Impacts of the COVID-19 lockdown measures on coarse and fine atmospheric aerosol particles (PM) in the city of Rome (Italy): compositional data analysis approach

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Abstract
In the year 2020, Italy faced a pandemic due to the virus SARS-CoV-2 for short COVID-19. Following this pandemic, a national lockdown period was imposed and throughout the year 2020 various measures were taken by the government to limit the mobility of people and contain the mortality associated with COVID-19. In Italy, pandemic measures led to a reduction in anthropogenic activities and provided an unprecedented opportunity to evaluate the possible effects that restrictions on anthropogenic activities may have on the air quality. Two background site (i.e., Cipro and Cinecittà) and a traffic sites (i.e., Corso Francia) were studied in the city of Rome. PM$_{10}$ and PM$_{2.5}$ were considered for the years 2019 and 2020. Moreover, the vehicular mobility, the emission classes of the vehicles, and the people mobility were taken into consideration along with meteorological variables. A compositional data analysis was used to evaluate the effect of pandemic measures on the fine- and coarse-size fractions of PM in the three considered sites. The results showed that in the traffic site (i.e., Corso Francia site) in 2020, there was a reduction of fine-size fraction of PM of about 10% when compared to the data of 2019, whereas in the background site (i.e., Cinecittà site) in 2020 there was an increase of fine-size fraction of PM of about 14% when compared to the data of 2019. No variation in the coarse- and fine-size fractions of PM were observed at the background site Cipro. This study showed how, in an urban context, PM can be influenced by strong changes in people’s habits and in vehicular mobility such as those recorded during the investigated period and due to pandemic lockdown measures.

Keywords COVID-19 lockdown · PM$_{10}$ · PM$_{2.5}$ · Compositional data analysis

Introduction
In the year 2020, Italy faced a pandemic due to the virus COVID-19. Following this pandemic and its dramatic consequences, a national lockdown period was imposed and several measures were taken by the Government to reduce people mobility and contain the mortality associated with COVID-19. All these actions, which led to the reduction of social activities with the aim of reducing the spread of the COVID-19 pandemic, also led to a wide decrease in many industrial and economic activities and the reduction in road traffic. The pandemic measures, adopted to reduce the virus diffusion, led to a reduction in anthropogenic activities and of their relating emissions and a consequent reduction in particulate matter emissions. Therefore, pandemic measures have provided an unprecedented opportunity to assess the possible effects that relevant restrictions on anthropogenic activities can have on air quality with particular reference to atmospheric aerosol particles (PM). Particulate matter (PM) has been extensively investigated over the past two decades due to its effects on human health, air quality, outside visibility, ecosystem, weather, and climate (Abuelgasim and Faragat 2020; Anderson et al. 2012; Grantz et al. 2003; Stocker 2013; Kelly and Fussell 2020; Mukherjee and Agrawal 2017; Pope and Dockery 2006; Speranza et al. 2022; Stieb et al. 2012; Wang et al. 2014; WHO 2016). The common indicators used to measure and investigate PM are PM$_{10}$ and PM$_{2.5}$, which refer to the mass concentration of particles with an aerodynamic diameter of equal to or less than 10 μm and of particles with an aerodynamic diameter equal to or less than 2.5 μm, respectively. The coarse-size...
fraction of PM (i.e., the mass concentration of particles with an aerodynamic diameter between PM$_{2.5}$ and PM$_{10}$) is mainly generated from anthropogenic and natural sources such as road dust, grinding and crushing of material, resuspension of soil by winds, desert dust, volcanic eruptions, and sea spray, while fine-size fraction of PM (i.e., PM$_{2.5}$) predominantly derives from combustion or gas-to-particle conversion processes (Andriani et al. 2010; Caggiano, et al. 2010; Margiotta et al. 2015). Vehicles are the major contributor both of PM$_{2.5}$ and PM$_{10}$ pollution which have hazardous effects on air quality and the health of human beings (Abbas et al., 2017).

Numerous investigators have focused their research on the impact of the COVID-19 pandemic on PM in many cities worldwide. Recent studies, using satellite and terrestrial data, have reported a variety of changes in PM levels due to the effects of the different pandemic measures on human activities, e.g., in India (Kumar et al. 2020; India), China (Filonchyk and Peterson, 2020; Fan et al. 2021), UK (Munir et al. 2021), France (Ikhlasse et al. 2021), Iraq (Hashim et al. 2021), Greece (Kotsiou et al. 2021), Australia (Duc et al. 2021), USA (Bekbulat et al. 2021), Poland (Filonchyk et al. 2021), and Vietnam (Nguyen, et al. 2021). For example, Kumar et al. (2020) reported that due to pandemic measures, there was a substantial reduction in PM$_{2.5}$ concentrations of 19–43% in Chennai and 41–53% in Delhi, noting that cities with high traffic volumes experienced a greater reduction in PM$_{2.5}$. Filonchyk and Peterson (2020) reported that in Shanghai, the PM$_{2.5}$ and PM$_{10}$ reduced by 9% and 77%, respectively, during the lockdown period when compared to the same period in 2019, though Bekbulat et al. (2021), in a study on the effect of pandemic measures on air pollutants in the USA, noted that the average PM$_{2.5}$ levels were slightly higher than expected by about 10% during the “stay-at-home order” period (i.e., a period of a few weeks depending on the US state in which people were asked to reduce their mobility).

In the Italian context, several authors have focused their studies on the effects of lockdown measures on PM. Gualtieri et al. (2020) investigated the period 24/02/2020–30/04/2020, and they reported that in the city of Rome the levels of PM$_{10}$ showed a small decrease of about 12–13% in urban traffic and background stations, whereas PM$_{2.5}$ levels remained comparable to those measured in the same period of 2019. Winkler et al. (2021) reported that, despite the lockdown (March–May 2020), PM$_{10}$ levels in the city of Rome remained similar to those measured in previous years and relating to the same period. In the city of Milan, Collivignarelli et al. (2020) stated that, during the considered lockdown period (March–April 2020), the overall levels of PM$_{10}$ and PM$_{2.5}$ decreased substantially when compared to the levels of PM$_{10}$ and PM$_{2.5}$ recorded previously in 2 weeks of February 2020. Putaud et al. (2020) showed that, in the city of Milan, PM$_{10}$ concentrations were not significantly affected during the lockdown period (March–May 2020). They concluded that the reduction in traffic-related PM$_{10}$ was compensated from an increase of PM$_{10}$ relating to domestic heating and wood burning. Donzelli et al. (2020) assessed the effect of the lockdown due to the COVID-19 outbreak on air quality in three medium-sized cities namely Florence, Pisa, and Lucca. They concluded that in the period January–August 2020, PM did not exhibit any substantial reduction compared to the same period of the previous year. Cucinelli et al. (2022) reported that in the small city of Avellino, the measures undertaken to contain the COVID-19 pandemic had a minor impact on the levels of PM atmospheric concentrations.

The present study deals with the application of compositional data analysis to atmospheric aerosol particles. PM$_{2.5}$ is a part of PM10. As such, PM data can be analyzed considering coarse (PM10-PM2.5) and fine, PM$_{2.5}$, size fractions as part of a total. These data are of a compositional nature. The sample space for compositional vectors is radically different from the real Euclidean space associated with unconstrained data and the handling of this type of data requires a specific approach. Observations in this regard can be dated to Pearson in 1897 with his fundamental article on spurious correlations (Aitchison 2005). The use of compositional data analysis allows to handle the data appropriately by applying methods that respect the nature of the PM (coarse- and fine-size fractions). The compositional data analysis permitted the use of common statistical methods to analyze PM fractions and produce results consistent with the nature of the data. Therefore, the use of compositional data analysis was preferred over the other methods used in the cited literature which did not take into account the compositional nature of PM.

The compositional data analysis began with Aitchison (1982, 1986) and has since been used in many practical applications relating to geoscience, fire emission, and particulate matter (Pawlowsky-Glahn and Buccianti 2002; Pawlowsky-Glahn and Buccianti 2011; Speranza et al. 2018; Speranza et al. 2019; Weise et al. 2020a; Weise et al. 2020b; Weise et al. 2021, Weise et al. 2022a, Weise et al. 2022b).

The study focuses on the impact of pandemic lockdown measures on particulate matter in the city of Rome (Italy). To this aim, daily mass concentrations of PM$_{10}$ and PM$_{2.5}$ measured in two background sites and one traffic site during 2019 and 2020 were analyzed. The monitoring stations of the three considered sites were managed in Rome by the Regional Agency for Environmental Protection (ARPA Lazio) of the Lazio region. Moreover, for the considered urban context the vehicular mobility, the emission classes of the vehicles, the people mobility, and their relating emission sources of PM were taken into consideration along with meteorological variables.
The objective of this study is to evaluate the possible changes in fine and coarse-size fractions of PM between the year 2020 and the year 2019 using compositional data analysis, in view of the extended impact that the pandemic measures have had on the anthropogenic activities over a year. Therefore, the new approach based on compositional data analysis provides further insight on the complex effects that pandemic lockdown measures have had on PM.

Materials and methods

Study areas

The PM$_{10}$ and PM$_{2.5}$ daily mass concentrations measured in three environmental sites in the city of Rome were considered. Rome, the capital of Italy, is the largest city with about 2.86 millions of inhabitants and has an area of about 1300 km$^2$. The city rises on the banks of the Tiber River, and it is located on the west coast of the Italian peninsula about 25 km from the Tyrrhenian Sea. The traffic in Rome is important with about 1.75 millions of cars and 157 thousand of light and heavy vehicles (Roma Capitale 2021; Comune and Roma 2020). The climate in Rome is Mediterranean. The Köppen-Geiger climate classification is Csa with warm temperate climate, hot and dry summers, and mild and humid winters (Rubel and Kottek, 2010). The study was conducted on three characteristic sites such as a traffic site called Corso Francia (N41.95, E12.47) henceforth Francia for the sake of brevity and two background sites called Cipro (N41.91, E12.45) and Cinecittà (N41.86, E12.57) (see Fig. 1). All the studied sites were within the “Grande Raccordo Anulare” (Great Ring Junction), which is a freeway of about 68 km that encompasses the city of Rome. The Francia site is placed in the north of Rome at a major crossroads characterized by a high volume of traffic. The Cinecittà site is located in a densely populated residential area with moderate traffic. This site is in the south-east of the city of Rome and at about 9 km from its center. The Cipro site is in a residential neighbourhood, it is close to a road with a large parking lot nearby (Fusaro et al. 2021; Matassoni et al. 2011; Winkler et al. 2021).

Data source

Two years of PM$_{10}$ and PM$_{2.5}$ daily mass concentrations provided by Regional Agency for Environmental Protection of Lazio region during the period January 2019–December 2020 were considered (ARPA Lazio, 2020).

PM$_{10}$ and PM$_{2.5}$ mass concentrations were performed using a SWAM5a FAI instrument. Further monitoring site descriptions are reported at https://www.arpalazio.it/web/guest/ambiente/aria/sistema-di-monitoraggio. The meteorological parameter such as temperature, relative humidity, wind speed, and rainfall for the years 2019 and 2020 were collected from the SCIA-ISPRA (2020) and they were relating to the sites Urbe (N41.95, E12.5), Monte Mario (N41.94, E12.44), Collegio Romano (N41.9, E12.48), Collegio Romano (N41.9, E12.48), Roma Eur (N41.84, E12.48), Eur (N41.82, E12.50), Ciampino (N41.78, E12.58), and Casilino (N41.87, E12.55) see Fig. 1. In order to evaluate the traffic variations due to the COVID-19 lockdown, the monthly percentage change of vehicular mobility in the city of Rome in the period March–December 2020 compared to the vehicular mobility recorded in February 2020 was considered (the data as retrieved from https://romamobilita.it/it/covid-19-impatto-sulla-mobilita).
Moreover, to evaluate the variation in the people mobility due to the COVID-19 measures, the change in the duration of time spent by people in their place of residence in the city of Rome in the period March–December 2020 compared to a baseline day was considered. The baseline day was the median value from the 5-week period (3 January–6 February 2020). This change in the duration of time spent in residential places was reported in terms of monthly residential percent change. The data as retrieved from Google LLC “Google COVID-19 Community Mobility Reports” (Google 2020).

The study was made considering a whole year because starting from March 2020, the lockdown measures and other measures linked to pandemic progression were modulated throughout the year 2020. Moreover, the analysis conducted over a whole year avoided possible misleading results linked to PM seasonal variability and its relating fluctuations. The year 2019 was used as baseline scenario and corresponding to a time in which the lockdown measures were not in place. The statistical software used was R (R software) and CoDaPack-Version 2.03.01 (Comas-Cufí and Thió-Henestrosa, 2011). A compositional data analysis was applied to the coarse- and the fine-size fractions of PM relating to the two considered years to evaluate the possible compositional variation.

**Fig. 2** Wind rose in the site of Ciampino: a 2020, b 2019, and c 2020 vs. 2019 wind rose comparison of frequency of counts by wind direction. Data at ASOS-AWOS-METAR (2022)
Compositional data and sample space

The sample space of compositional observation \( \mathbf{x} \) with \( D \) components is the unit simplex

\[
S_c^D = \left\{ \mathbf{x} = (x_1, \ldots, x_D) | x_j > 0, j = 1, \ldots, D; \sum_{j=1}^{D} x_j = c \right\}
\] (1)

The sample space of compositional observation \( \mathbf{x} \) with two components is the unit simplex

\[
S_c^2 = \left\{ \mathbf{x} = (x_1, x_2) | x_j > 0, j = 1, 2; x_1 + x_2 = c \right\}
\] (2)

PM\(_{10}\) is inclusive of PM\(_{2.5}\) and PM\(_{10}\) is the total amount of particulate matter. The daily PM\(_{10}\) and PM\(_{2.5}\) measurements were decomposed in terms of relative fractions as coarse, see Eq. (3) and fine, PM\(_{2.5}\), mass concentrations as originally proposed by Lundgren et al. (1996).

\[
PM_{2.5-10} = PM_{10} - PM_{2.5}
\] (3)

These size fractions were converted into compositions based on weight proportions following the strategy suggested in Aitchison (2005).

\[
\mathbf{x} = (x_1, x_2) = \left( \frac{PM_{2.5-10}}{PM_{10}}, \frac{PM_{2.5}}{PM_{10}} \right) \%	ext{ = (coarse, fine)\%}
\] (4)

The compositional variables (coarse and fine components) of this vector \( \mathbf{x} \) are non-negative and sum to a constant \( c = 100 \), see Eq. (2).

Transformation of compositional data

In order to perform statistical analysis of compositional data, an approach based on log-ratio transformation of \( \mathbf{x} \) is required. The compositional data are transformed into coordinate using isometric log-ratio (ILR) transformations (Egozcue et al. 2003). For \( \mathbf{x} \in S_c^D \), the isometric log-ratio is

\[
\text{ILR}_i = \sqrt{\frac{i}{i+1}} \ln \frac{\prod_{j=1}^{i} x_j}{x_{i+1}} \text{for} i = 1, \ldots, D-1
\] (5)

Thus, the composition \( \mathbf{x} \in S_c^2 \) can be represented as a real number.

\[
\text{ILR} = \frac{1}{\sqrt{2}} \ln \left( \frac{\text{coarse}}{\text{fine}} \right) = \frac{1}{\sqrt{2}} \ln \left( \frac{\text{PM}_{2.5-10}}{\text{PM}_{10}} \right) = \frac{1}{\sqrt{2}} \ln \left( \frac{\text{coarse}}{\text{fine}} \right)
\] (6)

Center of compositional dataset and perturbing operations

The center of a two part compositional dataset is defined as Eq. (7).

\[
g = C(g_1, g_2) \text{ where } g_j = \left( \prod_{i=1}^{n} x_{ij} \right)^{\frac{1}{n}} j = 1, 2
\] (7)

where \( C \) is the closure operation for a vector \( \mathbf{z} = (z_1, z_2) \) defined in Eq. (8). This operation divides each component of the vector \( \mathbf{z} \) by the sum of its components, hence scaling the vector to the constant \( c \) (Pawlowsky-Glahn et al. 2015). Equation (4) is the application of closure to \( \mathbf{x} \) since PM\(_{10}\) = \( (z_1 + z_2) \).

\[
C(\mathbf{z}) = \left( \frac{z_1}{z_1 + z_2}, \frac{z_2}{z_1 + z_2} \right)
\] (8)

The perturbation operation is defined as perturbation \( \mathbf{p} \) applied to a composition \( \mathbf{x} \) which produces composition \( \mathbf{v} = \mathbf{p} \oplus \mathbf{x} \) with \( \mathbf{v}, \mathbf{p}, \) and \( \mathbf{x} \) vectors in \( S_c^2 \) (Aitchison 2005).

\[
\mathbf{v} = C(p_1 x_1, p_2 x_2)
\] (9)

The perturbation difference is defined as perturbation \( \mathbf{p} \) to which a change can be attributed from a composition \( \mathbf{x} \) to a composition \( \mathbf{k} \), whatever the processes involved, \( \mathbf{v} = \mathbf{p} \oplus \mathbf{x} \) with \( \mathbf{k}, \mathbf{p}, \) and \( \mathbf{x} \) vectors in \( S_c^2 \) (Aitchison and Egozcue, 2005). The perturbation difference is calculated as in Eq. (10).

\[
\mathbf{v} = C(\frac{p_1}{k_1}, \frac{p_2}{k_2})
\] (10)

The perturbation difference is used to evaluate the level of the difference between fine and coarse components for the years 2019 and year 2020. For a given site, Eq. (10) is applied between the center evaluated in the year 2020, \( \text{coarse/ fine}_{2020} \) and the center evaluated in the year 2019, \( \text{coarse/ fine}_{2019} \). The evaluated perturbation difference, \( \text{coarse/ fine}_{2020-2019} \), provides either the enhancement or the decrease of coarse and fine components. The results are reported in percentage.

The total variance for a compositional dataset \( \mathbf{X} \) is

\[
\text{totalvariance}[\mathbf{X}] = \frac{1}{2D} \sum_{i=1}^{D} \sum_{j=1}^{D} \text{var} \left\{ \ln \left( \frac{x_i}{s_j} \right) \right\}
\] (11)

(Pawlowsky-Glahn et al. 2015).
Testing hypothesis of normal distribution and outliers

The test hypothesis of normal distribution of ILR, see Eq. (6), for the sites of Francia, Cipro, and Cinecittà for the two considered years were performed using the Anderson–Darling, Cramer-von Mises, and Watson tests as in Aitchison (1986) (p. 143). The univariate approach was used since there is only one ILR coordinate. The outliers were identified using the interquartile range (IQR = Q_{0.75} − Q_{0.25}), which is defined as the difference between the third (Q_{0.75}) and first (Q_{0.25}) quartile of the data. Outliers were those ILRs which were outside the interval (Q_{0.25} − 1.5⋅IQR, Q_{0.75} + 1.5⋅IQR) (Filzmoser et al. 2018) (p. 96).

t-test about two means

The objective of paired t-test was to determine whether the mean difference between the two ILR datasets, relating to the year 2019 and year 2020, at each considered site (i.e., Francia, Cipro, and Cinecittà) was significant. The null hypothesis (H0) assumed that the true mean difference between the paired ILR samples was equal to 0, while the alternative hypothesis (H1) assumed that the true mean difference between the paired ILR samples was not equal to 0. Testing the perturbation vector on the simplex is equivalent to testing the difference in the ILR coordinate for the 2 years. A p-value < 0.05 was chosen to reject the null hypothesis (Donzelli et al. 2020, 2021; Fisher, 1934).

Statistical test of the circular means for the wind direction was done using the “circular” package in R. Statistical power analysis was performed with ‘pwr’ package in R (Cohen, 2013).

Results and discussion

Overview of COVID-19 lockdown

In Italy, in the early period of the year 2020, due to the COVID-19 pandemic outbreak, a national lockdown period was imposed between 9 March and 3 May 2020. The lockdown measures included restrictions on the movement of the population except for proven work needs, health reasons, or emergencies. Furthermore, all non-essential commercial and industrial activities were closed and lessons in schools and universities were suspended. From 4 May to 7 October, new actions were taken to ease the containment measures of the pandemic and restore the normal course of public life. However, starting from 6 November, due to the exacerbation of the COVID-19 pandemic, new restrictive measures were introduced, e.g., night lockdown from 24:00 to 5:00 the following day to prohibit night travel. The night lockdown was adopted starting from 22 and 23 October by populous regions such as Lombardia, Lazio, and Campania. Other restrictive measures were adopted for the Christmas holidays (24–27 and 31 December 2020). Besides these measures, throughout the year 2020, distance learning was implemented in schools and universities and, where possible, distance working was adopted with a consequent large reduction of commuting.

PM data and meteorological variables

Hereafter are reported the average mass concentrations of the coarse- and fine-size fractions of PM at the three sites (see Table 1).

The meteorological variables such as temperature, humidity, rainfall, and wind speed for the years 2019 and 2020 in seven meteorological sites across the city of Rome are reported in Table 2. The temperatures in the sites of Collegio Romano, Monte Mario, and Roma Eur showed very close values with a percentage change between −0.5% and −2.8%. The humidity and the mean wind speed values in the sites of Urbe and Ciampino also showed non-substantial variations. In these two sites, the percentage changes were −6.9% and −0.7% for humidity and −7.1% and 0% for the mean wind speed, respectively. For each meteorological parameter, a t-test was used to evaluate the mean difference between the two considered years and they were found to be statistically non-significant (p-value > 0.1).

As shown in Fig. 2a and b, the prevailing wind direction in the site of Ciampino during 2020 and 2019 was South-West (SW) (Guattari et al. 2018). Moreover, the mean difference in wind direction was of about 29° (p-value < 0.05). The 2020 vs. 2019 wind rose comparison showed a difference between 2 and 4% of the frequency of counts by wind direction (Fig. 2c) (Carslaw and Ropkins 2012). Unlike the other meteorological variables, the values recorded for the rain in the year 2019 and in the year 2020 for the sites of Collegio Romano, Monte Mario, Casilino, and Eur showed considerable differences. The percentage change ranged between −26.6% and −29.5% indicating that the year 2020 was less rainy than the year 2019. However, for Collegio

| Sites  | Coarse mg/m³ | Fine mg/m³ | Coarse mg/m³ | Fine mg/m³ |
|--------|--------------|------------|--------------|------------|
| Francia| 11.15        | 13.16      | 10.79        | 14.14      |
| Cinecittà| 10.94        | 16.4       | 12.78        | 13.66      |
| Cipro  | 9.9          | 13.44      | 11.08        | 12.8       |
Romano and Monte Mario, and for Casilino and Eur meteorological stations, the t-test indicated that the mean difference between the rainfall for the two considered years were statistically non-significant ($p$-value > 0.1) and statistically significant ($p$-value < 0.05), respectively. It is important observing that the analysis of cumulative rainfall carried out at the national level by ISPRA showed that the year 2020 ranks 23rd among the least rainy years of the entire series since 1961 with an average cumulative precipitation anomaly of about −5%, while, with an average cumulative precipitation anomaly of about +12%, the year 2019 ranks eleventh among the wettest years in the series since 1961 (ISPRA 2019, 2020).

### Vehicular and people mobility

In the city of Rome, about 26%, 17.9%, and 28.6% of cars had an emission class Euro 4, Euro 5, and Euro 6, respectively, while the percentage of cars with an emission class Euro 0, Euro 1, Euro 2, and Euro 3 were around 27.2%. Similarly, about 15.6%, 15.5%, and 20% of light and heavy vehicles had an emission class Euro 4, Euro 5, and Euro 6,

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**Table 2**: Monthly average, minimum, maximum, and standard deviations of meteorological parameters such as temperature, rainfall, humidity, and mean wind speed for the years 2019 and 2020, and corresponding 2020-to-2019 percentage change.

| Sites              | 2019  | 2020  | ΔM (%) |
|--------------------|-------|-------|--------|
|                    | Min   | Max   | Mean   | sd  | Min   | Max   | Mean   | std  | ΔM (%) |
|                    |       |       |        |     |       |       |        |      |        |
| **Temperature (°C)** |       |       |        |     |       |       |        |      |        |
| Collegio Romano    | 8.1   | 29.4  | 19.0   | 7.2 | 10.4  | 29.2  | 18.9   | 6.7  | −0.5   |
| Monte Mario        | 6.1   | 26.5  | 16.7   | 6.9 | 8.6   | 26.3  | 16.4   | 6.4  | −1.8   |
| Roma Eur           | 6.8   | 26.8  | 17.9   | 6.8 | 9.9   | 27.1  | 17.4   | 6.2  | −2.8   |
| **Rainfall (mm)**  |       |       |        |     |       |       |        |      |        |
| Collegio Romano    | 0.6   | 269.4 | 72.6   | 73.2| 2.0   | 172.7 | 51.2   | 50.5 | −29.5  |
| Monte Mario        | 0.0   | 242.6 | 75.3   | 68.8| 13.0  | 193.8 | 55.3   | 53.5 | −26.6  |
| Casilino           | 0.2   | 275.4 | 78.4   | 83.7| 7.4   | 161.2 | 56.7   | 52.3 | −27.7  |
| Eur                | 0.8   | 280.2 | 69.3   | 85  | 2.4   | 154.6 | 49.9   | 45.5 | −28.0  |
| **Humidity (%)**   |       |       |        |     |       |       |        |      |        |
| Urbe               | 55    | 88    | 70.8   | 11.0| 43.3  | 88    | 65.9   | 14.9 | −6.9   |
| Ciampino           | 52.9  | 81.9  | 67.2   | 9.1 | 52    | 82.4  | 66.7   | 10.4 | −0.7   |
| **Mean wind speed (m/s)** |       |       |        |     |       |       |        |      |        |
| Urbe               | 2.1   | 3.3   | 2.8    | 0.3 | 1.6   | 3.5   | 2.6    | 0.6  | −7.1   |
| Ciampino           | 2.3   | 3.8   | 2.8    | 0.5 | 2.2   | 3.3   | 2.8    | 0.4  | 0      |

$\Delta M = \frac{(M_{2020} - M_{2019})/M_{2019}}{\times 100}$ is the percent change of the monthly average in 2020 against the 2019.

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Fig. 3 The monthly percent change of the vehicular mobility in the city of Rome from March to December 2020 as compared to vehicular mobility in February 2020. ([https://romamobili.ta.it/it/covid-19-impatto-sulla-mobilita](https://romamobili.ta.it/it/covid-19-impatto-sulla-mobilita))
respectively, while the percentage of light and heavy vehicles with an emission class Euro 0, Euro 1, Euro 2, and Euro 3 was around 48.6%. The electric vehicles and unclassified vehicles were around 0.3% and 0.4% for cars and light and heavy vehicles, respectively (Roma Capitale 2021). The higher the emission class, the lower the mass of PM emitted per kilometer. Vehicles with emission class Euro 6 and Euro 5 are five or more times less polluting than the other classes (e.g., Euro 4 or lower) in terms of PM emitted per km (May et al. 2013). Figure 3 shows the monthly percent change in vehicular mobility in the city of Rome from March to December 2020. In this year, the monthly percent change in the mobility of cars decreased from −14 to −69% with an average decrease of about −32%, while the monthly percent change in the mobility of heavy vehicles decreased from −7 to −41% with an average decrease of about −19%. The monthly percent change in the mobility of cars reached its minimum value in the month of April and then increased until the month of September except for the month of August. From September onwards, there was a gradual decrease of the monthly percent change in the mobility of cars until December. The monthly percent change in the mobility of heavy vehicles had a trend comparable to that of cars and reached its maximum value in October. In order to assess the people mobility in the city of Rome in the period from March to December 2020, the monthly residential percent change was considered (see Fig. 4). This index increased from 2 to 31% with a mean

![Fig. 4](image-url) The monthly residential percent change in the city of Rome from March to December 2020 (Google, 2020)

![Fig. 5](image-url) ILR box plot for Francia 2019 and Francia 2020
increase of about 12%. The monthly residential percentage change in the mobility of people reached its maximum value in April and then decreased until August.

From August onwards, the monthly residential percentage change gradually increased until December. The monthly residential percentage change and the monthly percent change in vehicular mobility follow a qualitatively opposite trend in that as one increases, the other decreases and vice versa. It is also worth mentioning that the measures due to the pandemic and the relating restrictions on mobility led to a reduction in the consumption of petroleum products. In Italy in 2020, the reduction in the consumption of petroleum products compared to the same period of 2019 recorded a −33% in March and −45% in April. In May, with the partial reopening of production activities and vehicular mobility, the reduction was −29%. This attenuation continued in June (−18%) reaching −7% in September. In October, the reductions in consumption began to grow again, reaching around −17% in December. In autumn, this decrease in consumption was recorded in conjunction with the new mobility restrictions due to the exacerbation of the pandemic. With reference to the period from March to December 2020, the main motor fuels (diesel engines and gasoline) decreased overall by 21% compared to the same period in 2019. By contrast, the consumption of natural gas on the distribution networks increased by approximately 1.6% in the period March–December 2020 when compared to the same period in 2019. By contrast, the consumption of natural gas on the distribution networks increased by approximately 1.6% in the period March–December 2020 when compared to the same period in 2019. The largest increases were recorded in the autumn, 40% in October and 10% in December 2020 (ENEA 2020). As indicated by the monthly residential percent change, people stayed at home, and this increased the residential energy consumption. It should be noted that in the city of Rome, several authors identified road traffic as the main source of particulate matter and pollution and as an additional factor the heating systems that contribute to pollution levels especially during the cold period of the year (Battista and de Lieto Vollaro 2017; Fanizza et al. 2018). Moreover, in Italy, the industrial sector was affected by the COVID-19 pandemic; however, there are no heavy industries around the city of Rome and the closest power plant is located at about 100 km from the urban area, as reported by Perrino et al. (2008).

### Coarse- and fine-size fractions of PM

The results relating to the changes of coarse- and fine-size fractions of PM between the year 2020 and the year 2019 in three selected sites of the city of Rome are reported. The coarse- and the fine-size fractions of PM measured in the sites of Francia, Cinecittà, and Cipro were considered and the relating compositional variables were evaluated for the years 2019 and 2020 as described in Eq. (4). Compositional statistical summary for these years are reported Table 3 and Table 4. In 2019, the observations considered for the sites of Francia, Cipro, and Cinecittà covered respectively about 96%, 94%, and 93% of all possible annual observations. The three compositional dataset showed center and median with very close values, indicating that the data were symmetrically distributed. The maximum value for the fine component was recorded in Francia (traffic site), while its minimum value was recorded in the Cinecittà (background site). The coarse component showed its maximum value in the Cinecittà site and its minimum value in the Francia site. Similarly, in 2020, the observations considered for the sites of Francia, Cipro, and Cinecittà covered about 91%, 94%, and 90% of all possible annual observations, respectively.

The three compositional dataset in the 2020 also showed center and median with very close values, indicating that the data were symmetrically distributed. The fine component showed its maximum values in the Cinecittà site and its minimum value in the Francia site. The maximum value for the coarse component was recorded in the Francia site and its minimum value in the Cinecittà site. The total variance was qualitatively lower for data measured in 2019 than for data measured in 2020. A lower total variance indicated greater homogeneity of the ratios between the coarse and fine components in the year 2019. In order to evaluate the possible variations of PM between the year 2019 and the year 2020 in

| Table 3 | Compositional statistics summary: number of observations, center, median, minimum, maximum, 1st, 3rd quartile, and total variance for coarse and fine components measured in the sites of Francia, Cipro, and Cinecittà for the year 2019 |
|--------|------------------------------------------------------------|
| Observations | Francia 2019 | Cipro 2019 | Cinecittà 2019 |
| Fractions | | | |
| Coarse | Fine | Coarse | Fine | Coarse | Fine |
| Min | 0.18 | 0.25 | 0.20 | 0.22 | 0.19 | 0.19 |
| 1st qu | 0.35 | 0.49 | 0.38 | 0.44 | 0.38 | 0.42 |
| Center | 0.43 | 0.57 | 0.46 | 0.54 | 0.48 | 0.52 |
| Median | 0.42 | 0.58 | 0.45 | 0.55 | 0.47 | 0.53 |
| 3rd qu | 0.52 | 0.65 | 0.56 | 0.62 | 0.58 | 0.62 |
| Max | 0.75 | 0.82 | 0.78 | 0.80 | 0.82 | 0.81 |
| Total variance | 0.13 | 0.14 | 0.14 | 0.18 | 0.18 |
the France, Cipro, and Cinecittà sites, a compositional data analysis was applied to the above evaluated compositional variables. The compositional variables were transformed into coordinate using ILR transformations as described in Eq. (6). The results are shown in Figs. 5, 6, and 7. ILR statistical summary is reported in Table 5. Figure 5 shows the ILR coordinates for the Francia site for the years 2019 and 2020. The ILR Francia 2019 ranges between −1.09 and 0.78, with a mean of −0.2. The corresponding coarse to fine component ratio ranges between 0.21 and 3.0, with a mean of 0.76. In the Francia site in 2019, the fine component was the dominant one, highlighting the traffic feature of the studied site. The ILR Francia 2020 ranges between −1.23 and 1.14, with a mean of −0.07. The corresponding coarse to fine component ratio ranges between 0.17 and 5.0, with a mean of 0.91. In the Francia site in 2020, the fine and coarse components were almost comparable.

A t-test was used to test whether the mean difference between the two sets, ILR Francia 2020 and ILR Francia 2019, was significant. Before, the two datasets were tested for normality. The distribution of ILR Francia 2019 and ILR Francia 2020 followed a normal distribution at a significant level greater than 15% (see Table 6). The t-test showed (see Table 7) that the true mean difference between the paired ILR samples was not equal to 0. This result confirms that fine component was less abundant in the Francia site in 2020. To evaluate the nature and the level of the difference between fine and coarse components for the year 2019 and the year 2020, the perturbation difference was calculated between the centers of the two compositional datasets.

The centers were (0.43, 0.57)_{2019} and (0.48, 0.52)_{2020} for the years 2019 and 2020, respectively. The perturbation difference was (0.55, 0.45)_{2020-2019} suggesting that relatively in the year 2020, there was a reduction of the fine component of about 10%. Francia is a traffic site. These results can be interpreted considering that the decrease in traffic due to the pandemic measures reduced the traffic relating emissions and this led to a reduction in the fine-size fraction of PM when compared to what was measured the previous year (Dimitriou and Kassomenos, 2014; Fanizza et al. 2018).

**Table 4** Compositional statistics summary: number of observations, center, median, minimum, maximum, 1st, 3rd quartile and total variance for coarse and fine components measured in the sites of Francia, Cipro, and Cinecittà for the year 2020

| Fractions | Francia 2020 | Cipro 2020 | Cinecittà 2020 |
|-----------|-------------|------------|----------------|
| Min       | 0.14        | 0.14       | 0.10           |
| 1st qu    | 0.37        | 0.43       | 0.43           |
| Center    | 0.48        | 0.45       | 0.41           |
| Median    | 0.47        | 0.53       | 0.41           |
| 3rd qu    | 0.58        | 0.63       | 0.53           |
| Max       | 0.83        | 0.86       | 0.81           |
| Total variance | 0.18 | 0.24 | 0.25 |

**Fig. 6** ILR box plot for Cinecittà 2019 and Cinecittà 2020
Several literature results are reported as a comparison, taking into consideration the variety of the studied sites in many cities of the world, the different periods considered, and the different survey techniques adopted. Xin et al. (2021) reported that in Beijing (China) in 2020 during the examined lockdown period (January 24 to March 15), there was
a reduction in travel intensity of 46.9% and a reduction in PM$_{2.5}$ of 5.6% when compared to the data of 2019. Donzelli et al. (2021) observed that in Valencia (Spain), in three urban traffic sites, during the lockdown period (15 March to 17 May 2020), there was a reduction of PM$_{2.5}$ level between 41 and 53% when compared to the same period of the previous year. Munir et al. (2021) reported that in Leeds (UK), in an urban traffic site during the lockdown in 2020 (24 March–10 May), there was a reduction of PM$_{2.5}$ of about 30% when compared to the data of 2019.

In the literature, a comparatively greater reduction in fine-size fraction of PM has been reported in some traffic sites. This outcome could be due to the differences between the vehicle fleet emission classes at different traffic sites studied worldwide. In the city of Rome, about 47% of the cars had an emission class either Euro 5 or Euro 6, while about 53% of the cars had an emission class Euro 4 or lower. The pandemic measures led to an average reduction in car mobility of around 32%. Therefore, the decrease in car traffic made up for about half of Euro 5 and Euro 6 cars has resulted in a reduced impact on the fine-size fraction of PM for the city of Rome than for other cities.

However, the reduction of the fine-size fraction of PM observed at the Francia site is an encouraging outcome towards the possible mitigation of PM linked to traffic emissions. The 10% reduction in the fine-size fraction of PM was due to a greater extent to the decrease in traffic of cars with low emission classes (e.g., Euro 4 or lower). The pandemic measures reduced the traffic of cars with low emission classes by about a third. Therefore, the replacement of polluting vehicles with higher emission class vehicles could mitigate the fine-size fraction of PM in traffic sites in Rome. In proportion, the reduction of fine-size fraction of PM could be about 30%. Figure 6 shows the ILR coordinates for the Cinecittà site for the years 2019 and 2020. The ILR Cinecittà 2019 ranges between −1.04 and 1.05, with a mean of −0.06. The corresponding coarse to fine component ratio ranges between 0.23 and 4.4, with a mean of 0.92. In the Cinecittà site in 2019, the fine and coarse components had close values.

The ILR Cinecittà 2020 ranges between −1.56 and 0.98, with a mean of −0.26. The corresponding coarse to fine component ratio ranges between 0.11 and 4.0, with a mean of 0.69. In the Cinecittà site in 2020, the fine component was the dominant one. Similarly, a t-test was used to test whether difference between the two sets, ILR Cinecittà 2020 and ILR Cinecittà 2019, was significant. The two datasets were tested before for normality. The distribution of ILR Cinecittà 2019 and ILR Cinecittà 2020 followed a normal distribution at a significance level greater than 15% (see Table 6). The t-test showed (see Table 7) that the true mean difference between the paired ILR samples was not equal to 0. This result confirms that fine component was more abundant in the Cinecittà site in 2020. To evaluate the level of the difference between fine and coarse components, the perturbation difference was calculated between the centers of the two compositional datasets. The centers were (0.48, 0.52)$_{2019}$ and (0.41, 0.59)$_{2020}$ for the years 2019 and 2020, respectively. The perturbation difference was (0.43, 0.57)$_{2020-2019}$ suggesting that relatively in the year 2020 there was an enhancement of the fine component of about 14%. The Cinecittà site is located in a densely populated residential area with moderate traffic. These results can be interpreted considering that although pandemic measures reduced traffic and its relating emissions, the adopted measures encouraged people to stay at home as confirmed from the monthly residential percent change. And this variation in people’s habits possibly increased domestic emissions (e.g., cooking and heating), which led, overall, to an increase in fine-size fraction of PM when compared to what was measured the previous year (Tofful and Perrino, 2015). Bekbulat et al. (2021) observed an increase in PM$_{2.5}$ (about 10%) during the “stay-at-home order” pandemic measure. They noted that while “stay-at-home order” reduced traffic, this measure potentially increased other emission sources such as wood burning for residential heating and cooking. In the Italian context, a similar compensation mechanism between PM emission sources was described by Putaud et al. (2020).

Figure 7 shows the ILR for the Cipro site for the years 2019 and 2020. The ILR Cipro 2019 ranged between −0.98 and 0.89 with a mean of −0.12. The values of coarse to fine component ratio ranged between 0.25 and 3.5 with a mean of 0.84. The ILR Cipro 2020 ranged between −1.27 and 1.08 with a mean of −0.15. The corresponding values of coarse to fine component ratio ranged between 0.166 and 4.6 with a mean of 0.81. In both datasets, the fine component was the dominant one. The ILR means were very close. However, a t-test was used to test whether mean difference between the two sets, ILR Cipro 2020 and ILR Cipro 2019, was significant. The two datasets were tested before for normality. The distribution of ILR Cipro 2020 followed a normal distribution at a significance level between 10 and 15%, whereas the distribution of ILR Cipro 2019 followed a normal distribution at a significance level between 5 and 10%, albeit at a significance level between 2.5 and 5% in one case, namely the Watson test (see Table 6).

However, the hypothesis of normality cannot be rejected. The t-test did not reject the null hypothesis (see Table 7) that the mean difference between years was equal to 0. This result suggests that there is no difference between the coarse- and fine-size fraction of PM measured in 2019 and those measured in 2020. The Cipro site is a residential area close to a road with a large parking lot nearby. At the Cipro site, it can be assumed that the decrease in fine particle emissions due to traffic reduction was compensated by the increase in fine particle emission linked to domestic-related emissions.
of the three studied sites, the compositional data analysis nearby the coarse- and the fine-size fractions of PM in the fraction of PM of about 14%. On the Cipro site, a residential lockdown measures showed that severe changes in people and vehicular mobility influenced the coarse- and fine-size fractions of PM in the studied sites at some extent.

The reported findings reveal how the pandemic measures have influenced the PM in a large European city within a year and how it is not possible to indicate a univocal general trend, since the results depend on the local environmental characteristics of the studied site (e.g., traffic or background). Moreover, the analysis carried out on atmospheric particulate matter at the traffic site, in consideration of the vehicle fleet emission classes and the variations in vehicles traffic, indicates that the replacement of polluting vehicles with higher emission class vehicles would lead to a mitigation of the fine-size fraction of PM. However, the analysis carried out on atmospheric particulate matter at background sites pointed out that the mitigation of PM emissions from vehicular traffic could be offset by domestic PM emissions. Therefore, in an urban context as the one object of study, these figures suggest that only a rethinking of all those human practices involving combustion processes and their relating emissions in a green perspective towards the abatement of PM can lead to an improvement in air quality for the benefit of public health and the environment.

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Author contribution Antonio Speranza provided the idea and designed the study. Antonio Speranza and Rosa Caggiano illustrated the figures and wrote the manuscript.

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ARPA Lazio (2020). ARPA Lazio Regional Emission Inventory – Emissions in the Lazio Region (2020) Available online https://www.arpalazio.it/, Accessed 1st November 2021.

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