Improvement of Air Quality during the COVID-19 Lockdowns in the Republic of Slovenia and its Connection with Meteorology

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ABSTRACT

Due to COVID-19 countermeasures, air quality temporarily improved in several countries around the world, especially in urban areas. This study investigates predominantly the changes in concentration levels of air pollutants (PM₁₀ and PM₂.₅) in the Republic of Slovenia during the year 2020, which was marked by COVID-19 lockdowns. In this study, the data for the year 2020 were divided into four periods, i.e., the period before COVID-19 (1 January–11 March 2020), the first lockdown (12 March–31 May 2020), after the first lockdown (1 June–17 October 2020), and the second lockdown (18 October–31 December 2020). The data were obtained from 25 ground-based nationwide stations, subdivided further by traffic and background sites. For comparison, data from 2018 and 2019 were evaluated as well. Our findings indicate that COVID-19 restrictions had a moderate and indirect impact on PM₁₀ and PM₂.₅ concentrations, which were more evident at PM₁₀ monitoring sites near traffic locations. The results were additionally supported by providing t- and F- statistical tests. The impact of meteorological conditions (wind speed, temperature, relative humidity, and precipitation) on the concentration levels was also studied. The results show that, the most significant decrease of PM concentration in 2020 compared to 2018 and 2019 was found in the period after the first lockdown, while precipitation was not significantly different between the years during this time.

Keywords: COVID-19 pandemic, Air pollution, PM₂.₅, PM₁₀, Meteorology

1 INTRODUCTION

At the end of 2019, an unexpected outbreak of the new coronavirus disease (COVID-19) caused by the virus SARS-CoV-2 spread rapidly around the world, affecting almost all countries. Measures set by the governments across Europe and the rest of the world, such as locking down cities, limiting public life and activities, and even international travel restrictions, led to having a strong impact on human health, the economy, and sociability (WHO, 2021a). It has been confirmed by several researchers (Travaglio et al., 2021; Yumin et al., 2021; Zhang et al., 2021; Zhao et al., 2021) that the above mentioned restrictions and self-quarantine measures during the pandemic led to a remarkable change in the climate and environment, with reduced air pollution as one of the most dramatic impacts.

Air pollution is defined as contamination of the indoor or outdoor environment by any chemical, physical, or biological agent that modifies the natural characteristics of the atmosphere (WHO, 2021b).
In the last decade, it became the second biggest environmental concern after climate change, particularly in urban areas (European Commission, 2012). According to the World Health Organization (WHO), 7 million people die annually because of air pollution, of which roughly 4.9 million deaths are caused by outdoor ambient air (WHO, 2021b). Today, the main sources of air pollution in urban areas are still traffic (combustion from vehicles), thermal power plants, domestic heating stoves, and agricultural facilities (Nadzir et al., 2020). Several studies already showed that air pollutants, such as sulphur dioxide (SO2), nitrogen oxides (NOx/NO2), particulate matter (PM10, PM2.5—particles with aerodynamic diameters < 2.5 µm and 10 µm, respectively), ozone (O3), and volatile organic compounds (VOC), truly present a major global threat to public health, climate, and even cultural heritage (EEA, 2021a; Ethan et al., 2022; Kuhn et al., 2021; Morawska et al., 2021; Ozkurt et al., 2013; WHO, 2021b; Zhao et al., 2019). Lately, special attention has been paid to particulate matter (PM) concentrations in outdoor and indoor environments, since it has been reported by the European Environmental Agency (EEA) that, from the epidemiological point of the view, PM has the most negative impact on human health. In the vast majority of particles, the main compounds are organics, metals, sulphates, nitrates, allergens and dust (Samae et al., 2022). They usually arise from anthropogenic sources, such as road traffic, fuel combustion, wood burning, and industrial discharges, or exist due to natural reasons such as dust storms, forest fires, or volcanoes (Otmani et al., 2020; Ryu et al., 2018).

Many studies that have been published recently are proving that air quality improved during COVID-19 lockdowns in cities, regions, or countries, as a result of the decrease in local transportation, aviation and international shipping (Lipsitt et al., 2021; Wu et al., 2021), and the decline in industrial processes (Albayati et al., 2021; Tian et al., 2021), although the improved air quality has been due to meteorology in some cases (Ismail et al., 2022; Sangkhram et al., 2021). In particular, it was confirmed that NO2 concentrations were reduced up to 60% in some cities, across cities, and/or countries, independent of meteorological conditions, as a result of reduced road transportation, while PM2.5 concentrations reached up to 30% of reduction in certain countries, also independent of meteorological conditions (EEA, 2020). To get further insights, Pandey et al. (2021) studied the impact of the lockdown and unlocked periods on ambient air quality of Delhi, the capital city of India. Their results revealed that the concentration of criteria pollutant gases and particulate matter (PM10, PM2.5) during the lockdown period (March–May 2020) declined nearly up to 50% for the gases and coarser PM, and up to 30% for finer PM, compared with the preceding year’s data from the same timeframe. Cucciniello et al. (2022) studied the concentrations of CO, O3, PM10, PM2.5, C6H6 (benzene), and NO2 during quarantine and lockdown measures in Avellino, which is an Italian city known to have some of the worst air pollution in the country. Results showed a significant reduction of traffic-based pollutants (benzene, CO, and NO2), whereas a minor impact was detected on PM atmospheric concentrations. Song et al. (2021) investigated the cause of the unanticipated haze pollution in China during the lockdown period, including meteorological conditions. Using a decomposition method, it was found that the meteorology (e.g., drastically elevated humidity levels, and weakened airflow) increased PM2.5 concentrations substantially in northern China; the most substantial increases were in the Beijing-Tianjin-Hebei region (e.g., by 26.79 µg m–3 in Beijing). Overall, Sokhi et al. (2021) and Adam et al. (2021) wrote a critical review on the changes in air quality during the COVID-19 outbreak in several cities around the world. Results showed that a reduction in primary air pollutants was observed in most cities during lockdowns, whereas secondary PM and O3 increased in some cities under favourable weather conditions.

In the Republic of Slovenia (RS), one of the smallest countries in the European Union (EU), the first official case of COVID-19 was confirmed on 4 March 2020. The first national lockdown was proclaimed on 12 March 2020. To prevent it from spreading quickly, the Slovenian government imposed strict measures and control policies to preserve the health and safety for Slovenian citizens, such as closing public institutions, working and schooling from home, cancelling all events with more than 500 people, suspending the provision of non-essential preventive health services in healthcare institutions, and, finally, shutting down public transportation and travel in and out of the country. However, some industrial and commercial activities remained open (i.e., the selling of essential or medical supplies). The Slovenian government decided to extend this state of emergency until 31 May 2020 (GOV.SI, 2020). During these 12 weeks of social distancing, 1,473 (0.07% of the Slovenian population) COVID-19 cases were confirmed (out of the whole...
population), of which 113 (7.67%) people died (NIJZ, 2021). Compared to other EU countries, such as Italy or Spain (Ceylan, 2020), the RS was among the EU countries in this period with zero, or a minimum number, of newly detected infections, leading to the government withdrawing the declaration of a pandemic at the end of May 2020. During the summertime, not a single new infection was detected for several days in a row, but, at the beginning of autumn 2020, the number of daily active cases started to increase again. The second pandemic wave was proclaimed on 18 October 2020. During the period, most restrictions on public life were implemented again, while new measures were put in place, such as the mandatory wearing of protective masks indoors and outdoors, and no public life between 21:00 and 5:00. On 6 October, a daily record of 300 infected people was confirmed (Bre et al., 2020).

According to the latest study by the EEA, the RS has been facing excessive air pollution in the last decade (EEA, 2021b). There have been alarmingly high levels of particulate matter (PM$_{10}$, PM$_{2.5}$) in the air, especially during the wintertime (NIJZ, 2018), as a result of the extensive use of residential and commercial biomass burning, coal-burning for energy generation, industrial emissions, waste burning, construction activities, transport vehicles and diesel generators (NIJZ, 2018). Moreover, as stated in the study from EEA, the data showed that Ljubljana, the Slovenian capital city, is plagued by poor air quality, whereas the situation is a bit better in Slovenia’s second largest city, Maribor. Nevertheless, Ljubljana and Maribor are approximately at the centre of the air quality distribution for EEA cities.

The current study presents the changes in PM$_{10}$ and PM$_{2.5}$ concentrations as a result of the measures set during the first and second wave of COVID-19 lockdowns in the RS, using data from nationwide and private monitoring stations. The analysis covers 2020 periods from before lockdown (1 January–11 March), during the first lockdown (12 March 2020–31 May), after first lockdown (1 June–17 October), and during the second lockdown (18 October–31 December). The obtained results were then compared to those from the same periods in 2018 and 2019 to better understand the changes in air pollution during the lockdowns. Besides, the study investigates the impacts of meteorological parameters (temperature, relative humidity, wind, precipitation) on the obtained concentration levels of PM. The results of the study provide useful information on the national air quality impact during COVID-19 lockdowns in contrast to pre-COVID-19 times.

### 2 MATERIALS AND METHODS

#### 2.1 Study Area

The RS (46.15°N and 46.08°E, average 492 m above mean sea level) is one of the smallest European countries situated in Central Europe (Fig. 1), with a total area of 20,271 sq. km, and a population of 2.1 million people. It is mainly a mountainous and forested country, with forests covering around 61.5% of the area. The climate is influenced by the variety of relief—the northeast experiences a continental climate with a stark difference in winter and summer temperatures; in the coastal region, there is a sub-Mediterranean climate; while a severe Alpine climate is present in the high mountain regions. Precipitation, often coming from the Gulf of Genoa, varies across the country as well, with over 3,500 mm in some western regions and dropping down to 800 mm in Prekmurje. Compared to Western Europe, RS is not very windy, due to its location in the slipstream of the Alps. The average wind speeds are lower than in the plains of the nearby countries. Generally, northeast wind, southeast wind, and a north wind are common in the country.

Systematic measurements of the concentrations of outdoor air pollutants at permanent measuring points in the RS began in the mid-1970s (Gjerek et al., 2018). Today, the national measuring network consists of 20 measuring points (ground-based nationwide monitoring stations) with an additional 5 locations owned by industrial companies or municipalities. This study examined 25 particulate measuring points from 13 different municipalities in 8 different regions, divided by area type (urban, suburban, rural) and furthermore by measurement type (traffic, background, industrial location), to obtain representative results. Fig. 1 shows a map of all the examined ground-based nationwide monitoring stations (marked from I to XXV). The ID, altitude, coordinates data, measurement type, area and characteristics of the area are added in the Supplementary material (Table S1), together with the explanation of the measurement and area type of locations. In addition to air quality measurements, meteorological parameters are measured at the specific locations.
2.2 Data Collection

Air quality monitoring systems use measuring instruments that comply with the Slovenian reference measurement methods. The method of monitoring and supervision is prescribed in the following regulations: *Decree on ambient air quality* ([Official Gazette of the Republic of Slovenia Nos. 9/11, 8/15 and 66/18; OGRS, 2011a]) and the *Rules on the assessment of ambient air quality* ([Official Gazette of the Republic of Slovenia, Nos. 55/11, 6/15, and 5/17; OGRS, 2011b]).

The data used in this work were provided by the Milan Vidmar Electric Power Research Institute (EIMV) and the Slovenian Environment Agency (ARSO), and are available on open access to the public. The PM10 data were collected at 24 of the ground-based monitoring stations, while PM2.5 was collected at 5 of the ground-based monitoring stations (Table S1). PM measurements were performed according to the standard gravimetric method SIST EN 12341: 2014, thus yielding daily 24-h PM10 and PM2.5 concentrations ([CEN, 2014]).

Measurements of wind direction and speed were performed with an ultrasonic anemometer (Vaisala Weather Transmitter WXT520). The anemometer measures the values of the 3D wind speed vector. The vector is determined on the basis of measuring the time of sound flight on three appropriately placed paths. In this way, the system combines the measurement of wind speed and direction without rotating the sensors mechanically. Measurements of air temperature were performed with a resistance thermometer (Thermometer TM RS232). Relative humidity measurement was performed with a capacitive encoder, which, with the help of an electronic circuit line, raises and amplifies the changes in humidity in the air, and converts them into a suitable analogue electrical output signal (Vaisala Weather Transmitter WXT520). Precipitation measurement was performed with a rain logger (RainWise Inc.).

2.3 Statistical Analysis

The change in the PM10 and PM2.5 concentrations was assessed for the year 2020 and then compared to the pre-COVID years, 2018 and 2019. The daily concentrations of PM10 and PM2.5 (µg m⁻³) in 2020 were analyzed within one of the following time bins: before lockdown, during the first lockdown, after the first lockdown, or during the second lockdown. The lockdown periods in the RS were from 12 March to 31 May 2020, and from 18 October to 31 December 2020 ([GOV.SI, 2020]). PM10 data were then divided into locations, and sorted by measurement types at background and traffic locations. Of the locations, 13 are categorised as background locations and 7 categorised as traffic locations (Table S1). The concentrations of PM2.5 were measured at 5 locations which were not additionally divided. The percentage change in the concentrations of PM pollutants was calculated by the following equation ([Pandey et al., 2021] (Eq. (1))):
Percentage change in concentration = \( \left( \frac{y_{2020} - y_x}{y_x} \times 100 \right) \)  
\( (1) \)

where \( y_{2020} \) represent the mean concentrations of PM10 or PM2.5 in 2020, and \( y_x \) represents the mean concentrations of pollutants in the previous year. It must be mentioned that in the period from 27 March 2020 to 29 March 2020 an episode of desert dust appeared across RS. Due to the very large amount of desert dust, the quantitative contribution could not be determined and since it was evident that the particles are of natural origin these data were not taken into account when determining compliance with air quality standards. The average daily (with Standard Deviation), minimum and maximum values were calculated for each data analysis. Additionally, t-test and F-test analyses were used to compare data between different years.

The meteorological data (temperature, relative humidity, precipitation, wind speed and direction) were obtained for the same periods as the concentration data. The data were described with average daily (with Standard Deviation), minimum and maximum values. The precipitation percentage was analysed based on Eq. (1).

### 3 RESULTS AND DISCUSSION

#### 3.1 Air Quality Changes during COVID-19 Lockdowns

##### 3.1.1 Particulate matter—PM\(_{10}\)

The average daily PM\(_{10}\) concentrations, presented as annual distributions (2018, 2019, and 2020) for each station type are presented in the Fig. 2. Additionally, Supplementary data (Fig. S1) contains the average daily PM\(_{10}\) concentrations, presented as annual distributions (2018, 2019, and 2020) for each individual measurement location (from I–XXIV). The yearly median value in COVID-19 year 2020 was found to be 18 \( \mu g m^{-3} \), whereas in the years 2018 and 2019, it was 22 \( \mu g m^{-3} \) and 19 \( \mu g m^{-3} \), respectively.

Table 1 presents the daily average, minimum and maximum values, and the range before and during the first and second COVID-19 lockdowns in the RS for PM\(_{10}\) concentrations across all measured ground-based monitoring stations. From the table it can be stated that, in the period before the first lockdown, the average value of concentrations was the highest of all study periods.

![Fig. 2. Distribution of daily average PM\(_{10}\) concentrations during 2018, 2019 and 2020 based on the station types.](image)
The average daily value with Standard Deviation (SD), minimum and maximum values, and the range before, after, and during the first and second COVID-19 lockdowns in 2018, 2019, and 2020, across all 24 measurement locations of PM₁₀.

### Table 1

**a) Traffic location**

<table>
<thead>
<tr>
<th>Year</th>
<th>Average daily value with SD</th>
<th>Range</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>32.30 ± 16.09</td>
<td>21.49 ± 8.23</td>
<td>0.00</td>
<td>113.00</td>
</tr>
<tr>
<td>2019</td>
<td>33.25 ± 16.45</td>
<td>18.64 ± 9.61</td>
<td>2.41</td>
<td>149.8</td>
</tr>
<tr>
<td>2020</td>
<td>30.43 ± 17.77</td>
<td>17.26 ± 8.00</td>
<td>1.81</td>
<td>118.16</td>
</tr>
</tbody>
</table>

**b) Background location**

<table>
<thead>
<tr>
<th>Year</th>
<th>Average daily value with SD</th>
<th>Range</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>29.88 ± 3.20</td>
<td>19.89 ± 1.19</td>
<td>0.00</td>
<td>103.00</td>
</tr>
<tr>
<td>2019</td>
<td>30.70 ± 4.24</td>
<td>17.31 ± 2.23</td>
<td>2.41</td>
<td>110.59</td>
</tr>
<tr>
<td>2020</td>
<td>27.99 ± 2.37</td>
<td>15.84 ± 2.27</td>
<td>4.88</td>
<td>49.12</td>
</tr>
</tbody>
</table>

**c) Industrial location**

<table>
<thead>
<tr>
<th>Year</th>
<th>Average daily value with SD</th>
<th>Range</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>27.81 ± 0.15</td>
<td>20.79 ± 0.33</td>
<td>6.62</td>
<td>81.00</td>
</tr>
<tr>
<td>2019</td>
<td>25.58 ± 1.18</td>
<td>17.31 ± 1.40</td>
<td>4.66</td>
<td>50.35</td>
</tr>
<tr>
<td>2020</td>
<td>38.22 ± 3.48</td>
<td>19.27 ± 0.04</td>
<td>6.00</td>
<td>119.97</td>
</tr>
</tbody>
</table>

in each year, which is characteristic of the typical seasonal trend in the particle pollution. Looking at years 2018–2020, throughout the all 24 measurement sites, the quantities of concentrations were the lowest in 2020 by 8% before the first lockdown, by 20% in the first lockdown, by 25% after the first lockdown and by 23% in the second lockdown.

As already stated, the PM₁₀ monitoring stations were divided according to station type into background and traffic locations. The background locations in Figs. 3 and 4 show that, before the first lockdown in 2020, the concentrations of PM₁₀ were lower compared to 2018; at 4 locations (XX, X, IX, and VIII) by more than 5 µg m⁻³ (–20%, –23%, –31%, –20%, respectively), whereas at 2 locations they were lower by less than 5 µg m⁻³ (locations XV (–3%) and VI (–0.4%)). Comparing years 2019 and 2020, a difference of more than 5 µg m⁻³ was recorded at only one background location (XX (–27%)), while at the other locations, this difference was negligible. The meteorological data will be explained further in Section 3.2.
Fig. 3. The plots depict the period PM$_{10}$ average difference for 2020 compared to 2018 and 2019 at 13 background stations.

<table>
<thead>
<tr>
<th>Background Measurement Locations – PM$_{10}$</th>
<th>I.</th>
<th>II.</th>
<th>VI.</th>
<th>VII.</th>
<th>VIII.</th>
<th>IX.</th>
<th>X.</th>
<th>XIII.</th>
<th>XIV.</th>
<th>XV.</th>
<th>XVI.</th>
<th>XX.</th>
<th>XXIV.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Difference 2020 - 2019</td>
<td>-0.5%</td>
<td>0.1%</td>
<td>-10%</td>
<td>-3%</td>
<td>-16%</td>
<td>-10%</td>
<td>-4%</td>
<td>-5%</td>
<td>-15%</td>
<td>-12%</td>
<td>25%</td>
<td>-27%</td>
<td>-13%</td>
</tr>
<tr>
<td>Difference 2020 - 2018</td>
<td>5%</td>
<td>9%</td>
<td>-0.4%</td>
<td>0.5%</td>
<td>-20%</td>
<td>-31%</td>
<td>-23%</td>
<td>4%</td>
<td>16%</td>
<td>-3%</td>
<td>25%</td>
<td>-20%</td>
<td>8%</td>
</tr>
<tr>
<td>During I. Difference 2020 - 2019</td>
<td>6%</td>
<td>4%</td>
<td>0%</td>
<td>-20%</td>
<td>-12%</td>
<td>-5%</td>
<td>-5%</td>
<td>-47%</td>
<td>-1%</td>
<td>-2%</td>
<td>13%</td>
<td>-32%</td>
<td>13%</td>
</tr>
<tr>
<td>Difference 2020 - 2018</td>
<td>-23%</td>
<td>-11%</td>
<td>-12%</td>
<td>-18%</td>
<td>-41%</td>
<td>-30%</td>
<td>-17%</td>
<td>-46%</td>
<td>-15%</td>
<td>-24%</td>
<td>-5%</td>
<td>26%</td>
<td>7%</td>
</tr>
<tr>
<td>After Difference 2020 - 2019</td>
<td>-3%</td>
<td>-10%</td>
<td>-18%</td>
<td>-23%</td>
<td>-21%</td>
<td>-22%</td>
<td>-15%</td>
<td>-53%</td>
<td>-20%</td>
<td>-13%</td>
<td>-20%</td>
<td>-12%</td>
<td>1%</td>
</tr>
<tr>
<td>Difference 2020 - 2018</td>
<td>-44%</td>
<td>-33%</td>
<td>-30%</td>
<td>-51%</td>
<td>-46%</td>
<td>-20%</td>
<td>-32%</td>
<td>-58%</td>
<td>-21%</td>
<td>-35%</td>
<td>-22%</td>
<td>-40%</td>
<td>13%</td>
</tr>
<tr>
<td>During II. Difference 2020 - 2019</td>
<td>5%</td>
<td>4%</td>
<td>4%</td>
<td>-2%</td>
<td>-5%</td>
<td>15%</td>
<td>-2%</td>
<td>-6%</td>
<td>10%</td>
<td>13%</td>
<td>23%</td>
<td>13%</td>
<td>-0.2%</td>
</tr>
<tr>
<td>Difference 2020 - 2018</td>
<td>-38%</td>
<td>-27%</td>
<td>-27%</td>
<td>-54%</td>
<td>-48%</td>
<td>-12%</td>
<td>-48%</td>
<td>-44%</td>
<td>-28%</td>
<td>7%</td>
<td>-55%</td>
<td>-19%</td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- Difference more than 20%  
- Difference from 0 to 20%  
- Difference from -0 to -20%  
- Difference more than -20%  

Fig. 4. Percent change in PM$_{10}$ concentrations at background stations in 2020.
Table 2. t-test and F-test analysis of PM$_{10}$ concentrations between years at background stations.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>71</td>
<td>0.41</td>
<td>0.97</td>
<td>0.25</td>
</tr>
<tr>
<td>During I</td>
<td>78</td>
<td>0.22</td>
<td>&lt; 0.05</td>
<td>0.21</td>
</tr>
<tr>
<td>After</td>
<td>139</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>During II</td>
<td>75</td>
<td>0.65</td>
<td>&lt; 0.05</td>
<td>0.27</td>
</tr>
</tbody>
</table>

In the second lockdown period in 2020, a decrease in PM$_{10}$ concentrations was detected at almost all locations compared to the same period in 2018, except on the location XVI, where concentration was higher by 7%. Comparing years 2018 and 2020, the highest decrease in concentrations was detected in locations (XX (–55%), XIII (–44%), X (–48%), VIII (–48%), and VII (–54%), whereas comparing years 2019 and 2020, the concentrations were slightly lower in year 2020 at locations XIII (–6%), X (–2%), VIII (–5%), and VII (–2%). In this period, the highest amount of precipitation was in year 2019.

In sum, during the four study periods, the largest difference was during the second lockdown between year 2020 and 2018, while negative trends were recognised in almost all locations after the first lockdown compared year 2020 by year 2018 or 2019. The first lockdown also showed more negative trends compared to before COVID-19 time.

The comparison of average concentrations, measured at all background sites, between the different periods (Table 2) showed that before the first lockdown, there were not significant differences in central values (t-test) or variances between the years (F-test). Then during lockdowns and in between, there were significant differences in the central values when comparing to 2018. Significant differences to those periods in 2019 were only apparent in the after first lockdown period. Throughout the year 2019 only the significant differences in central values (t-test) were recognized in the after lockdown period.

Before lockdown period the PM$_{10}$ concentrations at traffic locations (Figs. 5 and 6) were higher in 2020 compared to 2019 at 2 locations (XVII (3%) and IV (2%)), and at 5 locations (XXI (6%), XVIII (1%), XVII (14%), V (1%), and III (14%)) when compared to 2018. During the first lockdown in 2020, the concentrations were lower at all stations when compared to 2018 and 2019, except for station XVII when compared to 2019. At this location, the concentrations were higher by 1 µg m$^{-3}$ (5%). After the first lockdown, the pattern of difference in concentrations of PM$_{10}$ was similar to the pattern from the background measurement stations. Looking at the second lockdown period, the concentrations in 2020 were lower than in 2018 at all stations by more than 5 µg m$^{-3}$. The highest decrease was evident at location XIX (–43%). On the other hand, the concentration levels in 2020 were slightly higher than the ones in 2019 at 4 locations (XIX (6%), XVII (2%), V (4%), III (2%)), while a significant decrease was recorded at 3 locations (XXI (–18%), XVIII (–5%), IV (–5%)).

In sum, the relative decrease in PM$_{10}$ levels at traffic locations was slightly higher than at non-traffic locations. The same results were also shown in the study made by Le et al. (2021) and Li et al. (2020). Residential heating can remain a source of PM, even when people are under lockdown, when concentrations from transport and industry are reduced (EEA, 2021a).

The comparison of average concentrations between the different periods at traffic stations (Table 3) yielded the same results as for background stations: significantly lower values for the 2020 lockdowns periods and period in between when comparing to 2018, but only for the after first lockdown period when comparing to 2019.

3.1.2 Particulate matter—PM$_{2.5}$

On an annual level, it is clear that concentrations of PM$_{2.5}$ in 2020 were slightly lower than in 2018 and 2019. Only at location XIV was the concentration in 2020 almost the same as in previous years (Fig. 7).

Table 4 shows the average values for PM$_{2.5}$ concentrations in the same periods as mentioned before. Because there were only PM$_{2.5}$ measurement locations and include different site types, the concentration variability appears large. Nevertheless, the same trend was observed in both
Fig. 5. The plots depict the period PM$_{10}$ average difference for 2020 compared to 2018 and 2019 at 7 traffic stations.

![Chart showing PM$_{10}$ differences before and during lockdowns](image_url)

<table>
<thead>
<tr>
<th>Traffic Measurement Locations – PM$_{10}$</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>XVII</th>
<th>XVIII</th>
<th>XIX</th>
<th>XXI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference 2020–2019</td>
<td>-1%</td>
<td>2%</td>
<td>-13%</td>
<td>3%</td>
<td>-16%</td>
<td>-14%</td>
<td>-3%</td>
</tr>
<tr>
<td>Difference 2020–2018</td>
<td>14%</td>
<td>-17%</td>
<td>1%</td>
<td>14%</td>
<td>1%</td>
<td>-27%</td>
<td>6%</td>
</tr>
<tr>
<td>During I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference 2020–2019</td>
<td>-4%</td>
<td>-7%</td>
<td>-11%</td>
<td>5%</td>
<td>-12%</td>
<td>-20%</td>
<td>-5%</td>
</tr>
<tr>
<td>Difference 2020–2018</td>
<td>-5%</td>
<td>-30%</td>
<td>-22%</td>
<td>-19%</td>
<td>-20%</td>
<td>-30%</td>
<td>-30%</td>
</tr>
<tr>
<td>After</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference 2020–2019</td>
<td>-20%</td>
<td>-10%</td>
<td>-17%</td>
<td>-21%</td>
<td>-14%</td>
<td>-11%</td>
<td>-29%</td>
</tr>
<tr>
<td>Difference 2020–2018</td>
<td>-20%</td>
<td>-22%</td>
<td>-56%</td>
<td>-18%</td>
<td>-34%</td>
<td>-21%</td>
<td>-36%</td>
</tr>
<tr>
<td>During II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference 2020–2019</td>
<td>2%</td>
<td>-5%</td>
<td>4%</td>
<td>3%</td>
<td>-5%</td>
<td>6%</td>
<td>-18%</td>
</tr>
<tr>
<td>Difference 2020–2018</td>
<td>-24%</td>
<td>-51%</td>
<td>-46%</td>
<td>-5%</td>
<td>-39%</td>
<td>-43%</td>
<td>-29%</td>
</tr>
</tbody>
</table>

Legend:
- Difference more than 20%  
- Difference from 0 to 20%  
- Difference from -0 to -20%  
- Difference more than -20%  

Fig. 6. Percent change in PM$_{10}$ concentrations at traffic stations from 2018 or 2019 to 2020.
Table 3. t-test and F-test analysis of PM$_{10}$ concentrations between years at traffic stations.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>71</td>
<td>0.38</td>
<td>0.68</td>
<td>0.71</td>
</tr>
<tr>
<td>During I.</td>
<td>78</td>
<td>0.56</td>
<td>&lt; 0.05</td>
<td>0.16</td>
</tr>
<tr>
<td>After</td>
<td>139</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>During II.</td>
<td>75</td>
<td>0.46</td>
<td>&lt; 0.05</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Fig. 7. Daily average distribution of PM$_{2.5}$ concentrations at 5 locations during 2018, 2019, and 2020.

Table 4. Average daily PM$_{2.5}$ concentration with standard deviation (SD), minimum, maximum, and range values during four periods in 2018, 2019, and 2020.

<table>
<thead>
<tr>
<th>Year</th>
<th>Average daily value with SD</th>
<th>Before</th>
<th>During I.</th>
<th>After</th>
<th>During II.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Min</td>
<td>Max</td>
<td>Range</td>
<td>Min</td>
</tr>
<tr>
<td>2018</td>
<td>22.59 ± 16.84</td>
<td>12.89 ± 3.98</td>
<td>15.25 ± 10.72</td>
<td>21.86 ± 8.84</td>
<td>83.13</td>
</tr>
<tr>
<td>2019</td>
<td>23.04 ± 13.87</td>
<td>11.38 ± 11.18</td>
<td>10.72 ± 4.61</td>
<td>18.48 ± 9.28</td>
<td>109.51</td>
</tr>
<tr>
<td>2020</td>
<td>24.65 ± 13.73</td>
<td>11.18 ± 5.32</td>
<td>8.60 ± 6.39</td>
<td>17.82 ± 14.97</td>
<td>118.00</td>
</tr>
</tbody>
</table>
PM$_{10}$ and PM$_{2.5}$ concentrations. The highest concentrations were found in the first study period (before the first lockdown) in all examined periods.

Figs. 8 and 9 depict the changes in the average concentration of PM$_{2.5}$ during the study periods. Before lockdown period, at locations XI, XXV, and XXI the PM$_{2.5}$ concentrations were higher in 2020 than in 2018 by 7.3 µg m$^{-3}$ (121%), 7.1 µg m$^{-3}$ (36%), and 2.6 µg m$^{-3}$ (7%), respectively. During the first lockdown in 2020, a slight decrease in concentrations can be seen for most of the cases. A decrease of more than 4 µg m$^{-3}$ was found at location XXI (~45%) compared to 2019, while, in comparison with 2018, they were higher by 2 µg m$^{-3}$ (23%). In addition, the results showed that the largest decrease in PM$_{2.5}$ concentrations was in the period after the first lockdown, when PM$_{2.5}$ concentrations were the lowest at all five measuring sites. During the second lockdown, the concentrations were again lower in 2020 compared to 2018 (by more than 4 µg m$^{-3}$), and slightly higher than in 2019 (by 1 µg m$^{-3}$).

Therefore, it can be concluded that, before the first lockdown and during the first lockdown in 2020, the change in PM$_{2.5}$ concentrations was not significant; whereas the concentrations were significantly reduced during the second lockdown as compared to the same period in 2018. Although a decrease in concentrations of fine particulate matter (PM$_{2.5}$) was expected, a consistent reduction cannot yet be seen across European cities. This is likely since the main sources of the pollutants are more varied, including the combustion of fuel for the heating of residential, commercial and institutional buildings, industrial activities and road traffic (Sokhi et al., 2021).

In this case, the comparison of average yearly concentrations between the different periods (Table 5) showed that the most significant differences in mean value (t-test) were found in the period after the first lockdown when comparing to the same period in 2018 and 2019. Significant differences in variance (F-test) were recognized only during second lockdown period when comparing 2019 and 2020, while all periods were significantly different for the 2018 to 2020 comparison.

![Fig. 8. Average difference of daily PM$_{2.5}$ concentrations from 2018 or 2019 vs. 2020.](image)
3.2 Meteorological Conditions in 2018–2020 and Impact on Particle Concentrations

Meteorological variables including temperature, humidity, wind speed, and wind direction greatly impact particulate concentrations in the atmosphere (Khatri and Hayasaka, 2021; Zhu et al., 2020). As stated, the wind conditions in the RS are influenced by its varied relief, location and the Alps. Normally, the wind blows from a westerly direction. Compared to Western Europe, the RS is not as windy, as it is located in the lee of the Alps (Pucer and Strumbelj, 2018). Fig. 9 shows the wind rose plots for 5 different locations across the country from 2018, 2019, and 2020. These locations were chosen according to their nationwide positions. As can be seen from Fig. 10 and Tables S2 and S3, wind speeds and frequency statistics per wind direction during the examined years were similar. A slight difference can be seen in the wind speed between 2018 and 2019, but between 2019 and 2020 the difference was negligible. Significance tests on wind speed between the study periods (Table S4) showed no difference for period before COVID-19, meanwhile significant differences were shown between lockdowns for all data. Significant differences were also recognized for during II. period, except for the comparison years 2020 and 2019 for t-test.

Fig. S2 shows temperature (°C) and relative humidity (%) in all three years. The average temperatures in the period before the first lockdown were 2.04°C, 3.13°C, and 4.08°C for each year respectively. During the first lockdown and after it, the year-to-year temperature variation was minimal. During the second lockdown, the average temperature was 6.17°C in 2018; 7.12°C in 2019, and 5.13°C in 2020.
Fig. 10. Wind rose plots on 5 measurement locations during the years 2018, 2019 and 2020.
Regarding precipitation, there were significantly lower amounts in 2020 by ~50% as compared to both 2018 and 2019. As shown above, PM concentrations in 2019 and 2020 tested as not significantly different (Tables 3 and 5) during this period, which may have resulted from the much greater precipitation in 2019 having a similar effect on PM concentrations as the lockdown in 2020. On the other hand, 2020 PM concentrations were significantly lower than in 2018 during this period even though there was significantly lower precipitation in the former, highlighting the large impact from the lockdown on PM concentrations. In 2020, the most precipitation occurred in the period after the first lockdown, although the accumulated precipitation values were not significantly different than in 2018 and 2019. Thus, the significant decreases in PM concentrations during this period (Tables 3 and 5) highlight possible lingering impacts from the lockdown on human activities even after the first lockdown expired.

4 CONCLUSION

In this work, the impact of lockdown and measures set due to the COVID-19 outbreak on the air quality in the RS is discussed in order to add knowledge about the critical issues which arose in the last years. The concentrations of PM$_{10}$ and PM$_{2.5}$ were analysed on a daily basis by the real-time ambient air quality nationwide monitoring stations provided by EIMV and ARSO. The strength of this study is an assessment of the measurement data from 25 locations and consideration of the meteorological conditions. The study does not only include the shorter restriction periods, but also analyses a year-long period and their comparison with previous years. The results showed that the COVID-19 restrictions could have an impact on the improvement of air quality with regard to PM in the RS. The most significant decrease of PM$_{10}$ in 2020 compared to 2018 was found during both lockdown period and in between, whereas the most significant decrease of PM$_{10}$ in 2020 compared to 2019 was showed in the period between lockdowns. Throughout the PM$_{2.5}$ data the most significant data for both years were recognized in between period. The precipitation amounts during in between period were not significantly different. Additionally, the PM$_{10}$ concentrations exhibited similar trends at traffic stations although traffic stations showed greater decrease in concentrations in 2020. The relation between PM$_{10}$ and PM$_{2.5}$ concentrations showed a higher decline in PM$_{10}$ concentrations.

This study provides an important analysis of RS interannual air quality trends amidst meteorological changes and COVID lockdowns and should promote future studies that include additional pollutant measurements and air quality modelling in the RS.

ADDITIONAL INFORMATION AND DECLARATIONS

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary Material

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.210262

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