	0.625
T. A. Ave.	42.41	61.23	0.690
San Fernando			
2018	28.34	52.54	0.539
2019	34.93	**59.80**	0.584
2020	32.11	50.94	0.630
2021	**39.37**	53.56	0.735
2022	37.86	50.72	0.746
2023	35.02	49.27	0.711
T. A. Ave.	34.61	52.81	0.660

Higher averages are shown in bold. [a] The total data number for this region is 66,096.

T. A. Ave.: Total annual average

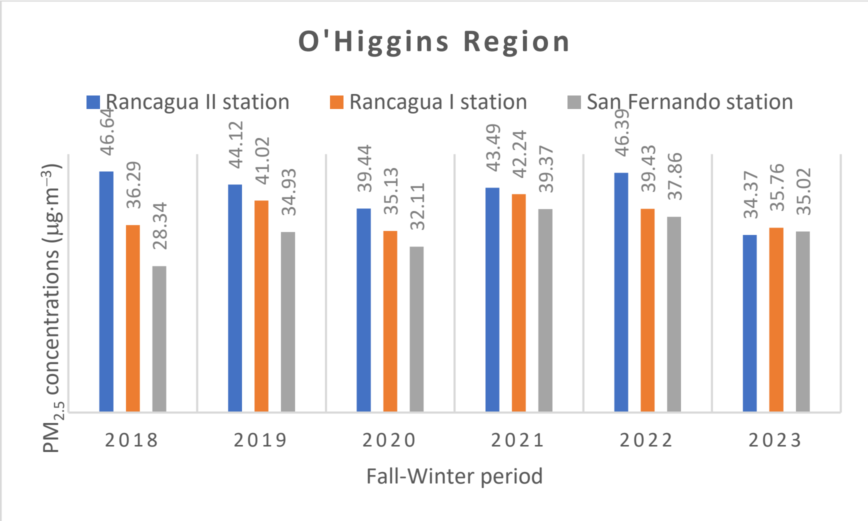

Figure 4: Fall-winter variation of $PM_{2.5}$ concentration from 2018–2023, O'Higgins region.

Source: own elaboration.

Figures 4 through 11 show the variation in $PM_{2.5}$ concentrations at the monitoring stations in each region under study. The period corresponds to the fall-winter period from 2018 to 2023. For the O'Higgins region, the station with the highest pollution was Rancagua II, in all study years except 2023. At the Maule region, the station with the highest pollution was La Florida, in all study years. From the Bío Bío region, the station with the highest pollution was 21 de Mayo, in all study years. In the Araucanía region, the station with the highest pollution was Padre Las Casas II, in all study years. In the Aysen region, the station with the highest pollution was Coyhaique II, in all study years. Finally, the Ñuble, Los Ríos, and Los Lagos regions had only one monitoring station. However, their values showed high levels of pollution throughout the study period.

Table 6. Basic statistics for $PM_{2.5}$ and PM_{10}: Maule Region[a].

Monitoring Station Years	$PM_{2.5}$ Average µg/m^3	PM_{10} Average µg/m^3	$PM_{2.5}/PM_{10}$
La Florida			
2018	**55.93**	63.53	0.880
2019	43.84	60.54	0.724
2020	48.05	54.95	0.874
2021	55.06	**65.94**	0.835
2022	43.44	52.33	0.830
2023	41.71	53.05	0.786
T. A. Ave.	48.41	58.39	0.820
U. Talca			
2018	**32.36**	46.**77**	0.692
2019	28.54	48.67	0.586
2020	25.95	38.55	0.673
2021	29.72	**51.21**	0.580
2022	24.86	45.73	0.544
2023	23.95	42.42	0.565
T. A. Ave.	27.56	45.56	0.610
U. C. Maule			
2018	**35.24**	45.35	0.777
2019	31.08	**48.16**	0.645
2020	27.62	40.06	0.689
2021	33.52	47.55	0.705
2022	26.38	34.58	0.763
2023	23.91	43.26	0.553
T. A. Ave.	29.63	43.16	0.690

Higher averages are shown in bold. [a] The total data number for this region is 66,096.

T. A. Ave.: Total annual average

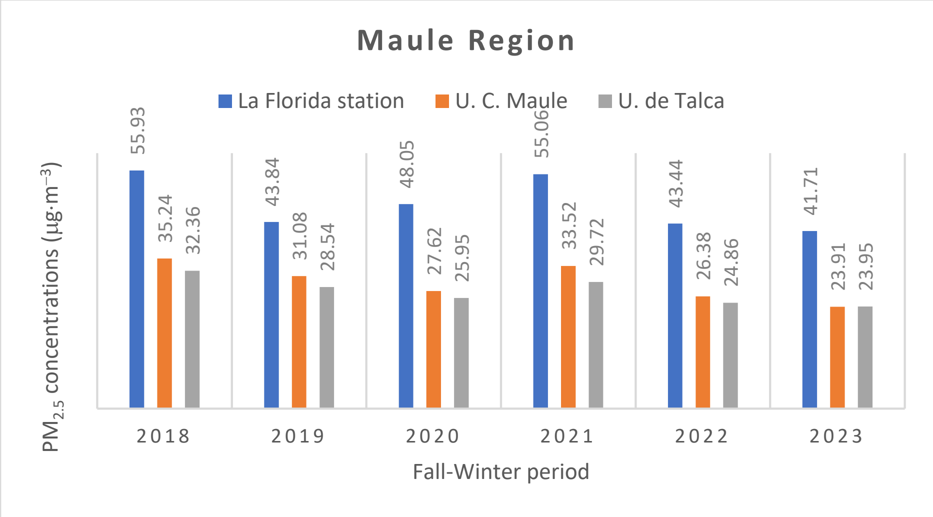

Figure 5: Fall-winter variation of $PM_{2.5}$ concentration from 2018–2023, Maule region.

Source: own elaboration.

Table 7. Basic statistics for $PM_{2.5}$ and PM_{10}: Bio Bio Region[a].

Monitoring Station Years	$PM_{2.5}$ Average μg/m³	PM_{10} Average μg/m³	$PM_{2.5}/PM_{10}$
San Vicente			
2018	**38.76**	**68.95**	0.562
2019	32.50	55.86	0.582
2020	31.61	51.36	0.615
2021	34.79	54.42	0.639
2022	29.34	47.78	0.614
2023	30.11	49.02	0.614
T. A. Ave.	32.85	54.57	0.600
21 de Mayo			
2018	**67.17**	**83.54**	0.804
2019	51.58	66.28	0.778
2020	46.58	57.07	0.816
2021	47.89	57.09	0.839
2022	41.24	48.84	0.844
2023	41.28	54.12	0.763
T. A. Ave.	49.29	61.16	0.810
K. College			
2018	**36.27**	**36.31**	0.999
2019	28.90	28.82	1.003
2020	26.73	26.71	1.001
2021	31.55	31.61	0.998
2022	27.74	27.56	1.007
2023	25.95	25.95	1.000
T. A. Ave.	29.52	29.49	1.000

Higher averages are shown in bold. [a] The total data number for this region is 66,096.

T. A. Ave.: Total annual average

It is suggested that a more thorough study be conducted of other sources of pollution besides wet firewood. For example, mobile sources.

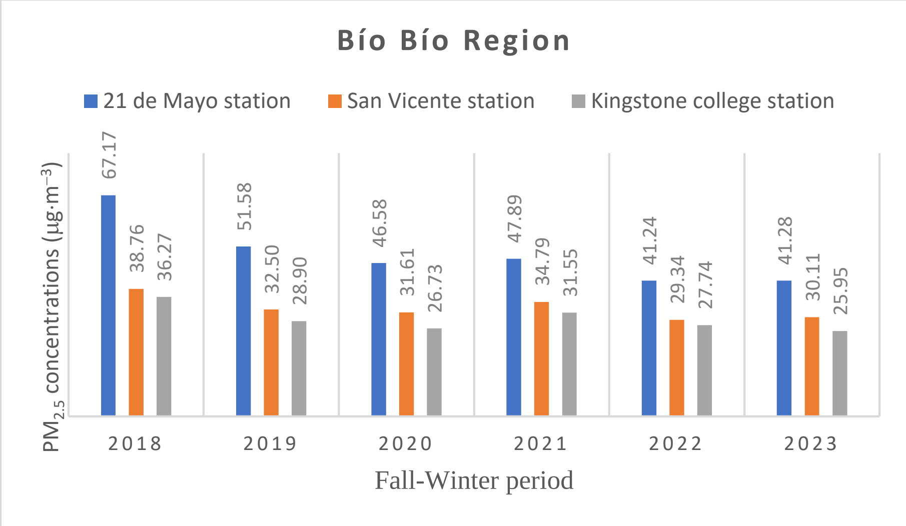

Figure 6: Fall-winter variation of $PM_{2.5}$ concentration from 2018–2023, Bio Bio region.

Source: own elaboration.

Table 8. Basic statistics for $PM_{2.5}$ and PM_{10}: La Araucanía Region[a].

Monitoring Station Years	$PM_{2.5}$ Average µg/m^3	PM_{10} Average µg/m^3	$PM_{2.5}/PM_{10}$
P. Las Casas II			
2018	**92.01**	**104.86**	0.877
2019	65.97	72.39	0.911
2020	64.42	69.52	0.927
2021	67.66	74.47	0.909
2022	65.67	69.24	0.948
2023	59.66	70.73	0.843
T. A. Ave.	69.23	76.87	0.900
Las Encinas			
2018	**63.67**	**74.55**	0.854
2019	38.41	51.96	0.739
2020	43.33	48.71	0.890
2021	47.54	55.44	0.858
2022	43.97	50.88	0.864
2023	34.15	48.49	0.704
T. A. Ave.	45.18	55.01	0.820

Higher averages are shown in bold. [a] The total data number for this region is 44,064.

T. A. Ave.: Total annual average

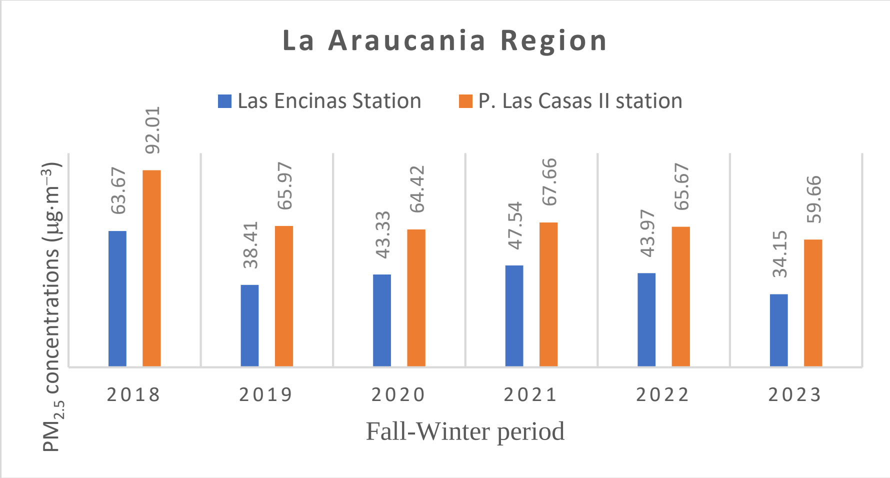

Figure 7: Fall-winter variation of $PM_{2.5}$ concentration from 2018–2023, La Araucanía region.

Source: own elaboration.

Table 9. Summary Statistics: Monitoring Station at Ñuble Region[a].

Monitoring Station Years	$PM_{2.5}$ Average µg/m^3	PM_{10} Average µg/m^3	$PM_{2.5}/PM_{10}$
Purén			
2018	72.53	**83.58**	0.868
2019	57.96	73.69	0.787
2020	48.19	57.28	0.841
2021	54.00	62.95	0.858
2022	**78.19**	69.24	**1.446**
2023	46.56	57.48	0.810
T. A. Ave.	59.57	64.84	0.930

Higher averages are shown in bold. [a] The total data number for this region is 22,032.

T. A. Ave.: Total annual average

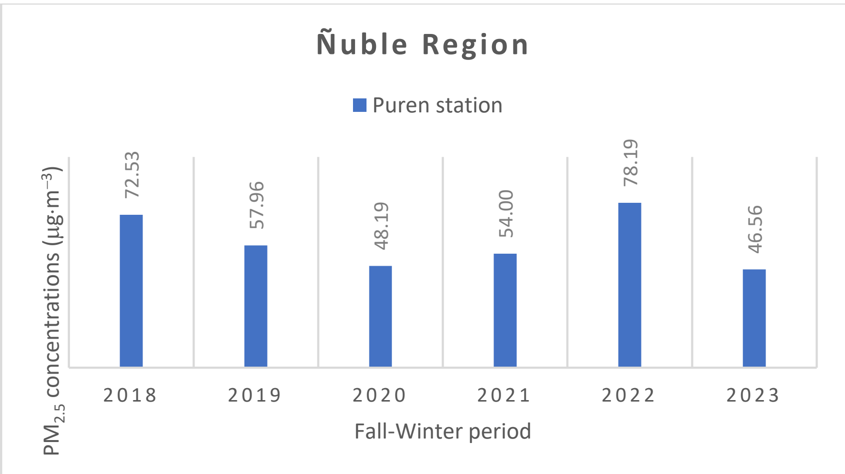

Figure 8: Fall-winter variation of $PM_{2.5}$ concentration from 2018–2023, Ñuble region.

Source: own elaboration.

Table 10. Basic statistics for $PM_{2.5}$ and PM_{10}: Los Ríos Region[a].

Monitoring Station Years	$PM_{2.5}$ Average µg/m^3	PM_{10} Average µg/m^3	$PM_{2.5}/PM_{10}$
Valdivia I			
2018	**67.05**	**76.96**	0.871
2019	51.27	57.25	0.896
2020	53.17	58.68	0.906
2021	48.08	53.02	0.907
2022	52.03	55.40	0.939
2023	39.11	47.72	0.820
T. A. Ave.	51.79	58.17	0.890

Higher averages are shown in bold. [a] The total data number for this region is 22,032.

T. A. Ave.: Total annual average

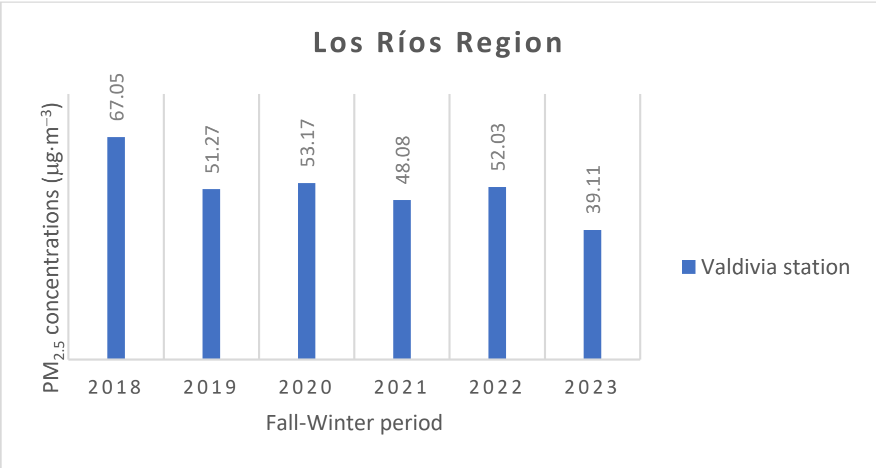

Figure 9: Fall-winter variation of $PM_{2.5}$ concentration from 2018–2023, Los Ríos region.

Source: own elaboration.

Table 11. Basic statistics for $PM_{2.5}$ and PM_{10}: Los Lagos Region[a].

Monitoring Station Years	$PM_{2.5}$ Average µg/m^3	PM_{10} Average µg/m^3	$PM_{2.5}/PM_{10}$
Osorno			
2018	**78.77**	**87.30**	0.871
2019	61.77	76.79	0.896
2020	61.25	65.30	0.906
2021	65.85	68.89	0.907
2022	72.84	77.34	0.939
2023	52.72	54.94	0.820
T. A. Ave.	65.53	71.76	0.890

Higher averages are shown in bold. [a] The total data number for this region is 22,032.

T. A. Ave.: Total annual average

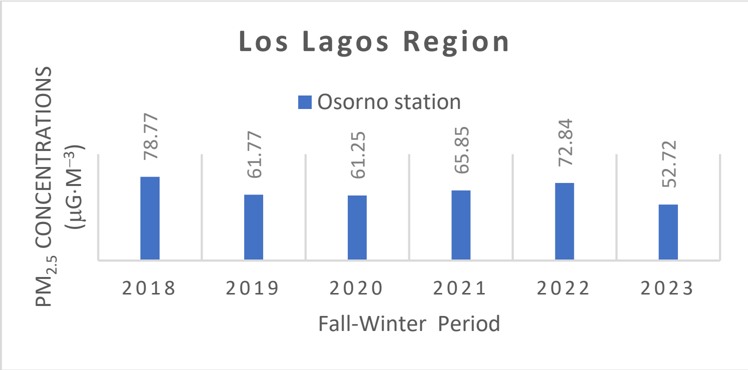

Figure 10: Fall-winter variation of $PM_{2.5}$ concentration from 2018–2023, Los Lagos region.

Source: own elaboration.

Table 12. Basic statistics for $PM_{2.5}$ and PM_{10}: Aysen Region[a].

Monitoring Station Years	$PM_{2.5}$ Average µg/m^3	PM_{10} Average µg/m^3	$PM_{2.5}/PM_{10}$
Coyhaique I			
2018	**99.50**	**130.05**	0.765
2019	70.02	80.57	0.869
2020	72.10	82.27	0.876
2021	64.30	77.59	0.829
2022	70.35	92.12	0.764
2023	63.26	76.35	0.829
T. A. Ave.	73.26	89.83	0.822
Coyhaique II			
2018	**92.43**	**105.19**	0.879
2019	70.42	81.58	0.863
2020	72.36	81.44	0.885
2021	68.99	74.54	0.926
2022	78.04	81.71	0.955
2023	69.33	75.04	0.924
T. A. Ave.	75.26	83.25	0.904

Higher averages are shown in bold. [a] The total data number for this region is 44,064.

T. A. Ave.: Total annual average

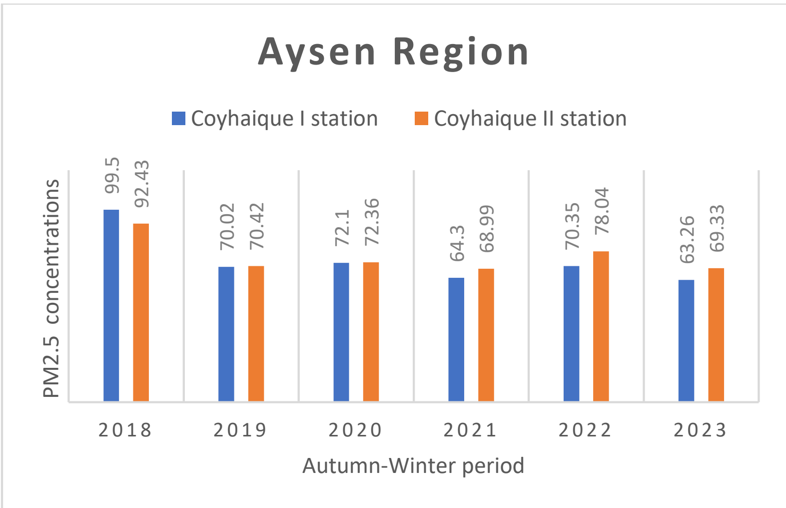

Figure 11: Fall-winter variation of $PM_{2.5}$ concentration from 2018–2023, Aysen region.

Source: own elaboration.

4. CONCLUSIONS

More than 90% of residents in medium-sized cities in Central and Southern Chile were exposed to fine and coarse particulate matter throughout the study period (Southern hemispheric Fall and Winter), exceeding Chilean and international standards. Despite ongoing overall improvements in air quality, current Chilean standards are far from being met in the South-Central region of the country, especially during fall and winter. During the COVID-19 pandemic, particulate matter pollution levels did not decrease significantly compared to other regions of the world during the same period. On the contrary, an increase in particulate emissions was observed. The most likely cause was the intensive use of very damp firewood for heating and cooking.

5. ACKNOWLEDGMENT

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